



Universitat de Girona

CONGESTION PROBABILITY ROUTING IN VIRTUAL PATH ATM NETWORK

Ramon FABREGAT GESA

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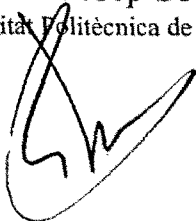
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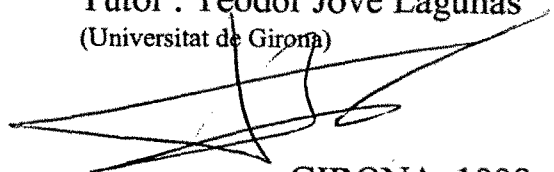
**“CONGESTION PROBABILITY ROUTING
IN VIRTUAL PATH ATM NETWORKS”**

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To my parents Ramón and Mercedes
and my sister Mayme

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1. Introduction

Asynchronous Transfer Mode (ATM) networks are playing an important role in the current communication networks panorama. This is because of their capacity to handle high bandwidth and their ability to support Quality-of-Service (QoS) guarantees. ATM networks are the basis for the development of multimedia applications. ATM networks consist of ATM switches (also known as nodes) interconnected by point-to-point links. The data in ATM networks is transmitted in the form of fixed length packets called cells. The standards specify the fixed length as 53 bytes, which includes a 5-byte header. The header contains information that is used to route the data cells from the source to the destination through the fixed path set up in the connection phase.

ATM is a connection-oriented networking technology. That means that the route selected for the establishment of a virtual connection or virtual path remains in use for an extended period of time, and the consequences of an inefficient routing decision will affect a connection for as long as that connection remains open. A virtual connection has to be established between two end-points before data can be transferred across the network. The virtual connection is identified by the combination of a Virtual Path Identifier (VPI) and a Virtual Channel Identifier (VCI). The current values of the VPI/VCI have only a local significance on a given link. These values are a part of the ATM cell header. Therefore, when the ATM cells are switched from one link to another at a switch, the VPI/VCI values are also translated. Since the VPI/VCI fields are small and of fixed length, the switching of ATM cells can be performed by hardware. Therefore, the hardware intensive ATM switches are capable of high-speed switching and handling very high bandwidth.

The International Telecommunications Union - Telecommunications Standardization Sector (ITU-T) and the ATM Forum has standardised the routing and signalling protocols for establishing point-to-point connections in ATM networks ([Q.93B], [Q.2931], [UNI-3.0] and [UNI-3.1]). Routing involves the mechanisms used for the computation of the route to be used for the connections. Signalling involves the actual establishment, maintenance and tearing down of connections. In order to compute efficient routes, the routing protocol provides mechanisms for gathering and maintaining the topology information. The topology information of a network comprises the state information pertaining to the links and the nodes of that network. This information is pertinent to the computation of an efficient route

across the network. Efficient routes result in better utilization of the network resources. As ATM is connection oriented, it is critical that routing protocols select routes carefully.

ATM allows the users to specify, when setting up a call, Quality of Service (QoS) and bandwidth parameter values that an ATM network should be able to guarantee for that call. Call establishment consists of two operations: (1) the selection of a route, and (2) the set-up of the connection state at each point along that route. The current routing protocols do not specify any single required algorithm for route selection. Route selection is done, in such a way that the route chosen appears to be capable of supporting the QoS and bandwidth requested, based on currently available information. The processing of the call set-up at each node along the route confirms that the resources requested are available. If they are not, then crank-back occurs, which causes a new route, if any, to be computed; thus the final outcome is either the establishment of a route satisfying the request, or refusal of the call.

To some extent efficient QoS-sensitive route selection is still a research issue. Also, some known algorithms for QoS-sensitive route selection, in the presence of multiple constraints, require consideration of multiple independent link parameters and are relatively expensive computationally. Therefore, it is very important that routing protocol allows flexibility in the choice of QoS-sensitive route selection algorithms.

In [DZI97] and [AMM97] point and multipoint connection are explained. The different types of connections that can possibly be supported are:

- **Point to point connection.** The connection involves a single sender (origin node) and a single receiver (destination node).
- **Multipoint connection.** The multipoint connection can involves multiple senders and/or receivers. In general the notion of multipoint connection refers to connections that involve a group of users with more than two members.

The term multipoint is used in [AMM97] to refer in general to all forms of communications with multiple participants, regardless of semantics. The term “multicast” has been used almost synonymously, even though it is often used to denote point-to-multipoint communication. The term “multipoint” is preferred because of its more general connotations. For example, “multicast” will be used to characterize the routing tree, whereas multipoint communication will be used to describe any type of communication within a group. This terminology is also used in this dissertation.

Future multimedia applications like video-servers, interactive video-games and distributed interactive simulations, which are likely to scale to large networks, require more efficient and faster multicast support. It is, therefore, desirable that multicast support be provided at the lower layers because this relieves the higher layers from the responsibility of

managing these connections. The underlying network has to provide multicast support to efficiently manage existing services as well as future applications.

The current specification provides excellent support for point-to-point connections. But, at present, support for multipoint applications in ATM networks is rudimentary. ATM networks, that are designed to handle high bandwidth applications and provide QoS guarantees, are better suited to run multicast applications. Excellent connection admission control schemes and packet scheduling mechanisms have been designed for these networks to support real-time applications. But, there is a lack of support for efficient multicasting schemes in ATM networks. Multicasting involves sending data from a sender to multiple receivers simultaneously using a single connection. The multicasting support can be provided at any of the seven OSI layers. If the network layer cannot support such a connection method, the data can still be sent to multiple receivers using a separate point-to-point connection from the sender to each of the receivers. The application then has to manage the set up and maintenance of the multicast session.

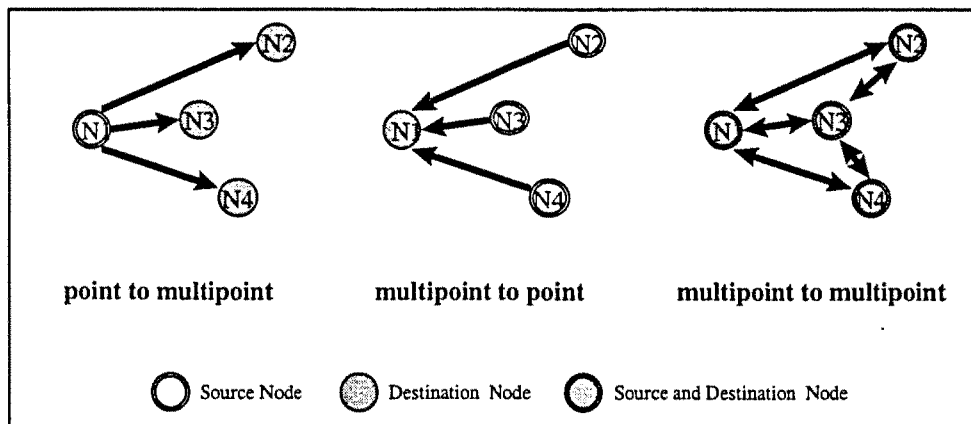


Fig. 1 : Multipoint Connections

Three basic categories of multipoint connections can be recognized: point to multipoint, multipoint to point and multipoint to multipoint, which are illustrated in above figure.

In the first category referred to as point to multipoint connections, there is one source and several destinations. Broadcasting of the same information to several users is a typical application in this category. In the opposite case, multipoint to point connections, the information from several sources is collected by one destination. Data collection and distributed measurements are possible applications within this category. Multipoint to multipoint connections constitute the third category where each of the group members can send and receive information to or from all other members. Applications for group communication such as teleconference, teleeducation, teleworking, etc. are examples in this category.

1.1 OBJECTIVES

This dissertation focuses on the problem of providing mechanisms for routing point to point and multipoint connections in ATM networks. In general the notion of multipoint connection refers to connections that involve a group of users with more than two members. The main objective of this dissertation is to contribute to design efficient routing protocols with alternative routes in fully connected VP-based ATM Networks for call establishment of point to point and multipoint VC connections. An efficient route should be computed during this connection establishment phase.

The principal grade of service (GoS) metric on the connection layer is Connection Blocking Probability (CBP) which is defined as the number of connections rejected (or blocked) divided by the number of connections requested.

A study of the routing protocols designed in datagram networks shows that these protocols are not very efficient for ATM networks.

The goals for routing include maximizing the load accepted by the network while providing satisfactory QoS to connections and treating all call requests fairly. These goals can be contradictory, so the search for optimal algorithms is in fact quite elusive. The principal objectives of our work has been are obtain an easy and efficient routing strategy.

Therefore, there are two main optimization criteria :

- **efficiency**, the objective of which is maximization of network resources' utilization and minimization of their cost. Transmission bandwidth and buffer space are the network resources maximized, while QOS requirements are fulfilled for all connections. A better utilization of the network resources is obtained when the CBP is minimized.
- **network access fairness** which is interpreted as fair access to network resources for all users. This criteria is achieved when a CBP equalization is obtained. The price to be paid for that equalization is that the network resources' utilization decreases.

Another important goal is that user performance should be relatively insensitive to variations in the arrival and departure of other users (**isolation**).

1.2 OVERVIEW OF THE PROBLEM

The first problem addressed in this dissertation involves the computation of a single route to be associated with a point to point connection. To obtain the improvement of resource utilization we use a dynamic routing scheme with alternative routes.

Different point to point routing algorithms are studied changing:

- the metric parameter of the VP cost,
- the composition rule of the alternative route cost,
- the route selection scheme, and
- the determination of available alternative routes.

Congestion Probability (CP), which is the sum of probabilities corresponding to rates greater than the capacity of the VP, is considered as VP cost function. The CP reflects the characteristics of the current network load.

Using alternative routes does not always decrease the CBP of the network. To overcome this drawback an alternative route is only considered (available alternative route) if the cost of each VP of the alternative route is smaller than a threshold that we call Routing Control Parameter (RCP).

One of the important distinctions between the point to point and multipoint connections is the possible dynamic nature of connections. It is quite likely that in some applications the group membership can vary during the connection's life time. This variability adds additional complexity to the already difficult problem of CAC and routing of multipoint connections. Dynamic Multicast Routing algorithms permit destination node to join and leave a multicast group and the corresponding multicast trees (or rings) at any moment.

1.3 MAIN CONTRIBUTIONS OF THE DISSERTATION

This dissertation addresses the problem of routing in ATM networks. The main contributions of this dissertation are:

- Proposing an adaptive point to point connection routing scheme with alternative routes, the Congestion Probability Routing (CPR) algorithm.
- Definition of Congestion Probability (CP) as a metric parameter of the VP cost function.

- Definition of the Routing Control Parameter (RCP) as a threshold of the Congestion Probability on the VP. The RCP inhibits alternative routing when the VP becomes too loaded and increases the probability that the direct routed calls are set up. This protective mechanism determines the set of available alternative routes.
- Study the CAC-routing cycle, the set of allowable states and the Call Blocking Probability of the CPR algorithm.
- The utilization of different composition rules to calculate the cost of alternative routes and different selection schemes are studied.
- Compare the performance of the CPR when other composition rules of the alternative route cost and route selection schemes are considered.
- Study how the Congestion Probability Routing can be extended to routing dynamic multipoint connections. Addition and deletion process are explained.
- Different tree solutions with constrained end-to-end Cell Loss Rate are presented.
- Subdivide the set of alternative routes in two subsets. When there are two or more destination nodes, the transit node of an alternative route could be one of the destination nodes. In this case, this transit node is known as an implicated node and the route is known as an "*alternative route through an implicated node*". Alternative routes through an implicated node are considered before those alternative routes in proposed algorithms.
- In alternative routing, the direct route is used with priority. In the proposed multipoint algorithms the Quality of Service of the direct route is considered to maintain this priority. Different algorithms are presented varying the precedence of the "*alternative route through an implicated node*" in relation with direct route.
- Propose a "**Ring**" solution which is considered when all (or several) nodes are simultaneously source and destination. These algorithms are based on a process that derives a ring of r nodes from a ring of $(r-1)$ nodes.
- We show by using simulations that these routing protocols compute efficient routes and multicast trees.

1.4 ORGANIZATION OF THE DISSERTATION

This dissertation is organized as follows. In Chapter 2, a survey of background and related work of routing of point to point connections in fully VP-based ATM networks is provided. The relation among Network Provisioning, Bandwidth Allocation, Connection Admission Control and Routing is described. The importance of the Virtual Path (VP) concept as a component of traffic control and resource management is explained. The definition of the VPN embedded in the physical network is also given in this chapter. Finally a brief introduction of dynamic, alternative and adaptive routing in ATM networks is explained. Congestion Probability Routing proposed to routing point to point connections is provided in Chapter 3. Based on simulation results, it is shown in Chapter 4 that the proposed routing algorithms computes efficient routes by point to point connections in most cases and that user performance are relatively insensitive to variations in the load of other users. The main issues associated with routing of multipoint connections are discussed in Chapter 5. We present an overview of different routing protocol based on the routing cost function that we would minimise, different ways to establish multipoint connections in ATM networks and a classification of multicast routing algorithms depending on the membership changes, both static and dynamic version. Some consideration about how the CPR algorithm can be extended to routing dynamic multipoint connections are explained in Chapter 6. Two solutions are proposed. The tree solution is based on adding the destination nodes one by one to the multicast tree. The ring solution is a ring-based approach which is considered when all (or several) nodes are simultaneously source and destination. The deletion process and the static version by the two solutions are also presented. Finally, in Chapter 7; the conclusions drawn from the study of the routing problem in ATM networks are provided. Pointers to areas of future work are also suggested.

2. Background and related work

Resource Management and Traffic Control in communications networks deals with the controlled use of network resources to prevent the network from becoming a bottleneck. In particular, when network resources are allocated to more connections/traffic than they can effectively support, network performance for users degrades (i.e., buffers start to overflow and delays increase beyond acceptable levels). Therefore, it is necessary to allocate and control the traffic so that the network can operate at acceptable levels even at times when the offered load to the network exceeds its capacity.

The first issue of a resource management and traffic control strategy in Asynchronous Transfer Mode (ATM) network is **efficiency**, the objective of which is maximization of the network resources' utilization and minimization of their cost. Transmission bandwidth and buffer space are the network resources maximized, while QoS requirements are fulfilled for all connections.

The second issue deals with the problem of **fairness** which is interpreted as fair access to network resources for all users within the established priority and cost constraints (on the cell and call layers).

ITU-T and the ATM Forum have defined a range of traffic and congestion control functions to maintain the QoS of ATM connections [I.371]. The relationships between different Network Provisioning¹, Network Resource Management², Connection Admission Control (CAC) and Routing are schematically given by the next figure. Routing is part of or applied in parallel with the above three control actions. The drawback of many existing routing algorithms is the lack of co-operation between congestion control and routing.

In [DZI97], a framework and some models are presented which would help to cope with the complex issue of a broad range of services, traffic characteristics, time scales, and performance constraints, integrated into one system.

¹ Physical Network Resource Management in [DZI97] terminology.

² Virtual Network Resource Management in [DZI97] terminology.

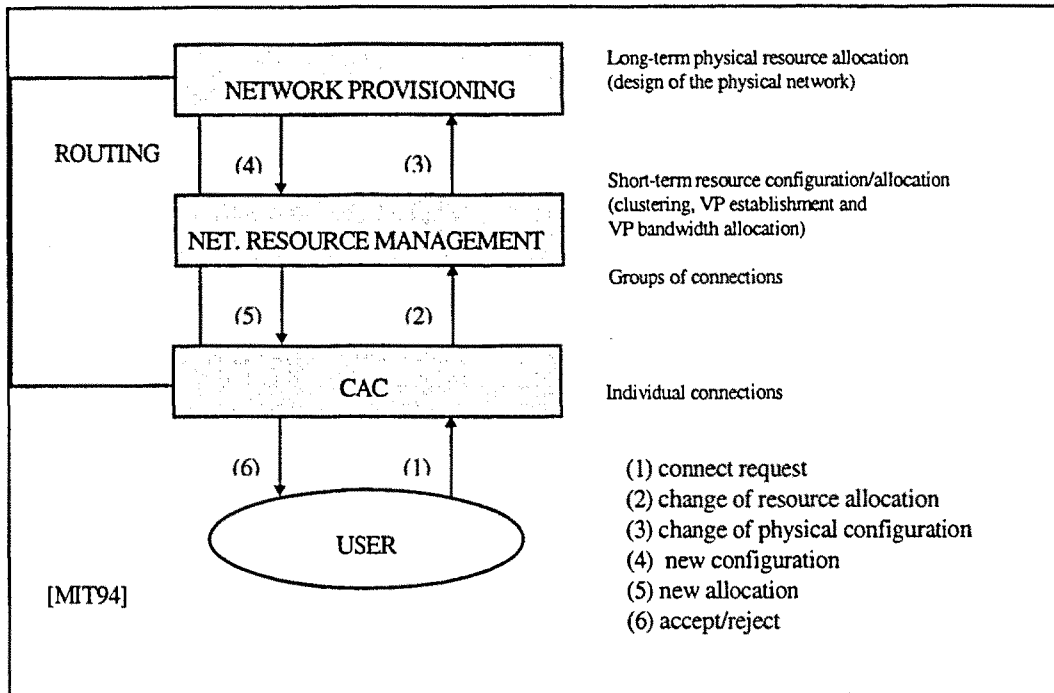


Fig. 2 : Network Provisioning, Network Resource Management, CAC and Routing relationship

Network Provisioning (NP) is the set of the long-term control actions that determine the physical quantities of the resources to be placed in the **physical network**. Therefore, the physical network can be seen as a set of nodes and transmission links connecting the nodes. The first issue is to create network connection topology and to allocate resources to each link for a given traffic demand and node configuration constraints. The design should ensure that overall throughput of the network can support the estimated traffic demand under required performance and reliability constraints. The second issue is to adapt the network topology and resource allocation based on the measurements of performance indicators from the lower layers. The third issue is to provide self-healing capabilities in case of equipment failures.

Connection-oriented services are supported by establishing a Virtual Channel (VC) between two points. To reduce network management complexity, multiple VCs which share the same physical network path may be logically grouped to form a Virtual Path (VP) [OHT88]. The routes for each VP on the physical network are predefined and are viewed as semipermanent network connections. Compared with managing individual VCs in a large network, using VPs simplifies call admission control and routing, streamlines network resource management, and reduces nodal processing. In ATM networks, Network Provisioning issues are based on the VP network concept.

Network Resource Management (NRM) is the set of control functions related to establish a **Virtual Path Network (VPN)** and to allocate resources (bandwidth and buffer), which are performed by the network in order to optimize performance and utilization objectives, namely to provide the required Quality of Service (QOS) and to maximize utilization, with simple Connection Admission Control (CAC) and Routing procedures. The

VPN layer represents a logical network located at an intermediate layer between Connection and Physical Network layers. CAC decides on the acceptance of new connections based on the resources made available to the various routes, while NRM must change the allocated resources to the Virtual Paths according to the demands placed by the users on CAC. Note that the admission control and routing are coupled problems since the network accepts a call only if it can find a suitable route. Routing could also be considered as belonging either to NRM or to CAC.

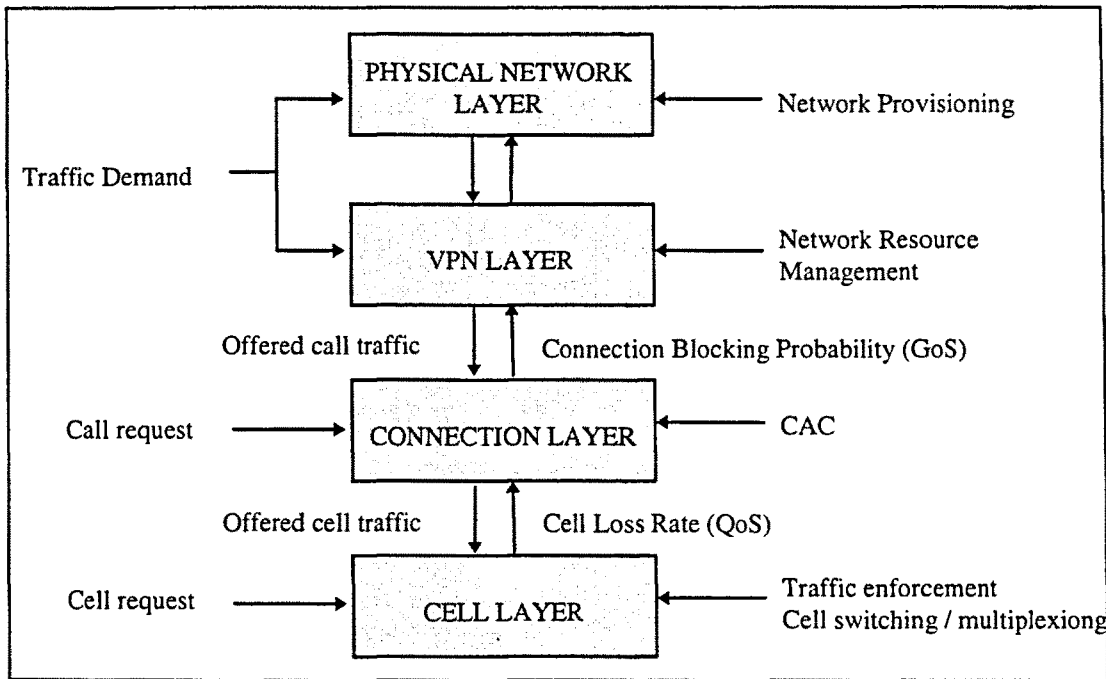


Fig. 3 : Layer architecture

There are three generic issues associated with a VPN concept for resource management: *VPN design*, *VPN adaptation to environment changes*, and *design of the backup VPN*. The objective of the VPN design is to optimize VPN topology and resource allocation based on the predicted traffic demand and performance constraints (GoS, fairness criteria). Once the VPN is set up, the initial design may be not optimal, due to either discrepancies between the real and predicted traffic patterns or changes in traffic patterns and cost factors. Thus an adaptive procedure is required to adjust the VPN resources allocation and topology. This procedure should be based on measurements of parameters relevant to the GoS, fairness, and resource cost. Other important issues of resource management is protection against link and node failures. The objective is to ensure that all (or a given fraction of) connections affected by the failure can be restored on the non-affected links (one failure at a time is assumed). A backup VPN is a very effective tool for this kind of fault management. The backup VPN is defined by distribution of restoration virtual path and virtual channels for existing connections. The main design issue is to optimize this distribution so that the resource allocated to the backup VPN are minimized.

One aspect of the Grade of Service (GoS) offered to the customers is the likelihood that a connection will be blocked (or rejected). If the connection blocking objectives are still not being met, the VP bandwidths could be adjusted in order to meet the changing traffic demands; failing this, the whole VP network could be reconfigured so as to increase the carried traffic based on the current network load. The issue of fairness deals with GoS distribution among the connection classes.

In a VP-based ATM network, a new connection is established by selecting a set of VPs which connect the source and destination. To establish a **connection** between two arbitrary nodes, an appropriate route through the network must be identified, and sufficient resources must be secured at every intermediate node along the selected route (**resource allocation**). The process of selecting the set of VPs is called **routing**. The selected route must have sufficient resources to guarantee the specified QoS requirements of the new call and those already in progress in that route.

Connection Admission Control (CAC) is defined as the set of actions, executed at connection set-up, taken to decide whether or not the connection requested establishment can be accepted. This decision is based on the connection's anticipated traffic characteristics, the requested Quality of Service and the current network load.

In order to increase the utilization of network resources it is convenient to define several distinct service categories [ATMF95] and [I.371]. A classification of Service Categories according to both specifications are presented in following tables. In general these categories are a function of the required QoS, cell rate distribution class and ability of the source to control its information rate during the connection. According to the ATM Forum specification the categories are: Constant Bit Rate (CBR), real-time and non-real-time Variable Bit Rate (VBR), Available Bit Rate (ABR) and Unspecified Bit Rate (UBR). The QoS parameters are specified in terms of the admissible Cell Loss Rate (CLR), Cell Transfer Delay (CTD) and Cell Delay Variation (CDV).

	CBR	real-time VBR	non-real-time VBR	ABR	UBR
CLR Cell Loss Rate	specified				unspecified
CTD Cell Transfer Delay	specified			unspecified	
CDV Cell Delay Variation	specified		unspecified		
Traffic Descriptors (Contract)	PCR, CDVT	PCR, CDVT, SCR, BT		PCR, CDVT, MCR, ACR	PCR, CDVT
Flow Control	no			yes	no

Tabla 1 : Service Categories according ATM Forum specification

The CBR service category is intended for real-time applications which require tight constraints on CLR, CDV and CTD. The traffic contract is defined by PCR and CDVT. The real-time VBR service category is similar to the CBR category except that the traffic contract is defined by the SCR and BT in addition to PCR and CDVT. The specification of the non-real-time VBR service category differs from the real-time case only by omitting the CDV constraint. The ABR service category is intended for non-real-time applications which can control, on demand, their transmission rate in a certain range (e.g., file transfer). The traffic contract is defined by PCR, CDVT and MCR. The last service category, UBR, is intended for non-real-time applications which do not have tight constraints on the CTD and CDV.

The categories defined in [I.371] are: Deterministic Bit Rate (DBR), Statistical Bit Rate (SBR), ABR and ATM block transfer (ABT).

	DBR	SBR	ABT	ABR
CLR Cell Loss Rate	specified			
CTD Cell Transfer Delay	specified			unspecified
CDV Cell Delay Variation	specified		unspecified	
Traffic Descriptors (Contract)	PCR, CDVT	PCR, CDVT, SCR, BT		PCR, CDVT, MCR, ACR
Flow Control	no			yes

Tabla 2 :Service Categories according ITU-T specification

From this table it is easy to ascertain that DBR, SBR and ABR categories correspond to the CBR, VBR and ABR categories in the ATM Forum classification. The new ABT category has some features of the DBR, SBR and ABR categories. It is intended for data transfer applications where the information can be transmitted in blocks of cells. Two

options of ABT service are defined : ABT with delayed transmission (ABT/DT) and ABT with immediate transmission (ABT/IT).

The resource management and traffic control associated with the **cell layer** are the ones which act on (or are influenced by) individual cells or the cell state (e.g., switch output buffer occupancy). These functions can be grouped into four categories : usage parameter control (enforcement of the connection traffic contract), scheduling (priorities and fairness), cell flow control, and measurements. This measurements of the cell process parameters (delay, losses, rate, etc.) in the switch output port can be used by the connection layer to adapt some procedures such as routing, connection admission, and bandwidth allocation.

In the cell layer, the instantaneous offered traffic in a VP W is evaluated by summing the traffic of all active calls.

$$W = \sum \text{Input rate} = \sum r_i \quad r_i = \text{rate of the active call}$$

Given several sources emitting cells at the corresponding velocity (depending on the current state of each source), the cells are saved temporarily in the output buffer. These cells are extracted from the buffer at a constant rate C . If cells arrive at a rate greater than C (during a relatively long period) the capacity of the buffer may be surpassed and consequently some cells are lost.

$$W > C \text{ (Available VP Rate)}$$

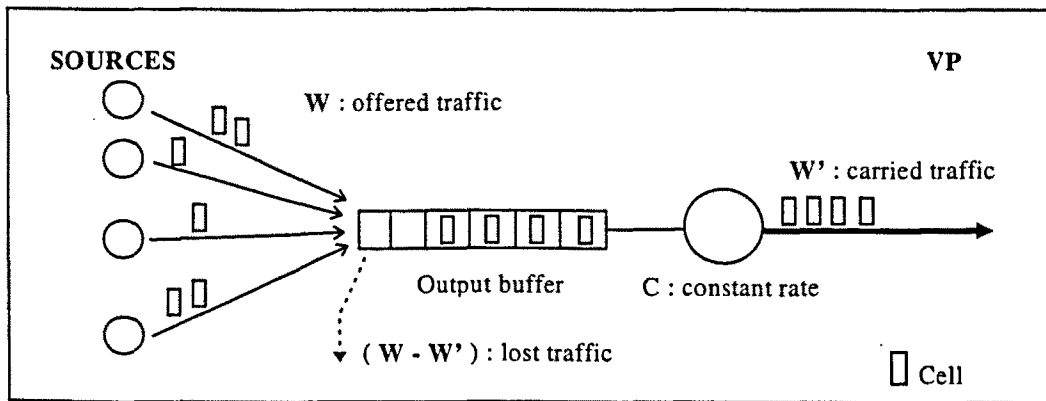


Fig. 4 : Offered, carried and loss traffic

The carried traffic corresponds to the load of the output resources W' considering the capacity of the VP C in terms of velocity. If W is greater than W' , the VP is in congestion ($W > C$) and the difference between W and W' is the lost traffic when the buffer is full. Obviously, the amount of lost traffic depends on the buffer size

This chapter starts with an explanation of the VPN layer embedded in the physical network. The Connection Layer is also explained. A brief introduction of routing in ATM

networks is also provided. Finally, the different types of connections depending on the number of members that are involved are also explained.

2.1 VIRTUAL PATH NETWORK LAYER

The importance of the Virtual Path (VP) concept as a component of traffic control and resource management is given in this section. Different VP Bandwidth Allocation schemes and the set of actions that determines the VPN are also explained. The section finishes with the description of the issues associated with VPN concept for resource management.

2.1.1 The Virtual Path Concept

The ITU-T Recommendations [I.113] and [I.371] define the Virtual Path (VP) concept and propose it as a component of traffic control and resource management in ATM network. VP concept is introduced to simplify traffic control and routing. The use of VPs in ATM networks reduces the call setup delay, simplifies the hardware in the transit nodes and provides simple VC admission control.

ATM is a connection-oriented technique, that make use of two levels of logical connections: Virtual Channel Connections (VCC) and Virtual Path Connections (VPC). Cells sent between end nodes are transported over a preestablished VCC. A VCC is a concatenation of one or more VPCs. A VPC may be a concatenation of one or more network links.

To transfer information from source A to destination B in an ATM network, a Virtual Channel Connection (VCC) must be established. A VCC is defined between two terminals that are exchanging information. A route is assigned to each VC in the network. Cells are transferred along the route assigned to the VC to which they belong. Every cell of this call will use the same route.

While the VCC approach can serve as a simple and efficient paradigm for network admission control, it has its drawbacks as well, particularly as we scale up to larger networks. These drawbacks may include relatively long network access delays and heavy computational requirements on intermediate switching nodes.

In an attempt to both reduce network access delays and eliminate redundant processing at intermediate nodes, many researchers have suggested a Virtual Path (VP) approach for routing in broadband networks. A logical transport path, called a Virtual Path (VP), has been proposed for the Asynchronous Transfer Mode (ATM) networks and adopted by ITU. The VP is a bundle of VCs and logically connects a pair of nodes which is not necessarily linked by a single cable.

At intermediate nodes along the path, a virtual path identifier (VPI) and a virtual channel identifier (VCI) in each cell header identify each cell as belonging to a particular channel and are used to route the cell along its fixed path.

At the VP's intermediate nodes all cells are switched by ATM switches according to its VPI incorporated in the cell headers and the VP routing tables. A VP routing table of an ATM node maps all VPIs of incoming VPs onto the nodes outgoing links.

A VP is an information transport path defined as follows [OHT88], [OHT92], [SAT90a]:

- A VP can be viewed as a single logical direct link between two nodes (source and destination) and may consist of two or more physical (transmission) links which together form a path.
- Each VP can accommodate a number of virtual channels simultaneously.
- A pre-defined route is defined for each VP in the physical facilities network.
- Each VP has been assigned a bandwidth, in other words, capacity which defines the upper limit for the total virtual channel bandwidth carried by it.
- VPs are multiplexed on physical transmission links at cell level.

Therefore, a virtual path is specified by its terminator nodes, the actual route between the terminators, the path capacity, and transmission quality (Quality of Service). The capacity of a VP can be deterministic or statistical according to the requirements.

Advantages

The approach of two connection levels (VC and VP), known as the virtual path concept, is a proposed ITU standard and it has been shown by a number of researchers to be a very useful and powerful transport mechanism for ATM networks. Several papers [ARV94a], [BUR91], [CHE94], [CHL93], [COH94a], [COH94b], [LIN93], [MIT94], [OHT88], [SAT90a], [SAT91b], [TOK93], [VEI94] describe its advantages:

- The load on the VCC control mechanisms are reduced because the functions needed to setup a path through the network are executed only once for all VCCs subsequently using that path.
- The call setup process are excluded from transit nodes and this leads to reduction in node processing and simplification of equipment by specialization of transit node functions.

- Decrease of call setup delays: at call setup, the routing tables of the transit nodes need not be updated. Routing procedure is also avoided at the transit nodes. CAC is simplified with a minimal processing at nodes crossed by the VP.

- Processing time can be reduced if groups of virtual channels are switched together on virtual paths rather than processed individually. Network management actions can then be applied to a small number of groups of connections instead of a large number of individual connections.

- By reserving capacity on VPCs, the processing required to establish individual VCCs is reduced. Individual VCCs can be established by making simple connection admission decisions at nodes where VPSs are terminated. Strategies for the reservation of capacity on VPCs will be determined by the trade-off between increased capacity costs and reduced control costs. These strategies are left to operators' decision.

- It is easy to change the virtual path bandwidth, easier than changing the physical link capacity.

- Logic service separation on network service access. Subscriber networks can effectively use VPs for logical service separation on a common physical link. Customers can directly access different service nodes with different VPs. It can be used to implement a form of priority control by segregating traffic types requiring different QOS.

- Increase survivability of VC connections, fast recovery from failures: if a VP fails due to a failure of an intermediate link or node, then instead of taking down all the VC connections established over the failed VP, a single simple protocol between the two end points of the failed VP can re-route them to a parallel VP.

The effectiveness of virtual paths can be extended by dynamic path controls such as dynamic path routing and dynamic path bandwidth allocation, which provides a network with dynamic reconfiguration capability. Adaptive reconfiguration capability of the network produces many enhancements of network performance.

Disadvantages

By reserving capacity on VP's, VCCs can be established quickly and simply. However, a priori reservation of resources on VP's also reduces the utilization of link capacity and the statistical multiplexing gains of the network, resulting in an increased probability that an

arriving call will be blocked [CHE94], [HWA94], [SAT90a]. The decrease in call set up complexity comes at the price of a reduced efficiency in the allocation mechanisms. To limit such a drawback, it is possible to manage VPs dynamically, so as to update their capacities according to the current occupancies and estimated traffic variations.

VP Bandwidth Allocation

One difficulty of the VP approach is to determine how much bandwidth to allocate to the VPs in order to support a given number of connections, [GER93] and [R2061/8], drawn from a certain class and when the bandwidth must be accommodated. Inversely, how many connections of each type can be accommodated within a VP, which has been allocated a certain amount of bandwidth is also another point of view of the same problem.

An efficient design of such an ATM network requires selecting suitable sizes for the virtual paths that have to be established. The bandwidth of a VP is set so that current traffic demands can be handled with an acceptable grade of service and this bandwidth defines the upper limit for total of VC bandwidth carried by it. Since VP bandwidth allocation can be easily changed, based on traffic demands, the link utilization factor will be increased.

To ensure that VP bandwidth allocation control is both flexible and powerful, path bandwidth allocation control is concentrated only at the network entrance. Intermediate ATM nodes do not participate in path bandwidth allocation, and are concerned with only path origin and destination. This reduces the work load incurred by bandwidth changes and permits fast bandwidth allocation. A number of bandwidth allocation strategies exists and they are described in detail in the literature [HUB93] :

- **dedicated bandwidth allocation (non-sharing).** The VP bandwidth is fixed and constant until the VP is released. Low link utilization, coupled with a minimum of processing load. Moreover, the bandwidth of each VP can not be shared with other VPs.
- **multi-hour engineering.** The VP bandwidth is not changed at every VC setup/release but over a period of time (i.e., daily, weekly, ...)
- **complete-sharing.** [SAT91a], [MIT94]. The (unused) bandwidth on a link is completely shared by all VPs on the link. An advantage is the optimal utilisation of the link bandwidth. This approach reduces the required total path and link capacity because of the statistical multiplexing effects between virtual channels in path, and between paths in links. The drawback is the required bandwidth change for a VP at every VC setup and release which causes a high processing load for the VP manager. It requires the highest processing load and achieves the best link utilization. In

[TAK93] a bandwidth scheme, named Group Virtual Path (GVP), sharing among multiple VPs are proposed.

- **dynamic bandwidth allocation (partial-sharing).** [ARV94], [BUR91], [GER93], [HUB93], [KE096], [SAT90a], [OHT88], [OHT92], [ORD96], [WU95]. Dynamic bandwidth allocation means that the bandwidth allocated to a VP (or, equivalently, the maximum number of connections allowed in the VP) is changed from time to time, in order to be adapted to the traffic variations and to obtain better resource utilization [R2081/8]. Since allocations depend on current values of link capacities and offered traffics, changes in these will require re-evaluations of capacity distributions.

In [ANE96th] a taxonomy of previous approaches to the problem of VP bandwidth allocation problem is presented and their strengths and weaknesses are identified. It is important to understand the fundamental trade-off between the overall network throughput and the processing load on the signalling system and to provide an algorithm for VP bandwidth allocation that achieves an optimal network operating point while guaranteeing the QoS at the call level and satisfying a priori bounds on the processing load of the call processors. A supporting algorithm framework to the network manager for formulating a bandwidth allocation policy for Virtual Paths, that guarantees QoS both at the cell and the call levels has been presented. QoS at the cell level can be guaranteed through the concept of the Contract Region [HYM93]. At the call level, QoS is guaranteed by bounding the blocking probability of the VC service for every Source-Destination pair in the network and the average connection set-up time. In [ORD96], based on a threshold scheme, a new VP bandwidth allocation scheme is presented which handles the inherent tradeoff between bandwidth utilization and processing costs. The influence of the step size is studied in [WU95].

2.1.2 Virtual Path Network design

From the Virtual Channel Connection (VCC) establishment point of view, the B-ISDN transport network can be viewed as an overlay semi-permanent Virtual Path Network (VPN) on top of the ATM network. A VPN is defined by a set of the network nodes and a set of VPs connecting the nodes. The configuration of VPs increase the apparent direct connectivity of the network. The VPN is embedded on the original network. The VPN forms a higher layer which is logically independent of the underlying physical network. In most cases there is more than one VP on any given physical link. Several VPs may share a physical link with each VP having resources assigned.

Several VPN can co-exist in a physical network. They can constitute independent entities, but in some cases a VPN can be nested in another VPN. There are two main motivations for using the VPN concept. The first is the separation of management functions in order to make them customized to particular needs of some services and user groups. The second is virtual separation of bandwidth in order to simplify the resource management functions and provide QoS and GoS guarantees for some services and user groups.

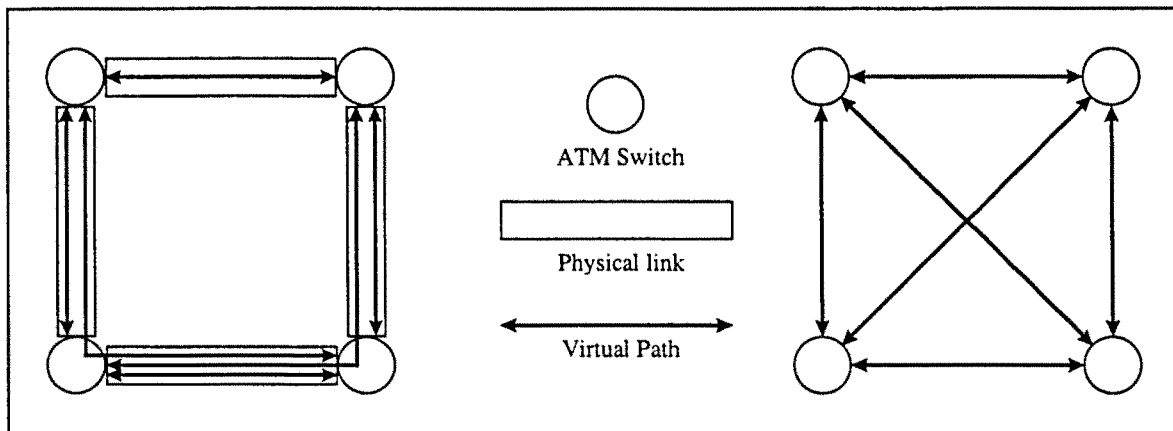


Fig. 5 : Physical Network with VPs and VP Network

The VPN is represented by a directed graph $G=(N,VP)$, where N denotes the set of ATM switches, and VP , the set of VPs connecting the ATM switches.

Given a network topology, link capacity of each physical link and traffic requirement of each origin-destination pair, the design of the VPN is decomposed in a process with three phases [LIN93b], [CHE93], [CHL93], [CHL94] and [COST242]:

- find the optimal structure of the VP network.
- route VPs on the physical network.
- map demand on VPs, i.e. load, and dimension the VP network.

The problem of finding the VP layout, clustering and VP establishment, have been studied in [AHN94], [ARV94b], [CHL93], [CHL94], [GER95], [GER96], [LIN93] and [SUR94].

In the first phase pairs of nodes that will be connected by VPs, the so-called VP terminator nodes are selected. This is done using a clustering algorithm. The clustering also defines an initial load assignment for the VPs.

The task of the second phase is to route the VPs on the physical network. This route selection is done by a randomized algorithm that is based on random choices among the set of all possible shortest paths connecting the given terminators. The objective is to distribute the routes in the network as evenly as possible to avoid overloading of links. The load of a

link is interpreted as the total load of VPs traversing it. Has been proven in several studies, [COST242] and [ANE96th], that this algorithm produces a VP route-distribution close to the best possible.

Having found the VP terminators and the corresponding routes, a refined loading and dimensioning of VPs is done in the third phase.

The following table shows the different design variables determined in each phase.

PHASE	DESIGN VARIABLES
Clustering	How to select VP terminator nodes ?
VP establishment	How to choose the VP routes between the ATM switches ?
VP bandwidth allocation	What is the optimal amount of capacity to be reserved for each VP ?

Tabla 3 : Design VPN phases and design variables

The detailed study of these three phases: clustering, VP establishment and VP bandwidth allocation, is out of the scope of this dissertation. In order to isolate the advantages of the proposed routing algorithm, only dedicated bandwidth allocation strategy is considered in this dissertation. Other allocation strategies will be implemented in further studies.

When the VPN has been determined, the routing assignment for each virtual channel, to minimize the expected connection blocking rate subject to call set-up time constraints, or alternately, to minimize the call set-up delay subject to the expected connection blocking rate constraints, will be considered. In this phase, the questions to solve are : a) how distribute traffic among the virtual paths ? and b) which call routing algorithm to use to realize the desired assignment?

2.2 CONNECTION LAYER

The main resource management and traffic control functions operating within the connection layer are : logical bandwidth allocation to connections, connection admission control and routing. The objective of these functions is to deliver high bandwidth utilization and fair access for all users (within the considered VPN) providing that the QoS constraints on the cell layer are met. In this section, the description of these functions and the interaction between them are explained.

2.2.1 Bandwidth Allocation

The crucial element of the resource management on the connection layer is the logical allocation of the link bandwidth to the connections (virtual channel connections). The importance of this allocation lies with the fact that it allows us to separate traffic control algorithms on the connection and higher layers from the cell layer. This feature can simplify

the resource management and traffic control functions significantly. Moreover, it can be observed that the bandwidth allocation to virtual channels makes the system similar to the circuit-switched environments on the connection layer.

The issue of logical bandwidth allocation to connections is quite complex due to several requirements. This logical bandwidth depends on the characterization of the bandwidth required for each individual connection and the resulting load on network links and buffer utilization. Moreover, the QoS constraints can be different for different services so the bandwidth allocation can also be a function of the QoS constraints. In particular, the bandwidth allocation should provide high resource utilization and QoS guarantees at the same time. This logical bandwidth also includes buffer allocation, the scheduling mechanism, and the flow control algorithms since these elements influence the QoS.

When the calls are admitted according to their peak bandwidth requirements all the existing connections on a link are not statistically multiplexed and the efficient use of transmission capacity is not obtained. In principle, it lies somewhere between the mean and the peak bit rate of the traffic source. Some authors assign an equivalent bandwidth that reflects its characteristics for each source. In these cases, the accuracy of the *bandwidth evaluation* is seriously affected, especially with heterogeneous traffic. To provide traffic control functions in real-time is a major challenge. Usually this involves a reduction in the complexity, and therefore a reduction of the accuracy of the evaluation models.

In literature several proposals exist to calculate the bandwidth amount needed to support a given QoS requirements which is usually called the equivalent or effective bandwidth or sometime the equivalent capacity. In this case, resources (bandwidth and buffer) for the connection are reserved to guarantee end-to-end QoS requirements. The idea behind this concept is that the acceptance region for CAC is approximately linearly constrained and thus the CAC algorithms in an ATM network can be thought of as operating like a circuit switched environment with a linear resource allocation strategy. When equivalent bandwidth is used, the routing mechanism using this predetermined bandwidth can be modelled as a multi-rate circuit-switched network.

In [WAL90] the equivalent bandwidth is calculated using an estimation of the bandwidth variance. Another approach based on the mean and peak bit rate was presented in [COST224]. In [DEC91] the burst length was also taken into account for the determination of the equivalent bandwidth. Estimates for the equivalent bandwidth of ON/OFF sources have been proposed in [GUE91]. The proposed approach combines two basic approximated models to study Bandwidth Allocation: the **fluid flow model**, which estimates the equivalent capacity when the impact of individual connection characteristics is critical, and the **stationary model**, which is representative of bandwidth requirements when the effect of statistical multiplexing is significant. By the second model, the convolution approach is the most accurate method used in bandwidth allocation when a priori traffic estimation is

considered. The exact evaluation of the offered load in ATM Networks can be calculated by convolution approach. In fact, the convolution approach obtains a probability density function for the offered system load, expressed as the probability that all sources together are emitting traffic at a given rate. However, the convolution approach has a considerable computation cost and a high number of accumulated calculations. Nevertheless, in critical near-congestion situations, the convolution is an algorithm that gives sufficient accuracy in order to exploit a maximum multiplexing gain. One important aspect of Bandwidth Allocation is CAC.

In [MAR93], [FAB94] and [MAR97th] the use of the Enhanced Convolution Approach (ECA) is proposed. In this case, to accept a new connection the ECA could be calculated. Given the VP capacity, the supported traffic and the QoS requirements, the ECA returns a value which indicates if the new connection is accepted. These papers have studied the usage requirements (complexity as processor capacity and memory required to do the calculations) for bandwidth allocation based on the convolution approach. These papers show reasonable evaluation cost and storage requirements whenever the multinomial distribution function and some cut-off mechanisms are used. In this case the ECA offers a possible fast evaluation without loss of accuracy.

In [MAR97th] the utilisation of the Probability of Congestion as a bandwidth decision parameter has been presented. The validity of using PC is compared in situations when only the CLR parameter is relevant, i.e. QoS parameters for bufferless scenarios. It can be summarised that the convolution algorithm seems to be a good solution for CAC in ATM networks with relatively small buffers. If the source characteristics are known actual Cell Loss Probability (CLP)³ can be estimated very well. Furthermore, this estimate is always conservative allowing the network performance guarantees to be kept [R2061/8]. The convolution algorithm ignores both buffer size and burst length. Experiments to confine the limits of the burst length with respect to the buffer size conclude that a minimum buffer size is necessary to achieve adequate cell contention. Normally, small values for the buffer size are involved. On the other hand, by increasing the buffer size, the cell loss, as shown by analysis, becomes too conservative. Then results obtained by analysis become inaccurate, as the mean burst length approaches the buffer size. Finally, a comparison with non-stationary methods is presented. It is seen that convolution approach obtains a more accurate cell loss result in the presence of bursty traffic and by using relatively small buffers.

2.2.2 Connection Admission Control and Routing

Connection admission control and routing functions are key elements of resource management and traffic control in broadband networks. In ATM based networks, the two

³ CLP represents the same parameters that CLR. While CLR are the rate of cells that are losses and it is done in cell per second and, CLP is the ratio between cell losses and cells offered.

historically separate CAC & routing domains are combined. This fusion makes the general problem of CAC & routing design more difficult since it has to take into account both bandwidth and QoS constraints at the same time. While the connection admission control function and the routing function are often treated as two separate issues, in fact they are parts of the same problem which is the selection of the best route from a set of alternative routes to carry a new connection.

The routing function can be defined as a choice, from the set of alternative routes, of a route recommended for carrying a new connection. Then the connection admission control function decides whether the recommended route under consideration can be used for carrying the connection. If, according to the CAC algorithm, the recommended route is inadmissible, the routing algorithm can recommend another route or the connection can be rejected.

The purpose of [MED96a] is to understand the implication and interaction of admission control with various dynamic routing schemes in a multi-service setting with different bandwidth requirements for each service type. To this end, they have proposed various dynamic routing schemes and a simple admission control policy, and have studied their interaction and network performance through network simulation. They observe that in an integrated environment, for low bandwidth service (such as voice), the various routing schemes provide similar performance; this is not so for high-bandwidth service (such as video). In this paper, the variety of services are limited to services that require peak rate allocation of bandwidth for the duration of a call while the peak rate may be different for different services. The performance issue is Grade of Service, i.e., call blocking for each service type.

Routing and CAC mutually interact with each other in ATM networks. Routes selected by Routing may be rejected by CAC if CAC considers that their establishment would significantly deteriorate the QoS of existing calls. If its selected routes are rejected by CAC, Routing may try to find alternative ones to route the call. The interaction between these two mechanisms creates a problem called "Routing-CAC cycle" [LIU95]. The process of CAC & Routing can be interpreted as a selection of the best route from a set of alternative routes. The set of alternative routes can contain all potential routes or can be limited for technical or performance reasons. The route selection can be a function of VP metrics, route metrics, and the applied signalling protocol. We consider a system where all information is available instantly to the CAC & Routing algorithm.

CAC addresses a set of actions taken by the network at the connection set up phase (or during the connection re-negotiation phase) in order to establish whether a new connection can be accepted or rejected. The decision is made based on the knowledge of the current network loading, on the traffic descriptors and on the cell loss and/or cell delay performance requirements (QoS) of the new connection and those of the connections already existing.

The second aspect of CAC deals with the question of whether the connection should be admitted on a VP which ensures that the QoS constraints are met. This function is related to the GoS characteristics (connection layer performance metrics). There might be several reasons for rejecting the connection, even though it could be accepted from the resource availability viewpoint. These reasons will be explained in the “two VP constraint” paragraph and the “Routing Control Parameter” subsection.

The adopted CAC policy has a strong influence on the routing performance. Routing algorithms define the procedure by which a route is sought and defined for network wide connections. Routing algorithms are based on the network topology, on the current state of the loading and on fast signalling techniques to perform the control.

Routing consists on assigning a route to the incoming connection demands during the call⁴ set up. For each new call, the network must select a route that has sufficient bandwidth available to support the new connection and to guarantee the required Quality of Service (QoS). Otherwise, the new call will be blocked (or rejected). The aim of an efficient routing algorithm is to allow the acceptance of the largest possible number of calls while satisfying the negotiated QoS parameters to all the admitted calls.

The objective of the routing is to find a route which optimizes some criteria (such as network resource utilization and average cell delay), while the connection admission procedure verifies whether certain constraints are not exceeded (such as maximum link bandwidth available to the connection class or maximum end-to-end cell delay), on the selected route.

The routing scheme gives an individual call a better chance of success, perhaps by increasing the number of ways it can traverse the network. However, the success of this call could potentially prevent the success of more than one other call, creating a less than satisfactory solution overall. This is a symptom of the classic dichotomy between individual and social optimization. From the individual call’s point of view, we want as much freedom as possible so that it has the best chance of finding a route through the network; whereas to achieve a global optimum (where the carried traffic is at a maximum), we might have to limit an individual’s freedom.

The optimality criterion is not straightforward due to several potential metrics which should be considered. The metrics can be grouped into two categories: QoS metrics and resource metrics. The QoS metrics were already defined (Cell Loss Rate, Cell Transfer Delay and Cell Delay Variation) and in general each connection class requires that the QoS metrics do not exceed pre-defined constraints. The resource cost metrics are the ones which take into account the cost of the resources engaged in the connection.

⁴ Throughout this paper the terms “call”, “connection demand” and “Virtual Channel” are interchangeable.

In general the potential optimization criteria can be divided into two categories: the ones associated with the cell layer (functions of QoS characteristics such as cell losses and delay) and the ones linked to the connection layer (functions of GoS characteristics such as connection rejection probabilities).

There are two basic routing techniques that have been used in networking depending on what node selects the route to connect the source with the destination: hop-by-hop routing and source routing.

In **hop-by-hop routing**, each node independently selects the next hop for that route, which results in progress toward the destination provided that the decisions made at each hop are sufficiently consistent.

Hop-by-hop routing does have some disadvantages in this type of network: creation of routing loops, no optimal solution due to inconsistency among the routing databases and the replication of the cost of the route selection at each node.

There are several possible causes of routing loops: Inconsistency in routing decisions when switches use different routing algorithms, and inconsistency in routing databases among the switches (typically due to changes in topology information that have not fully propagated yet).

Inconsistency in routing decisions lead to a fundamental constraint of hop-by-hop routing, which is that the route selection must be fully specified, and all systems must implement it exactly as specified.

Further, due to inconsistency among the routing databases it is also possible for routes to be followed as a consequence of the individual hop by hop decisions that are far from optimal yet contain no loops. Any connection established with such an inefficient route will use that route for as long as that connection remains open.

Another disadvantage of hop-by-hop routing is that it replicates the cost of the route selection at each node. While this is less serious for connection-oriented networks (where the cost only occurs at connection set-up) the QoS-sensitive route selection of Private Network Network Interface (PNNI) may be far more costly.

A hop by hop routing algorithm, called Adaptive Minimum Hop (AMH) routing, is proposed in [JOR96]. This algorithm overcomes the limitations of existing routing algorithms by using multiple, minimum hop routes to balance the load in the network.

In [ARA97] a new hop by hop routing algorithm is proposed which is shown to perform adequately under symmetrical and non-symmetrical loading, for both highly and sparsely connected VPC topologies.

In **source routing**, the originating (or source) node selects the route to the destination and other nodes on the route obey the source's routing instructions. It does this based on its local knowledge of the network topology. Since only one database is involved, loops are not possible, nor will the routes be inefficient due to database inconsistency. Furthermore, since only the source selects the route, the algorithm used need not be the same in every system, and the cost of executing it is only incurred once. In addition, it is much easier to make route selection based on specialized considerations, because there is no requirement for the algorithms to be consistent among all the nodes.

Initially, either routing technique can be applied to connection-oriented networks, such as ATM. To avoid the difficulties stated above of using hop by hop routing with connection oriented service, and to gain the advantages of source routing, PNNI uses source routing for all connection setup requests [PNNI-1.0]. Therefore, in this dissertation a source routing is considered.

2.3 ROUTING IN ATM NETWORKS

The purpose of the routing algorithms is to route an incoming Virtual Channel Connection (VCC) request, i.e. the choice of the VPC links along the cells of this connection will be transmitted from the source to the destination node. The routing decision criteria basically depends on the type of source of the new connection and on the characteristics of the current load supported by the network.

When establishing a VCC so that a pair of terminals can communicate, a route consisting of a set of VPs is selected. Routing attempts to maximize the network throughput by uniformly distributing traffic to use the network efficiently. When routing a VCC in the VPN, the routing algorithm needs to consider the traffic characteristics of the VCCs in progress. The routing algorithm must also take into account the VC's Quality of Service (QoS) requirements.

The traffic produces random variations in the link occupancies in the network. Another aim of a routing scheme is to induce, as far as to the possible, these random variations in the pattern of link occupancies to maximize network resources utilization and to minimize Network Connection Blocking Probability (NCBP) which is defined as the global probability of an arriving call finding no suitable idle route for its connection establishment. The routing policy attempts to find the route that causes the least damage to the network.

In ATM networks, a Virtual Path route is established by setting the ATM routing tables cross-connected between Virtual Path Terminators. The information for routing is obtainable simply by changing routing information in the path connection tables at nodes along the path. Each input has its own Virtual Path Identifier conversion table. VP routing is

easily controlled by changing table contents. Static and dynamic routing policies can be considered. To perform dynamic routing policies, each node must maintain a table specifying, at each moment, the route selected which depends on the state of the network at the instant of call arrival. In static routing, this table is fixed.

In section 6.3 of [ONVURAL] various routing schemes proposed and implemented in current public and commercial networks from an ATM network perspective are discussed.

2.3.1 Dynamic Routing

A Dynamic routing scheme is one in which routing decisions are influenced by current traffic conditions. Dynamic routing is an efficient method of traffic control in which call routing is frequently altered according to the status of the network and anticipated demand shifts, so that the network can respond quickly and properly to the changes in traffic and facility conditions. The dynamic routing scheme increases network efficiency by routing calls away from busy areas through lightly loaded portions of the network. Dynamic routing schemes, for example allow a network to respond to fluctuating demands and failures by rerouting traffic and reallocating resources.

Dynamic routing is complementary to alternative and adaptive routing, being similar to the adaptive method. However, the time scale over which traffic conditions are assessed is different (hours rather than minutes/seconds). The method can exploit, for example, the non-coincidence of busy hours across a large network. If the VP concept is used to the full, dynamic routing can effectively mean the reconfiguration of the VPN layer.

2.3.2 Alternative routing

The essence of alternative routing schemes is that the possible routes to be used between two end switches are pre-defined. Alternative routing provides a call with a choice of two or more routes. When a new call requests establishment between a pair of switches, it is possible to consider routing schemes in VP networks which always offer the direct VP first; then this route will be used with priority. If a call is blocked on the direct VP, the call is set-up on an allowable alternative route. Otherwise, the call is blocked.

If there is only one route defined for each source-destination pair, the scheme is known as a fixed alternative routing scheme. More commonly, a dynamic alternate routing scheme is used. In the latter case, a different set of pre-planned routes is used for different time periods, to take advantage of the differing time zones and at different times of day. Thus, the routing decision is based both on current traffic status (a route is rejected if busy) and historical traffic patterns (which determines the sequence of routes to be considered).

The ability to employ a number of alternative routes greatly enhances network availability and security, and does not involve reserving transmission bandwidth.

If concatenate VPs are not implemented but only direct VPs are established in the network, the actions of CAC when a VC set up occurs are as follows [KEO96]:

- The source and destination addresses of the new VC are used to determine the direct VPs that connect the source and destination nodes of the new VC.
- Among the direct VPs, VPs with sufficient resources to accommodate the new VC are selected. If no direct VP is selected, the VC set up is blocked.
- If multiple direct VPs are selected, a VC routing algorithm is used to select a VP to accommodate the new VC. The VC set up is accepted and an amount of resources are reserved on the VP for the new VC.

The routing algorithms differ in how they choose from among the set of allowable alternative routes. By providing alternative routes, ATM networks will be able to achieve lower CBP and higher network throughput, while still satisfying various QOS requirements through the rigorous application of CAC. The CBP can be decreased by using alternative routes [SPI94].

If direct and concatenate VPs are implemented in the network, the direct VPs are tried first. If no direct VP is selected, then the concatenate VPs are tried. The actions of CAC on the concatenate VPs are as follows [KEO96]:

- The source and destination addresses of the new VC are used to determine the concatenate routes that connect the source and destination nodes of the new VC.
- Among the concatenate routes, concatenate routes with sufficient resources on all concatenate VPs of each concatenate route to accommodate the new VC are selected. If no concatenate route is selected, the VC set up is blocked.
- If multiple concatenate routes are selected, a VC routing algorithm is used to select a concatenate route to accommodate the new VC. The VC set up is accepted and an amount of resources are reserved on all concatenate VPs of the concatenate route for the new VC.

The following figures show an example of an alternative routing scheme. To establish a VCC from N1 to N2, the VCC is offered first to the direct route (direct VP). If the direct route is unavailable, a set of alternative two-VP routes through a transit (or intermediate) node is considered. If any alternative two-VP route is available the VCC is rejected. To

simplify the VPN figure, VP from N_i to N_j and VP from N_j to N_i are drawn as a single line with two arrows. The direct route from N_1 to N_2 and the set of alternative two-VP routes available which is considered if the direct route is unavailable are also shown.

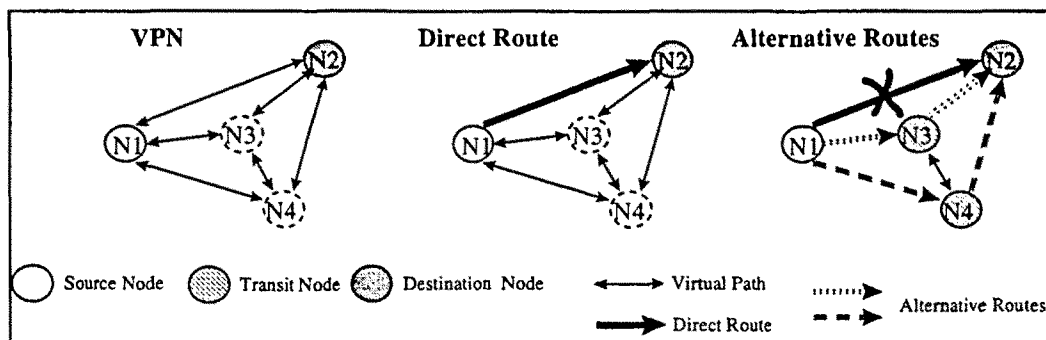


Fig. 6 : Example of Alternative routing in VP-based ATM Networks.

Two VP constraint

Following the practice of routing in telephone networks and circuit-switched networks, routes that consist of more than two VPs are excluded, i.e., we shall consider only direct VP and two-VP alternative routes in our routing decision. The heuristic idea is that it wastes too much network resources to route call over a route with more than two VPs. It is better to reject the call so that the spare resources can be used to support other users. The two VP constraint simplifies routing implementation and ensures loop-free routing.

Several studies exclude alternative routes that consist of more than two VPs ([BAH94], [CHU95], [CHU97], [DZI97], [GUP93], [HWA94], [HWA95b], [HWA95c], [KOL94], [KRI94] and [OSE94]).

Removing the restriction to two-VPs, of course, allows a wider choice of alternative routes. One effect of this is that it gives more flexibility in routing and, thus, tends to reduce the CBP. Another effect is the reduction of the effective capacities of the VPs. This effect tends to increase the CBP, which implies that the effect of the increase of routing flexibility is outweighed by the effective capacity reduction. However, in general, there is a price to be paid for the use of a multiple VP for a single call, viz., the fact that it constitutes an inefficient use of network resources to tie up several VPs for the sake of a single call, while those VPs might be used to complete several separated calls [KRI94] and [LIN93a]. Furthermore, Krishnan [KRI94] shows that restricting to two-VPs routes imposes no penalty on network cost in broadband ATM networks.

Moreover, the cost of routing the call over a multiple-VP route is the sum of costs of routing the call over its constituent VPs [KOL94]. In [LIN93a] and [CHE94] the effects of limiting the maximum number of physical links for each path are discussed. It is shown in [AHN94] that providing even as few as two or three multiple paths per source-destination pair will result in a marked decrease in CBP. Superior results in terms of a higher percentage

of offered traffic satisfied are obtained with a greater number of total VPs in the network, fewer VPs per route, and fewer physical links per path.

When a call is to be routed on an alternative route consisting of two VPs, the following problems are again encountered: how to characterize the traffic in a VC as it travels along the alternative route and how to assign end-to-end QoS requirements to each link of the alternative route; note that for a call that is alternatively routed, cell loss, cell delay, etc., can occur at either of the two VPs along the route.

Traffic Characteristic

When a VCC traverses more than one VP, we assume that the traffic characteristics offered by the VCC to all VPs on the route are the same, i.e., the traffic characteristics of a single VCC are not changed as it passes through a VP along its route. For example, cell loss at origin node may result in intermediate node receiving traffic whose characteristics are very different from those at the network edge. Any such changes in connection traffic characteristics are ignored. This assumption is also adopted in [ANE96th], [CHU95], [CHU97], [HWA94], [HWA95b] and [NAG93]. Therefore, we will assume in our network model that traffic class i alternatively routed maintains direct traffic characteristics. The existence of alternatively routed connections through a VP only has influence in the QoS requirements that will be considered.

QoS division

The second problem, how to divide the end-to-end QoS requirement into local QoS requirement, and then determine the resources required at each link in order to achieve the local QoS, is considered in some papers.

Decomposition methods for end-to-end (cell-loss) QoS are also studied in [NAG93]. In [NAG93th] the problem of providing statistical QoS guarantees is addressed. Firstly, different policies for allocating the end-to-end requirement to nodal requirements are examined. In the second part, appropriate QoS criteria and mechanisms to guarantee these criteria at the nodal level are studied.

In [FIR95] two policies for dividing the end-to-end QoS requirements among the VPs on the alternate route were presented. The first, attempts to divide the QoS requirements evenly among the VP (even division policy), whereas the second allocates more stringent QoS requirements to VPs having more available resources (proportional division policy). The second one is designed to balance the loads on the links in the network over the long term by allocating fewer resources for each new session on those links that are more highly utilised and thus avoiding the formation of bottleneck links.

In [RAM94] an approach towards supporting diverse quality-of-service requirements in broadband networks based on ATM was investigated. The approach involves deterministic bandwidth reservation at the VP level and statistical multiplexing within each

VP. A Weighted Round Robin (WRR) server is used to enforce bandwidth reservations. This paper deals with VCs which go through a single VP. The multiple VP case is left for future work. It is shown that the amount of network bandwidth required by a VP is minimised by allowing all the allowable loss to occur at the first link of a VP, when there is no statistical multiplexing across VPs.

When **equivalent bandwidth** is used, to guarantee an end-to-end QoS requirements an effective bandwidth for the connection is reserved. If the route is of one VP length, meaning that it traverses only one VP from its source to its destination, then, that end-to-end QoS, can be guaranteed by assigning an effective bandwidth for the end-to-end QoS on the VP. If the routes traverses two-VPs however, then that end-to-end QoS can only be guaranteed by assigning a higher effective bandwidth on each VP than previously, equal to QoS /2, so that in a worst case scenario the end-to-end QoS is still guaranteed. Therefore, the longer the route chosen on the VPN, the higher the effective bandwidth required on each VP to guarantee the end-to-end QoS. In order to support multiple QoS requirements in a VP, dedicated buffer to each class of QoS is adopted in [GUP93], [HWA94] and [CHU97].

2.3.3 Adaptive routing

Adaptive routing can be incorporated as a extension to the alternative routing scheme, where the second choice routes are not pre-determined but they are established according to the current traffic conditions. Such adaptation to the network state obviously requires more control processing, and it may incur greater delays in the call establishment process.

The existing adaptive routing algorithms can be classified into two categories: Markov Decision Process-based (MDP-based) [OTT85] and Least Loaded Routing-based (LLR-based) [ASH85].

The **MDP approach** formulates the routing problem as a Markov decision process ([BEN66], [DZI89], [KRI90]). The formulation of the routing problem in traditional circuit-switched networks as a Markov decision process has been studied as early as 1966 [BEN66]. However, solving an exact Markov decision process to obtain an optimal routing policy is computationally infeasible for any realistic network due to the huge state space. Krishnan and Ott [OTT85] proposed a computationally feasible, MDP-based routing scheme, referred to as State-Dependent Routing (SDR) scheme.

In Chapter 5 of [DZI97] a model for CAC & routing is derived from the Markov decision theory (a short introduction to Markov decision theory is given in Appendix B of [DZI97]). In this case each connection is characterized by a reward parameter, and the objective of CAC & routing is to maximize the reward from the accepted connections. The CAC & routing decision is based on state-dependent link shadow prices interpreted as a predicted price for seizing link "bandwidth" by the connection. The route with a minimal

shadow price cost (sum of link shadow prices over the links constituting the route) is recommended by routing functions. This formulation has several advantages. It is derived from Markov decision theory, which provides an optimal solution to the problem. While this solution is difficult to implement, after applying some approximations a sub-optimal implementable solution is achieved. This sub-optimal solution can be classified as CAC & routing based on state-dependent and adaptive link costs.

In the MDP approach, the routing strategy is based on the concept of a state-dependent link cost. This cost can be interpreted as a price for using the link “bandwidth”. The cost of a path is defined as the sum of link costs and the path is selected with a minimal cost. The nice feature of this formulation is that the same link costs can be used for CAC decision.

Some works use an MDP approach because it has been shown to be more general and efficient than the LLR approach in other contexts (e.g., [HWA92] and [OTT85]).

The **Least Loaded Routing (LLR)** tries to route an incoming call to the direct link, the link between the source node and destination node, first. If the call is blocked (because of no free circuits), the “least busy” route, i.e., the route that has the maximum number of free circuits, is then tried.

The basic idea of LLR approach is to carry the new connection on the route with the maximum residual capacity C_j^{max} where the route residual capacity, C_j^k , is defined as the minimum link residual capacity over the links constituting the route k .

$$C_j^{max} = \max_{k \in W_j} \{C_j^k\} \quad \text{and} \quad C_j^k = \min_{s \in S^k} \{C_j^s\}$$

Results obtained in [HWA94] and [HWA95b] found that the MDP-based routing algorithms slightly outperforms the LLR-based routing algorithms. The reason is that carrying an alternate call on a VP, in general, is more “expensive” than a direct call, in the sense that it consumes more network resources due to more stringent QoS requirements. Thus the chance and advantage of dynamic alternate routing are not as great as in traditional circuit-switched networks. Although these works only cover the case of supporting homogeneous traffic class in VP-based ATM networks, this may give a hint on the performance of using MDP routing in multiple traffic case. Due to the simple implementation of LLR, they propose a modified LLR to handle the multi-class environment.

2.3.4 Routing algorithms

Different routing algorithms could be defined changing various factors: the metric parameter of the VP cost function, the composition rule of the alternative route cost, the

route selection scheme and the determination of available alternative routes. The last three aspects are explained in this sub-section. A new metric parameter to define the VP cost function will be presented in next chapter.

Composition rules of the alternative route cost function

When an alternative route has more than one VP, different composition rules are considered in [CRO95], [FIR95], [WAN95] and [WAN96] to evaluate the cost of the alternative route:

- Cost additive: the cost is the addition of those of the VPs it goes through. The delay and the Log(1-CLP) are two examples of additive metrics.
- Cost restrictive: the cost of an alternative route going through a list of VPs is the minimum of their cost. The Bandwidth is an example of this rule.
- Cost multiplicative: the cost is the multiplication of those of the VPs it goes through. The CLP is an example.
- Cost no-restrictive: the cost of an alternative route going through a list of VPs is the maximum of their cost. In this case, the bandwidth could be considered.

cost(2-VP alternative route)	Name
$\text{cost}(\text{VP}_i) + \text{cost}(\text{VP}_j)$	Additive
$\min [\text{cost}(\text{VP}_i), \text{cost}(\text{VP}_j)]$	Concave or Restrictive
$\text{cost}(\text{VP}_i) * \text{cost}(\text{VP}_j)$	Multiplicative
$\max [\text{cost}(\text{VP}_i), \text{cost}(\text{VP}_j)]$	Convex or No-Restrictive

Tabla 4 : Composition rules of the alternative route cost function

The composition rule for CLP is more complicated. An upper limit for the end-to-end CLP is :

$$\begin{aligned}
 \text{CLP (on 2-VP alternative route (VP}_i + \text{VP}_j))} &= \\
 \text{CLP}(\text{VP}_i + \text{VP}_j) &= \\
 1 - [(1 - \text{CLP}(\text{VP}_i)) * (1 - \text{CLP}(\text{VP}_j))] &= \\
 1 - [1 - \text{CLP}(\text{on VP}_i) - \text{CLP}(\text{on VP}_j) + \text{CLP}(\text{on VP}_i) * \text{CLP}(\text{on VP}_j)] &= \\
 \text{CLP}(\text{on VP}_i) + \text{CLP}(\text{on VP}_j) - \text{CLP}(\text{on VP}_i) * \text{CLP}(\text{on VP}_j) &\approx \\
 \text{CLP}(\text{on VP}_i) + \text{CLP}(\text{on VP}_j) &
 \end{aligned}$$

However, the loss probability metric can be easily transformed to an equivalent metric (the probability of successful transmission). Suppose that the CLP for a VP is CLP(VP), the corresponding success probability as 1-CLP(VP). The composition rule for success

probability is $CLP(VP_i + VP_j) = CLP(VP_i) \times CLP(VP_j)$. However, if we define $SUC(VP) = \log(CLP(VP))$, we have $SUC(VP_i + VP_j) = SUC(VP_i) + SUC(VP_j)$.

Alternative Route selection scheme

If an arriving call could be established on more than one alternative route, a function to select the alternative route from the set of available alternative routes is necessary. Different algorithms which differ in how they select an alternative route are presented. These algorithms focus on selecting a route that is capable of satisfying the traffic requirements, while at the same time trying to minimize the amount of network resources that need to be allocated to support the traffic.

There are five possible schemes that can be used to select an alternative route from a set of available two-VPs routes. Similar schemes are presented in [KEO96], [ONV94] and [CHU95].

1. **Minimum (MinRC)**. All available alternative routes are ordered according to the route cost, in ascending order. Then, a new connection is allocated to the first route, which has the *minimum* route cost.
2. **Maximum (MaxRC)**. All available alternative routes are ordered according to the route cost, in descending order. Then, a new connection is allocated to the first route, which has the *maximum* route cost.
3. **First in, first allocated (FifaRC)**. A new connection is allocated to the first route on the list that can accommodate the connection, independent of the current status of VPs.
4. and 5. **Random Routing**. Two schemes are considered in this case. An alternative route is selected randomly from all alternative routes (*RavailableRC*) than can accommodate the connection or an alternative route is selected randomly from *all* alternative routes (*RallRC*). In the last case, the new connection can be rejected if the selected alternative route is unavailable.

To compare the performance of the previous algorithms, the Direct Routing scheme is also considered:

6. **Direct Routing (DR)**. This is an extremely simple routing algorithm in which an incoming VCC connection request is always routed along the direct VPC. If the direct VPC cannot support any additional connections, the incoming connection request is rejected.

Some characteristics of these alternative route selection schemes are summarized in [ONV94]:

- Choosing the alternative route with the minimum route cost for existing connection (MinRC) attempts to balance the traffic carried at each route in the network.
- This scheme is similar to the Least Load Routing (LLR) Algorithm, which is used in traditional networks. In [GUP93], [GUP94] and [HWA95a], LLR algorithms are applied to VP-based ATM networks.
- It may be possible to allocate the new connection to a highly utilized VP and still deliver its requested grade of service without degrading the performance of the existing connections (MaxRC). Doing so would utilize a VP as much as possible while leaving big chunks of bandwidth available for future requests. This may be proved to be a desirable feature in ATM networks where various applications with significantly differing bandwidth requirements are carried in the same network.
- It is suggested in [GUP94] that packing of narrow-band calls (calls require relatively smaller bandwidth) should be employed on some links to leave room on other links for wide-band calls. In [SIE94] an algorithm known as Minimum Free Capacity Routing (MFCR) for VP- based ATM networks is proposed. The MFCR algorithm picks the direct VP with the smallest residual capacity among those VPs having enough residual capacity to accommodate the required bandwidth of the new VC. In [CHU95] the MFCR is modified using both the packing and the LLR concepts. The modified algorithm is very similar to LLR except that it chooses the 2-VP alternative route with the smallest free capacity.
- This packing concept is also used in different management of network resources: Traffic Control, Admission Control, VP Bandwidth Allocation, Routing and Network Restoration [ANE96], [DIG95], [GUP94], [HYM93], [NEV94] and [NOR95].
- It may be possible to choose the first VP from the list of all alternative routes defined between the two nodes that can accommodate the connection (FifaRC), minimizing the processing times by establishing VCC requests.
- Finally, since communication networks are nonstationary environments, their states vary with the time. Under rapidly changing conditions, information about the state at a time instant may no longer be true at the next time instant. One of the desirable properties of RallRC and RavaiRC is their speed of response. Choosing a route probabilistically is an attempt to minimize the effects of uncertainty in decision making. This scheme is similar to Dynamic Alternative Routing (DAR) developed by British Telecom [STA87] and used in traditional switched networks.

The performance of these schemes are summarized in [ONV92]:

- MaxRC favors VCCs with larger bandwidth requirements over VCCs with smaller bandwidth requirements.
- MinRC favors VCCs with smaller bandwidth requirements over VCCs with larger bandwidth requirements.
- Although a more thorough investigation is necessary, it is concluded that MinRC discriminates more against VCCs with larger bandwidth requirements than MaxRC against VCCs with smaller bandwidth requirements.
- FifaRC does not discriminate against any type of VCC. This scheme causes fewer VCCs requests to be lost for low bandwidth VCCs than MaxRC, and similarly MinRC for high bandwidth VCCs. However, FifaRC causes more VCC requests to be rejected for low bandwidth VCCs than MinRC, and MaxRC for high bandwidth VCCs.

In the context of computer memory management similar strategies are proposed to minimize the amount of external storage fragmentation. The performance of these strategies are investigated in [SHO75]. The problem studied here differs slightly from the other studies. One scheme is better than the other if it maximizes the total throughput between two nodes while treating all classes fairly.

The Demanded Bandwidth of a Connection as Parameter of the Alternative Route Selection Scheme To combine the characteristics of the MaxRC and MinRC, a new alternative route selection scheme will be considered. In this case, the selection of the alternative route depends on the demanded bandwidth of the new connection:

Demanded Bandwidth RC (DemBanRC). All available alternative routes are ordered according to their Congestion Probability (CP), in ascending order. Then, a wide-band connection is allocated to the first route, which has the *minimum* CP, but a narrow-band connection is allocated to the last route, which has the *maximum* CP. Note that this scheme could only be considered in networks with heterogeneous traffic

Routing algorithms

By jointing the different composition rules and the possible schemes to select an alternative route, the next combinations can be considered. Note that the metric applied as *VP cost function* is not yet defined. These algorithms are summarized in the following table:

		COMPOSITION RULES		
		ADD	MAX	MIN
Alternative Route Selection	MIN	[MinRC(+)]	[MinRC(max)]	[MinRC(min)]
	MAX	[MaxRC(+)]	[MaxRC(max)]	[MaxRC(min)]
	FIFA	[FifaRC] ¹		
	RAVAI	[RavaiRC] ¹		
	RALL	[RallRC] ¹		
	DEMBAN	[DemBanRC(+)]	[DemBanRC(max)]	[DemBanRC(min)]
Direct		DR		

Tabla 5 : Congestion Probability Routing algorithms

¹ In these schemes the composition rule considered is irrelevant.

Determination of available alternative routes : Trunk Reservation

In circuit switched networks to prevent wide-band connections and direct routed connections from excessive blocking (**efficiency**) and to equalize blocking probabilities from calls of different connection classes (**fairness**), it has been necessary to implement a *protection mechanism*.

The price to be paid for the blocking probability equalization is that the total transmission link utilization decreases with trunk reservation. The trunk reservation mechanism is a solution for the multiservice fairness problem.

The basic idea of trunk reservation is to block every arriving call, if a connection of the service class with largest bandwidth requirements or a direct connection could not be established, i.e., to protect wide-band connections or direct routed connections if the number of **idle channels** falls below a certain tolerance on the direct link which is needed primarily in overloaded conditions and for network stability.

Trunk reservation requires that one more than a specified number of trunks - the "reservation level"- be free on each trunk group before an alternative-routed connection or wide-band connections is allowed. This prevents calls that normally use a trunk group from being swamped by alternative-routed connections or by narrow-band connections.

In ATM networks, it is assumed that connections have an equivalent bandwidth and a certain amount of capacity is reserved to be only accessed by a particular traffic type. During the holding time of a call of type i , a constant bit rate denoted by C_i , the **equivalent bandwidth** of the source i , is reserved for this call and released after the call has completed. If trunk reservation is considered, a call of type i will be blocked if $C_R < C - \Theta_i$, and accepted

otherwise. A capability threshold θ_i is assigned to every traffic class i . The parameter C_R again denotes the available capacity of the transmission link upon arrival of a call of type i .

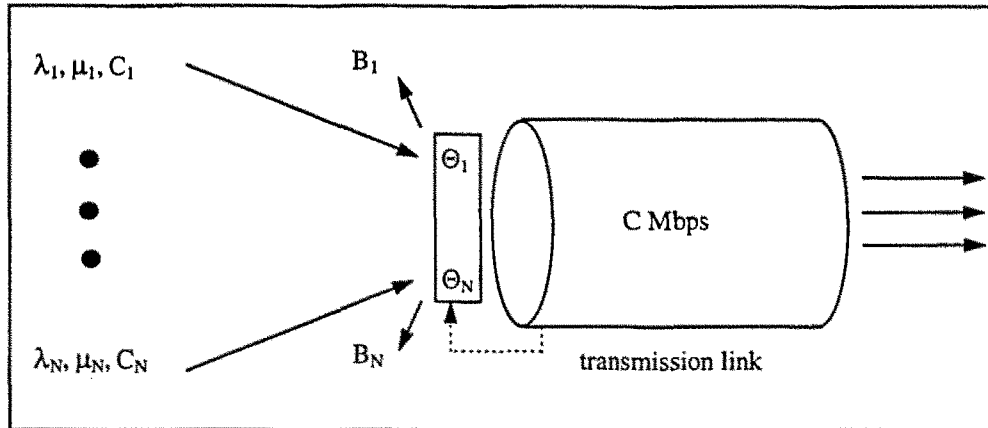


Fig. 7 : Basic link model for trunk reservation mode

In the absence of controls, wide-band connections and direct connections can experience much higher blocking probabilities than narrow-band connections and alternative routed connections respectively. Note that trunk reservation mechanism can be used to provide higher priority for *wide-band* connections and for connections using *direct route*.

Different priorities for different connection classes are achieved by reserving a part of the resources (channels or capacity) for some connection classes. Previous studies on point-to-point routing have shown that the trunk reservation level affects network performance significantly [WEB64], [AKI93], especially when traffic load is very high.

By means of exact and approximate techniques, it is shown that blocking is sensitive to changes to mean holding time ratio. To reduce the chance of alternative routing of a wide-band call, different values of trunk reservation threshold for different classes of calls could be set.

In [COST242] it is mentioned that, when trunk reservation is employed, the common blocking probability is in general also dependent on the ratio of the mean holding times of the different classes of calls. However, it would be very complicated to consider also the relationships between all the mean holding times when the number of traffic classes is large. Thus, it is assumed in some approximations that the mean holding times are equal and the result is meant to cover cases when they are in the same order of magnitude (pp. 50). The Connection Blocking Probabilities (CBP) also depend on the mean holding times and the holding time distribution type when trunk reservation is employed (pp. 60).

Given the offered load, the blocking probabilities for each routing algorithm depend on the choice of the trunk reservation parameter; hence to obtain the best performance we need to fine tune the parameter.

The optimal trunk reservation problem in single rate loss networks has been well studied in the literature [KEY90], [NEG90], [REI91]. Most previous research has focused on the optimal trunk reservation problem for networks with point-to-point routing only and limiting the length of alternate routes to be at most two. In [HWA95a], the authors solve the optimal trunk reservation problem based on the Markov decision theory, as proposed in [KEY90]. However, they formulate the Markov decision process slightly differently from that of [KEY90] and, thus, obtain a different set of expressions for computing the optimal trunk reservation levels.

In addition to the trunk reservation mechanism there are several other access control strategies for influencing the call blocking probabilities in the heterogeneous networks discussed in the literature. Examples of such strategies are partial sharing or class limitation. In this dissertation we focus exclusively on trunk reservation, since it is the simplest and most effective method for influencing connection blocking.

2.3.5 Related routing proposals

In [GUP93] routing VCs in a VP networks is considered. Two properties, heterogeneous sources (yes or no) and statistical multiplexing inside the network (yes or no), lead to four classes of ATM networks. Various Least Loaded Routing (LLR) algorithms are proposed and developed to reduce the Network Connection Blocking Probability (NCBP). The QoS requirement only involves cell loss.

In [GUP94] the issue of routing call requests, arriving from a diverse set of source types, in a non-hierarchical broadband network, is considered. Specifically, policies for dynamic routing calls, where the selection of a route depends on the state of the network at the instant of call arrival are proposed. The objectives of “sharing” network resources and providing “isolation” between classes are taken into consideration and two distinct classes of routing policies are proposed. In the absence of a direct route, the call is routed on a candidate route which has the largest incremental capacity for class 1, the largest residual capacity for class 1 or the largest residual capacity. The optimal choice of parameters (virtual capacities and reservation thresholds) depends on the arrival and departure processes of various classes. The class isolation capability of a routing policy is measured by the change in Connection Blocking Probability (CBP) of a given class 1 as the arrival and departure rates of classes other than 1 are varied. For a policy that provides “good” isolation, the CBP of class 1 should be relatively insensitive to variations in the arrival and departure of other classes. The ability of a routing policy to allow efficient sharing is measured by the expected rate at which revenue is generated by the network. Clearly effective isolation between classes is not possible. In this paper, a modified LLR algorithm with packing to deal with this problem for circuit-switched networks is proposed.

In [HWA94b], [HWA95b] adaptive routing algorithms based on the Least Loaded Routing (LLR) concept are designed and evaluated for VP-based ATM networks in which resources are reserved on VP's. Two VP capacity allocation strategies are examined. The deterministic strategy reserves dedicated resources on VP's and the statistical strategy, instead of reserving dedicated resources, reserves a dedicated number of VC's, each with a guaranteed QoS, for each VP. Although the second strategy was able to achieve better statistical multiplexing gain, VP were required to provide a more stringent QoS. They also proposed an ADAPTIVE scheme for more efficiently establishing multiple classes of QoS on a physical link or VP. In [HWA95a] the LLR algorithms presented are compared with MDP algorithms presented in [HWA94].

Siebenharr [SIE94] proposes a dynamic algorithm known as the Minimum Free Capacity Routing (MFCR) for VP-based ATM networks with several direct VPs connecting a node pair. The MFCR algorithm picks the direct VP with the smallest residual capacity among those VPs having enough residual capacity. Hence, MFCR tries to aggregate the unused bandwidth on one path. From the VC routing task several routing algorithms like fixed alternate routing, LLR or the MFCR can be used. These algorithms are compared in [SIE94] and the minimum free capacity routing looks quite favourable for VP based ATM networks.

In [CHU95] and [CHU97] the problem of using dynamic routing on VP-based ATM networks, by transforming it into an equivalent multi-rate circuit network problem, is studied. They consider that the VPN supports multiple traffic classes with heterogeneous traffic characteristics and that all traffic requires identical end-to-end QoS requirements. To further simplify the analysis, they restrict the choice of a path to single-VP and two-VP routes. They propose a dynamic routing algorithm based on the LLR with packing. In these papers, the authors modify the MFCR to find 2-link alternative routes instead of 1-link direct route as originally proposed in [SIE94]. The modified MFCR algorithm is similar to LLR except in the selection of the alternative route. The modified MFCR picks the 2-VP alternative route with the smallest free capacity. Although the MFCR algorithm can achieve maximum packing, it leads to non-uniform distribution of traffic. It is because packing (to obtain **efficiency**) and uniform distribution of traffic (to obtain **fairness**) are two conflicting objectives and there is a trade-off between them.

2.4 SUMMARY

The relation between Network Provisioning, Network Resource Management, Bandwidth Allocation, Connection Admission Control and Routing are examined in this chapter. The importance of the Virtual Path (VP) concept as a component of traffic control and resource management and the definition of the VPN embedded in the physical network is also given. A brief introduction of dynamic, alternative and adaptive routing in ATM networks is explained. The problem of routing point to point connections in VP ATM networks is presented to determine the scenario of this dissertation. Finally, a survey of background and related work is provided.

3. Point to Point routing based on Congestion Probability

There are two main optimization criteria in CAC & Routing algorithms: network resource utilization (**efficiency**) and network access (**fairness**). While high resource utilization is important from the network operator's viewpoint, equitable access to the network is important from the network users' viewpoint. Moreover, user performance should be relatively insensitive to variations in the arrival and departure of other users (**isolation**).

In this dissertation, we assume the multi-hour engineering scheme, a semi-permanent VPN topology that can be updated periodically if changing traffic demands make it necessary. The time interval between two VPN topology changes is significantly larger than the call set-up time and call interarrival times. Under this assumption, the establishment of VCC can be performed as if the topology of the VP networks were fixed. The VPN is referred to as a heterogeneous VPN because at least a VP supports connections that have different traffic characteristics and/or QoS requirements.

The point-to-point routing algorithm presented in this chapter should be classified as :

- **Source routing** : the originating (or source) node determines the complete route from origin node to destination node.
- **Dynamic routing** : the scheme is one in which routing decisions are influenced by current traffic conditions.
- **Alternative routing** : the process of selecting a route in the network is made between two or more routes.
- **Adaptive routing** : The VCC is offered first to the direct route, but the second choice routes are not pre-determined, they are established according to the current traffic conditions. The set of possible routes varies with the state of the network.
- **LLR routing** : The route that has the maximum available resources is tried.

To completely define the **Congestion Probability Routing (CPR)** algorithm the following is proposed :

- The performance criteria by CAC is Individual Cell Loss Rate (Individual_CLP) which are evaluated using the New Convolution Approach (NCA).
- The utilization of the Routing Control Parameter (RCP) determines the set of **available alternative routes**.
- As alternative routes are limited to the concatenation of two VPs, the end-to-end QoS requirements, Individual_CLP in this case, is divided evenly among the VPs of the alternative route (**even division policy**).
- The **VP cost function** considered is the Congestion Probability (CP) which is also obtained with the NCA.
- The **composition rule** of the alternative route cost is the addition of each VP cost value. Note that as a direct route consists on only one VP, the **route cost** of direct route is defined by their VP cost value.
- The **alternative route selection scheme** considered is the **minimum**.

The main contributions of the CPR algorithm proposed are :

- to define the Congestion Probability (CP) as a metric parameter of the VP cost function,
- to implement a *protection mechanism*, the **Routing Control Parameter**, which allows an equitable access to the network (**fairness**), to prevent the network from excessive blocking (lower **efficiency**) when the CP is the metric of the VP cost function, and
- to study the **isolation** obtained with the proposed algorithm.

By providing alternative routes, the direct route would be able to achieve lower Call Blocking Probability (CBP) and higher network throughput. However, the use of alternative routes entails the utilization of other VPs and, therefore, a reduction of their capacity and an increasing of their blocking probabilities. VP congestion can occur at any VP along the route and more stringent QoS requirements must be considered. Therefore, the CBP increases, because connections that could be accepted on these VPs along a direct route are rejected with the new QoS requirements. As we mentioned previously, two classes of QoS requirements have to be established on a VP that contains alternatively routed connections. Moreover, if the route has several VPs, the QoS calculated on the origin node of each VP must be sent to the origin node of the previous VP to calculate the end-to-end QoS.

The following scenario is considered in [GUP93], [HWA94] and [DZI97] to give an intuitive explanation for this claim :

Assume overload conditions in the network and a new connection demand which could be accepted on an alternative route consisting of two-VPs. If this connection is rejected, it is likely that, in the “bandwidth” space released by the rejection, two connections can be accepted on the VPs constituting the path under consideration which will be used as direct routes. When an alternative call is added to a VP, the maximum number of direct calls that can be added to this VP may decrease by more than one, because the QoS requirements of the alternative route are more stringent than the QoS requirements of the direct route. Thus, from the network utilization viewpoint, it may be beneficial to reject the alternative connection. Note also that, after an alternative route is accepted, all new connections, direct and alternative only could be accepted if the most stringent requirements of alternative connections are achieved. In this case, the direct connections will encounter significantly higher rejection rate due to the fact that more stringent requirements are needed.

The remainder of this chapter presents a detailed analysis of the relationship between Congestion Probability (CP), Cell Loss Rate (CLR), buffer size and other QoS parameters. The motivation of the utilization of the Congestion Probability as VP cost function is also explained. The Routing Control Parameter (RCP) is defined, which is the protection mechanism, for the direct traffic on the VP, considered in Congestion Probability Routing. CAC-routing cycle, the set of allowed states and calculation of CBP are also presented.

3.1 CONGESTION PROBABILITY AS A METRIC PARAMETER OF THE VP COST FUNCTION

Routing algorithms characterise the VP cost with a set of routing metrics which determine the criterion for route selection. The VP cost function typically associates each VP with a certain value that is adjusted dynamically according to the varying load of the VP. In the simplest case, the function cost returns one of two values indicating whether the VP is available. The calculation of the metric value is based on the knowledge of the current network load, on the traffic descriptors and on the QoS requirements of the new connection and of the already existing connections. These QoS requirements are normally expressed in terms of Cell Loss Rate (CLR), Cell Delay Variation and Maximum Cell Delay.

Normally multiple metrics (e.g., delay, bandwidth and loss probability) can certainly model some characteristics of a network more accurately. However, it may not be feasible to have many parameters as metrics since the problem of finding a route subject to multiple

constraints is inherently difficult. The computation complexity is primarily determined by the composition rules of the metrics.

Note that all QoS requirements have to be mapped onto the considered metrics and those metrics should be orthogonal to each other (i.e. no redundant information among the metrics).

The Maximum Cell Delay can easily be imposed by having a finite buffer to limit the maximum queue length and consequently the maximum delay. Moreover, the network is engineered to satisfy the maximum end-to-end delay requirements. This is done by properly sizing the outgoing VP buffers and limiting the maximum number of hops of the route set. Some authors, i.e. [ATK94], [BAH94], [GUP93], [LEE94b], [NAG93] and [MED97c], choose the CLR as the QoS requirements considered.

If statistical multiplexing is considered, it may happen that the bandwidth required by the accepted connections exceeds the capacity of the VP. The probability of the bandwidth required by the accepted connections exceeding the capacity of the VP is evaluated by the Congestion Probability.

3.1.1 Congestion Probability (CP)

Cells are statistically multiplexed among the VPs for transmission, so a buffer is needed. In this chapter, only small buffers are considered for short duration congestion. If the buffer is full, some cells may be lost. The following figure shows the instantaneous aggregated rate of all sources connected against time.

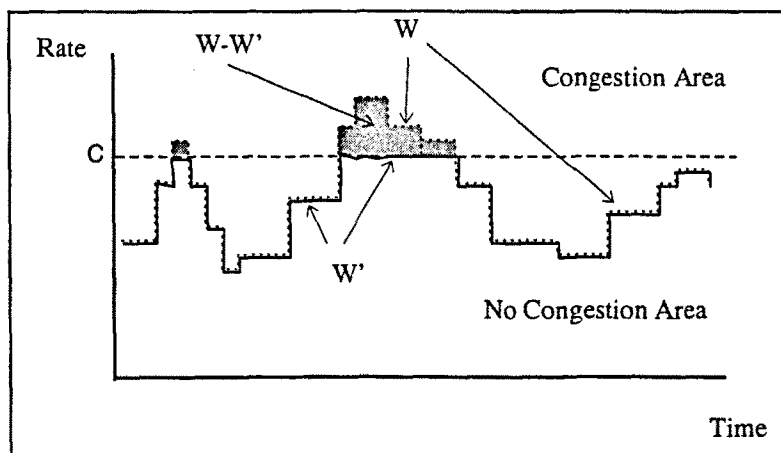


Fig. 8 : Time scale of Congestion.

The following figure shows the probability associated to a given instantaneous aggregated bit rate of all sources. The figure shows that all situations corresponding to rates greater than C (at right of C) are in a congestion state.

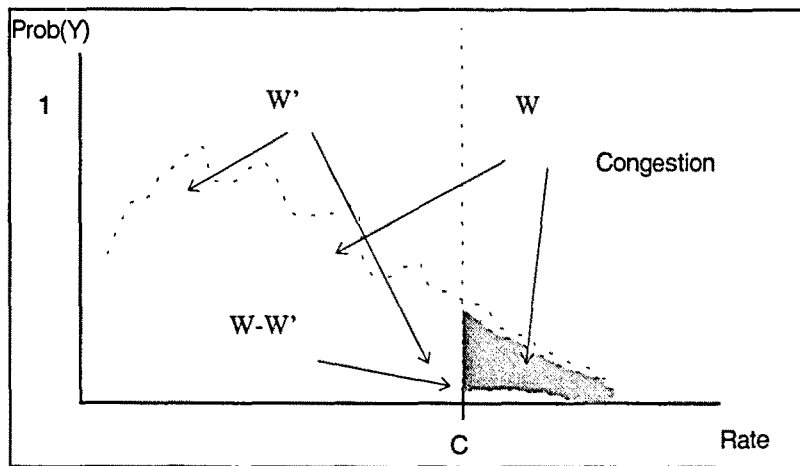


Fig. 9 : Probabilistic scale of Congestion

The congestion probability (CP) is the sum of probabilities corresponding to rates greater than C, which is the shadow area. The CP states neither how many cells are lost nor the duration of the congestion state, but only that there is cell loss [IVE91].

Congestion Probability evaluation

There are two major ways to evaluate the CP in an VP: empirical methods based on the declared statistical traffic parameters, and methods based on measures acquired directly from the system. From the point of view of the QoS, learning methods have an important problem: normally connections do not use all their assigned bandwidth, but it is possible that all connections, or some of them, suddenly become active so that the traffic control functions cannot avoid an excessive loss of cells. Consequently, empirical methods are more widely used, see [MAR97th].

The load region admissible is approximated using parameters [KLE91] such as; the mean load, the CP and the ratio of cells exceeding the VP capacity for the total cell stream and for each individual connection: CLR_i.

The mean bandwidth required by a VP is evaluated by applying:

$$E(Y) = \sum_{i=1}^S N_i \cdot E(X_i)$$

- Y Rate distribution of the instantaneous offered rate
- N_i Rate distribution of the source i.
- S Number of sources.

For arbitrary mixes, the load of the VP may provide only a small amount of information about the cell loss probabilities [KLE91]. Cell losses are quite likely if the bandwidth required at the burst level exceeds the capacity of the VP. These events are taken into account by the CP [KLE91].

$$CP(Y) = P(Y > C) = \sum_{L>C} P(Y = L)$$

C VP Capacity.

However, the CP does not give any information about the number of cells lost in case of congestion unlike Cell Loss Rate (CLR). In a short congestion state, all cells may be buffered with no cell losses occurring. Nevertheless, when a burst length is longer than the size of the buffer, then almost all cells exceeding the VP capacity are lost. In this case, the relation between CP and CLP is approximated by:

$$CLP(Y) = \frac{\sum_{L>C} (L - C)P(Y = L)}{E(Y)}$$

If the buffer size is large enough for cell contention, the evaluated CLP provides an upper limit to the total cell loss probabilities [KLE91]. The CP model is a stationary approximation, in other words, a probabilistic scheme.

The small buffer assumption

To work with small buffers implies that the traffic bursts cannot be saved in the buffer. Therefore, the burst length is irrelevant because all cells will be lost. At cell scale, losses are the object of the buffer dimensioning problem and the burst level approximation concerns the Call Admission Control [CAST91]. On the other hand, it is not likely that users will be able to supply information about the burst length at connection set-up. Moreover, it might be difficult to guarantee a certain burst length distribution for policing functions [KLE91].

The accuracy of this assumption depends on both buffer size and burst length. A set of simulations are presented in [MAR97th] to illustrate how close the actual CLP is to the evaluated CLP. It is known that an increase in burst length leads to an increase in the CLP. Results are shown in [MAR97th] which demonstrate this point. Results provided by both analysis and simulation have been presented. In the analysis, a convolution approach is used to obtain the corresponding CLP evaluation. This evaluation ignores both buffer-size and burst length. Note that the convolution approach is a stationary model.

3.1.2 Congestion Probability and QoS relationship

In the Congestion Probability Routing (CPR) scheme, all QoS requirements are mapped onto the routing metric considered, the Congestion Probability. This is because it uses the CLP requirements as the performance criteria for CAC and the CP can be related with the CLP. This single metric, the CP, models the characteristics of a network accurately, because it mixes the CLP of the current VCCs and the residual bandwidth that is available

for the new VCC. For this reason the CP is a value of the VP utilization. The CP, the Total CLP and the Individual CLP can be calculated using the Enhanced Convolution Approach (ECA) [MAR97th].

Since traffic characteristics differ across sources, the CLP of individual source types is not necessarily equal to the overall CLP. Hence, it is not always sufficient to maintain a QoS that is the most stringent among all source types to meet the demands of all VCCs. For simplicity consider the case of two source types with $\text{burstiness}_1 > \text{burstiness}_2$. It is shown that the CLP for source 2 (with less burstiness) is less than the overall CLP and that for source 1 is more than the overall CLP. Further, the difference between the CLP of the two sources increases with the difference in their burstiness”.

In traditional circuit-switched networks, direct route and alternative routes are not distinguished because they require the same amount of bandwidth along the path but it is not the case in ATM networks because, when a VCC is routed on an alternative route, it requires a more stringent QoS at each VP on this alternative route, since QoS is an end-to-end measure and multiple VPs are now the end-to-end route. Note that for an alternatively routed VCC, cell loss can occur at either of the two VPs.

If the two-VP alternative route through a transit node is considered, the end-to-end QoS needs to be decomposed into several “local” QoS which must be satisfied on each VP on the route. The problem of how to decompose the end-to-end *Individual_CLP* into local *Individual_CLP* optimally is beyond the scope of this dissertation.

We assume *Individual_CLP* as end-to-end Quality of Service (QoS) requirements, which are divided in equal shares among the VPs of the two-VP alternate route (*even QoS division policy*), that is, *Individual_CLP* requirements / 2 for each VP of the alternative route. In this case, two classes of QoS are established on each VP; one for direct calls and other for alternate calls.

The following table shows the relation between *Individual_CLP* calculated by the ECA and the end-to-end QoS requirements that could be support a new connection, depending on the traffic (direct or alternated) carried by the VP’s, to be accepted.

	Return of ECA function		end-to-end QoS requirements
If there are only Direct traffic over the VP a new direct connection is accepted if	Individual_CLP calculated	<	<i>Individual_CLP</i> required
If there are Alternated traffic over the VP, a new connection is accepted if	Individual_CLP calculated in first VP Individual_CLP calculated in second VP	< and <	<i>Individual_CLP</i> required / 2 <i>Individual_CLP</i> required / 2

Tabla 6 : Relation between Individual_CLP and the end-to-end QoS requirements

Note that, in heterogeneous networks, different requirements can be demanded by each class of traffic. In this case, as Individual_CLP by each class of traffic is obtained with the ECA function, this table will be considered by each class. A new connection will be accepted if it is accepted by all traffic class.

3.2 ROUTING CONTROL PARAMETER

In algorithms based on the dynamic *alternative routing technique*, the VCC is offered first to the direct route. If the direct route is unavailable, *alternative two-VP routes* are considered. Finally, if no alternative route is available the VCC is rejected.

Using alternative routes does not always decrease the Network Call Blocking Probability. To overcome this drawback, the following protection mechanism is defined :

An alternative route is only considered if the CP on each VP, of the alternative route, is smaller than a threshold: the *Routing Control Parameter* (RCP). When the RCP is used, some amount of CP is reserved for direct traffic into a VP.

This is a protective allowance for the direct traffic on the VP, its role is to divert traffic from the VP when it is nearly fully occupied and is used to control Call Blocking Probability (CBP) among different classes. Note that an alternative route is only considered if the CP on each VP of the alternative route is smaller than the choose RCP. This increases the probability of the direct routed calls being set up.

When RCP is ignored, the cost per connection (number of VPs and physical links per connection) will be increased because carrying out a connection by an alternative route utilizes two VPs instead one direct VP. As is show in the experiments, there is a trade-off between the utilization of the VP and the cost-penalty when two VPs of an alternative route with a more stringent QOS are considered.

While in circuit switched networks the resource reserved are idle circuits and in ATM networks the resource reserved is capacity, in CPR algorithms using the RCP proposed is

this dissertation the resource reserved in available Congestion Probability. The reader should view the RCP as being analogous to the trunk reservation parameter for single-rate circuit-switched networks [WEB64].

NETWORK	PROTECTION MECHANISM	RESOURCE RESERVED
Circuit switched network	Trunk Reservation	Idle circuits
ATM network using equivalent bandwidth to characterize the connections	Trunk Reservation	Capacity
ATM network using the Congestion Probability as VP cost function	Routing Control Parameter	Congestion Probability

Tabla 7 : Relationship between type of network, protection mechanism and resource reserved.

3.3 ROUTING-CAC CYCLE OF THE CPR

In the previous chapter the relation between the Routing and the CAC are explained. While the routing selects the best route from a set of routes (direct route and alternative routes), the CAC deals with the question of whether the connection should be admitted on a route which ensures that the QoS constraints are met. Routes selected by Routing may be rejected by CAC if CAC considers that their establishment would significantly deteriorate the QoS of existing calls.

The aim of an efficient routing algorithm is to allow the acceptance of the largest possible number of calls while satisfying the negotiated QoS parameters to all the admitted calls. The objective of the routing is to find a route which optimizes some criteria (such as network resource utilization and fairness), while the connection admission procedure verifies whether certain constraints are not exceeded (QoS requirements), on the selected route.

The set of alternative routes can contain all potential routes or can be limited (available alternative routes) for performance reasons. In the proposed algorithm, the set of available alternative routes are limited by the Routing Control Parameter and it is related to the GoS characteristics (connection blocking probability as metrics of the connection layer performance). Therefore the route is not available, even though it could be admissible from the resource availability viewpoint.

The proposed CAC-Routing cycle is showed in this diagram :

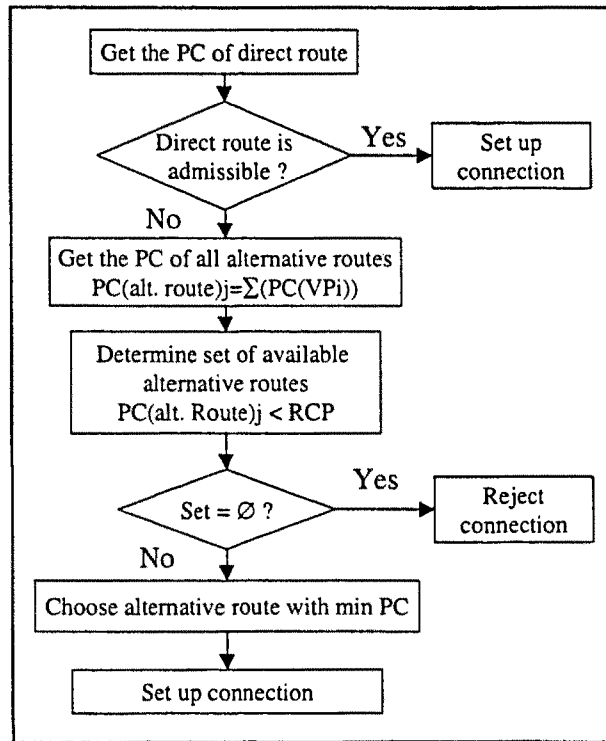


Fig. 10 : CAC-Routing cycle of the CPR algorithm

The set of available alternative routes is all the alternative routes that have an associated CP less than the RCP. The CP is calculated with the ECA. The following diagram show the input parameters of the CAC and the result obtained.

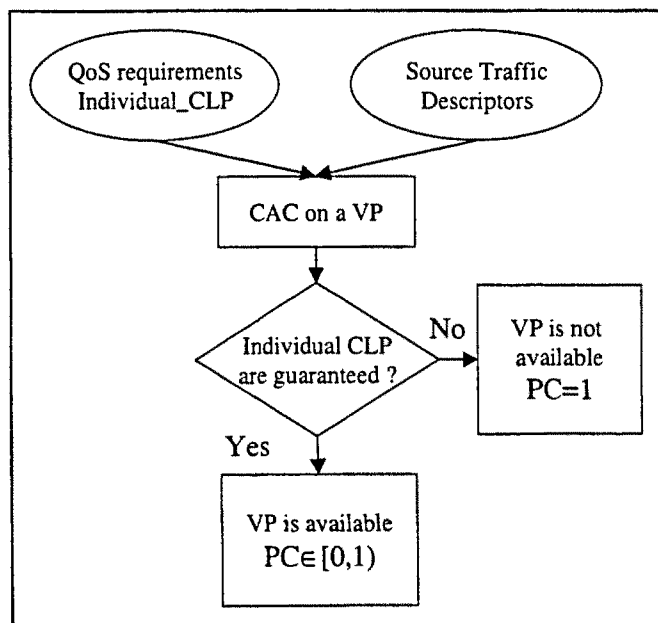


Fig. 11 : Connection Admission Control on a VP

The CPR algorithm is shown in the following pseudocode:

```
choose direct route if direct route is admissible
else out of all available alternative routes choose alternative route with
                                         min(cost(2-VP alternative route))
else reject
```

where:

- *performance criteria by CAC*: the direct route is admissible if the Individual CLP is smaller than the Individual CLP requirements by all traffic over the route (direct VP).

- *even QoS division policy*: one VP of an 2-VP alternative route is **available** only if Individual_CLP(VP) is smaller than the Individual CLP requirements / 2.

- the Congestion Probability (CP) is the metric parameters of the *VP cost function*.

- *protection mechanism*: an alternative **route** is **available** if all VP are available and the CP(VP) of all VPs of the alternative route are smaller than the Routing Control Parameter value.

- *composition rule*: addition, i.e., $\text{cost (2-VP alternative route)} = \text{CP}(\text{firstVP}) + \text{CP}(\text{secondVP})$

- *alternative route selection*: minimum.

Note that an alternative route, formed by two available VPs, could be unavailable because some CP(VP) is greater than the fixed RCP. In this case, first the CAC is applied and finally the selection of the route.

3.3.1 Connection set-up scheme

To accept a new connection, one ECA in each alternative route could be applied to know the cost of the route. If the ECA is calculated after the connection is demanded (On-line scheme), the response time of the connection setup could be unacceptable.

To obtain an accurate fast response with the CPR algorithms, different evaluation schemes can be considered: on-line scheme, on-line pre-evaluation scheme, store the on-line evaluations (storing the past) and off-line pre-evaluation scheme. The first two can be combined.

On-Line Pre-Evaluation Scheme

The on-line pre-evaluation scheme calculates dynamically the VP cost of all the possible states of the VP when the CAC-evaluation subsystem is idle. For each type of

source a new virtual connection must be considered. This process allows the system to know whether or not it is possible to allocate this hypothetical new call. Using the pre-evaluated CP table, it is possible to know beforehand if the QoS requirements of this selected VP are not exceeded and the VP supports new connection of a given type.

Storing the past

As the probability of congestion only depends on the current traffic demands and the value of the VP capacity assigned to the VP and as we suppose that the VPN is semi-permanent, often the same situations may be calculated. Therefore, an immediate response can be obtained if all evaluated results are stored.

Moreover, the status of the output VP exhibits a locality, meaning that the status of the system does not suffer drastic changes and for a relatively long period of time the number of connections on the VP are only a relatively small fraction of all possible cases. When the entire possible status is in the memory, the CAC-evaluation subsystem will offer a response without making any calculations.

Off-line evaluations

If there is sufficient memory to hold the entire possible status, all the calculations can have been made previously (Off-line evaluations). If the available memory is too small to hold the entire possible status, the CAC-evaluation subsystem will make many calculations.

3.4 SET OF ALLOWED STATES

In this section, the variations on the set of allowed states depending on the resource reserved and the protection mechanism considered are studied. We consider a single VP with a fixed capacity C measured in Mbps and a number of N of different traffic classes use this VP.

The arrival traffic of service class i is assumed to follow a Poisson process with rate λ_i . During the holding time T_{Hi} of a call of type i , a constant bit rate denoted by C_i is reserved for this call and released after the call has completed. This bit rate C_i may either be the equivalent bandwidth of the source in case of a Variable Bit Rate (VBR) call or the bit rate which is required during the whole holding time in case of Constant Bit Rate (CBR) calls. The call holding time T_{Hi} is assumed to have a negative-exponential distribution function with mean $1/\mu_i$.

Comentar cuales son, cuando estamos considerando unicamente trafico directo, y cuando alternativo, y en que casos podriamos obtener una solucion analitica de la CBP.

3.4.1 CAC: available capacity

In this case, the available capacity of the VP, i.e., the capacity that is not reserved to already accepted calls, is the CAC algorithm considered.

The system state is defined by the number of accepted calls from each class (n_1, \dots, n_N). Thus, the multi-dimensional state space has as many dimensions as the number of traffic classes. The set of allowed states S is determined by the capacity constraint

$$S = \{(n_1, \dots, n_N) \mid \sum_{i=1}^N n_i C_i \leq C\}$$

The sets of blocking states S_i are defined by

$$S_i = \{(n_1, \dots, n_N) \mid C - C_i < \sum_{j=1}^N n_j C_j \leq C\}$$

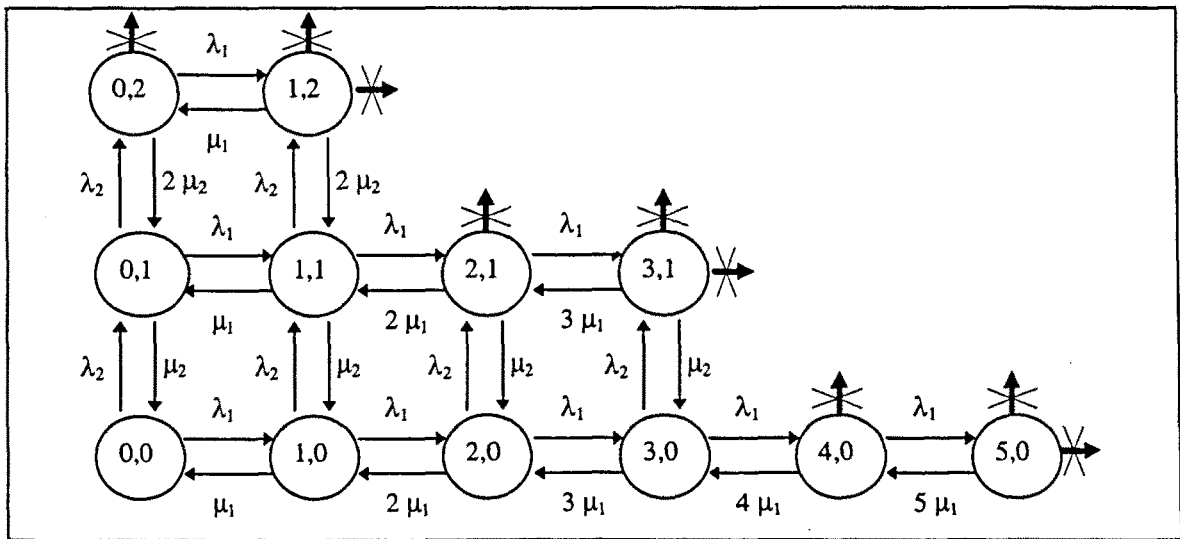


Fig. 12 : State space example for product form solution ($N=2, C=10, C_1=2, C_2=4$)

In previous figure, the set of blocking states for the two classes are

$$S_1 = \{(n_1, \dots, n_N) \mid 10 - 2 < \sum_{j=1}^N n_j C_j \leq 10\} \quad \text{and} \quad S_2 = \{(n_1, \dots, n_N) \mid 10 - 4 < \sum_{j=1}^N n_j C_j \leq 10\}$$

$$S_1 = \{(1,2), (3,1), (5,0)\} \quad S_2 = \{(0,2), (1,2), (2,1), (3,1), (4,0), (5,0)\}$$

3.4.2 Protection mechanism: trunk reservation

In [TRA93] the following simple and general rule for balancing blocking probabilities of calls from different classes was proposed:

Rule: For any subset of traffic classes $\omega \subseteq \{1, \dots, N\}$ the corresponding call blocking probabilities B_i ($i \in \omega$) are equal, if all thresholds Θ_i for $i \in \omega$ are set to $\lfloor (C - \max\{C_k | k \in \omega\}) \rfloor$

When employing the trunk reservation, a call of class i is accepted only when C_i bandwidth are available upon arrival and not more than Θ_i Mbps are occupied. When calls from a class j will not be subject to trunk reservation, Θ_j is set to $C - C_j$. This setting is reasonable, because class- j calls are blocked anyway if more than $C - C_j$ Mbps of the transmission link are occupied. Hence the call acceptance of class- j calls are not affected if Θ_j is set to this value.

The set of possible allowed states S is also determined by the capacity constraint:

$$S = \{(n_1, \dots, n_N) \mid \sum_{i=1}^N n_i C_i \leq C\}$$

but there are some transitions between neighbouring states that are not possible if the trunk reservation is considered. In this case, the sets of blocking states S_i are defined by

$$S_i = \{(n_1, \dots, n_N) \mid \Theta_i < \sum_{j=1}^N n_j C_j \leq C\}$$

In following figure the values $N=2$, $C=10$, $C_1=2$, $C_2=4$, $\Theta_1=6$ and $\Theta_2=8$. are considered.

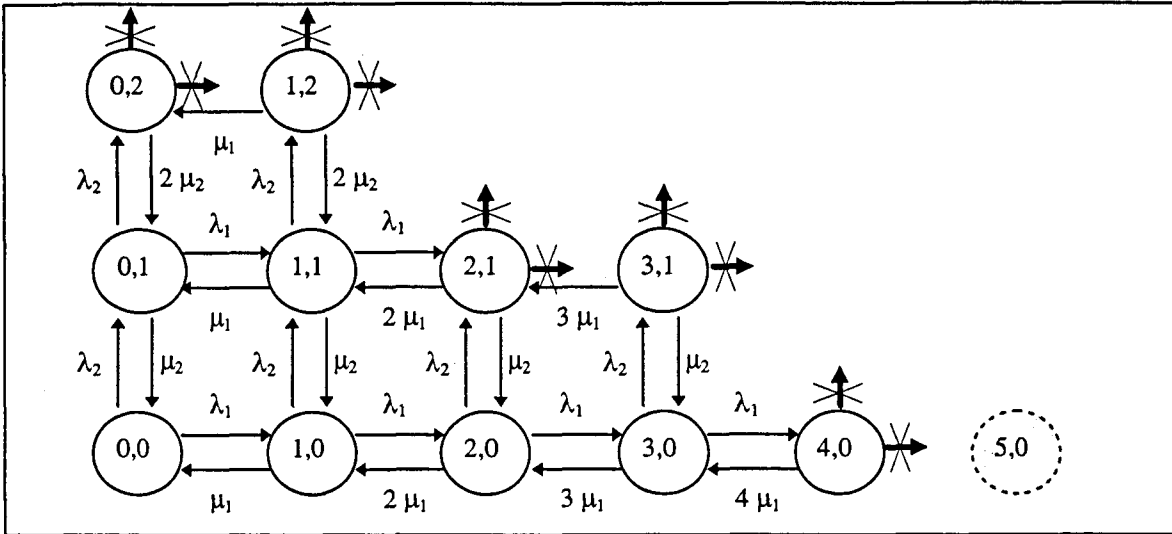


Fig. 13 : Trunk reservation mode: State space example for product form solution

Note that

- the state (5,0) never will be achieved.
- in states (0,2), (2,1) and (4,0) a new class-1 call could be accepted if class-1 calls are not subject to the trunk reservation.

In previous figure, the set of blocking states for the two classes are

$$S_1 = \{(n_1, \dots, n_N) \mid 6 < \sum_{j=1}^N n_j C_j \leq 10\} \quad \text{and} \quad S_2 = \{(n_1, \dots, n_N) \mid 8 < \sum_{j=1}^N n_j C_j \leq 10\}$$

$$S_1 = S_2 = \{(0,2), (1,2), (2,1), (3,1), (4,0), (5,0)\}$$

3.4.3 CAC: individual cell loss probability

When NCA is considered as CAC algorithm, the Individual_CLP are obtained and the set of allowed states S is determined by the CLP requirements constraint.

In this case,

$$S = \{(n_1, \dots, n_N) \mid \text{Ind_CLP}(n_1, \dots, n_N)_i < \text{CLP requirements}_i \quad \forall i = 1, \dots, N\}$$

and the set of blocking states, S_i , are :

$$S_i = \{(n_1, \dots, n_N) \mid \begin{array}{l} \text{Ind_CLP}(n_1, \dots, n_N)_i < \text{CLP requirements}_i \\ < \text{Ind_CLP}(n_1 + I_{i,1}, \dots, n_N + I_{i,N})_i \end{array} \mid \}$$

where

$$I_{i,j} = \begin{cases} 0 & \text{if } i \neq j \\ 1 & \text{if } i = j \end{cases}$$

Alternated traffic

If alternative routing is considered, the VP could carry direct traffic and alternated traffic. By traffic class which alternated traffic is carried in the VP, a more stringent QoS is required, and the set of allowed states S is

$$S = \{(n_1, \dots, n_N) \mid \text{Ind_CLP}(n_1, \dots, n_N)_i < \text{CLP requirements}_i / 2 \quad \forall i = 1, \dots, N\}$$

and the set of blocking states, S_i , are :

$$S_i = \{(n_1, \dots, n_N) \mid \begin{array}{l} \text{Ind_CLP}(n_1, \dots, n_N)_i < \text{CLP requirements}_i / 2 \\ < \text{Ind_CLR}(n_1 + I_{i,1}, \dots, n_N + I_{i,N})_i \end{array} \mid \}$$

3.4.4 Protection mechanism: routing control parameter

If the Routing Control Parameter is considered, the set of allowed states S is

$$S = \{(n_1, \dots, n_N) \mid \begin{array}{l} \text{Ind_CLP}(n_1, \dots, n_N)_i < \text{CLP requirements}_i / 2 \quad \text{and} \\ \text{CP}(n_1, \dots, n_N)_i < \text{RCP} \end{array} \mid \forall i = 1, \dots, N\}$$

and the set of blocking states, S_i , are

$$S_i = \{(n_1, \dots, n_N) \mid \begin{array}{l} \text{Ind_CLP}(n_1, \dots, n_N)_i < \text{CLP requirements}_i / 2 \quad \text{and} \\ \text{CP}(n_1, \dots, n_N)_i < \text{RPC} < \text{CP}(n_1 + I_{i,1}, \dots, n_N + I_{i,N})_i \end{array} \mid \}$$

3.4.5 Numerical example

In following figures, we compare the maximum number of traffic type 1 and traffic type 2 connections that can be supported on a VP with 50 Mbits/s of capacity under different Individual CLR requirements according to traffic characteristics defined in the following table.

Traffic Class	(rate; probability) state 0	(rate; probability) state 1	mean rate	burstiness	CLR Requirements	demanded bandwidth
1	(0 Mbit/s; 0.9)	(4 Mbit/s; 0.1)	0.4 Mbit/s	10	1.0 E-5	1.3
2	(0 Mbit/s; 0.6)	(4 Mbit/s; 0.4)	1.6 Mbit/s	2.5	1.0 E-6	3.9

Tabla 8 : Traffic descriptor parameters of traffic class 1 and 2.

The RCP considered in both figures is 1.0 E-5. A point (CN1 to CN2) on the shadowed area can be interpreted as follows: CN1 traffic type 1 connections and CN2 traffic type 2 connections can be supported to guarantee the required QOS. In second figure, the Individual CLR requirements are more stringent (Individual_CLP/2), therefore, the number of allowed states is less. The CAC and the routing algorithm must be applied using the first figure if only direct traffic is carried out on the VP, and using second figure if alternative traffic is carried out.

Different areas could be defined :

- On *No Congestion* (NC) area the capacity required by CN1 and CN2 connections does not exceed the VP capacity.
- On *Alternative Traffic Admitted* (ATA) and *Only Direct Traffic Admitted* (DTA) areas the offered traffic exceeds the capacity of the VP but the connections are accepted. Moreover, on ATA area the CP is less than the RCP considered; that is, connections over VPs with alternative traffic are admitted. But on only DTA admitted area only direct traffic is considered.
- The border line between ATA area and ODTA area goes to NAC area if the RCP grows (1.0 E-4). But it goes to NC area by smaller RCP (1.0 E-6). ATA area only depends of the RCP, therefore they are the same in both figures.
- On *No Admissible Congestion* (NAC) area, connections can not be supported with the Individual CLR requirements.

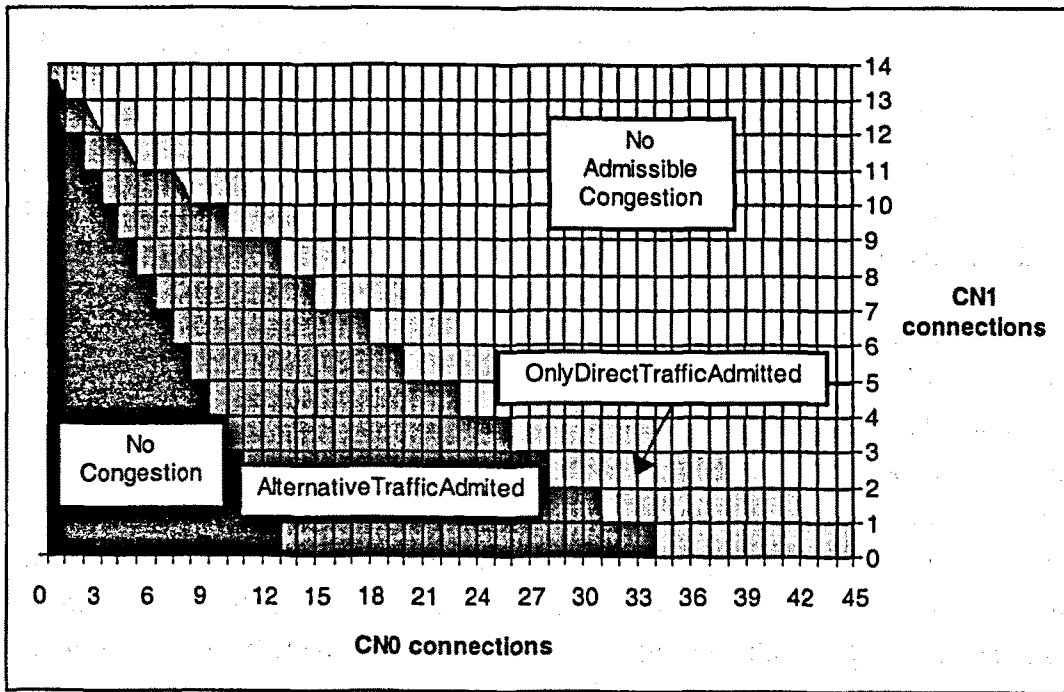


Fig. 14 : CP by CAC using Individual CLR requirements.

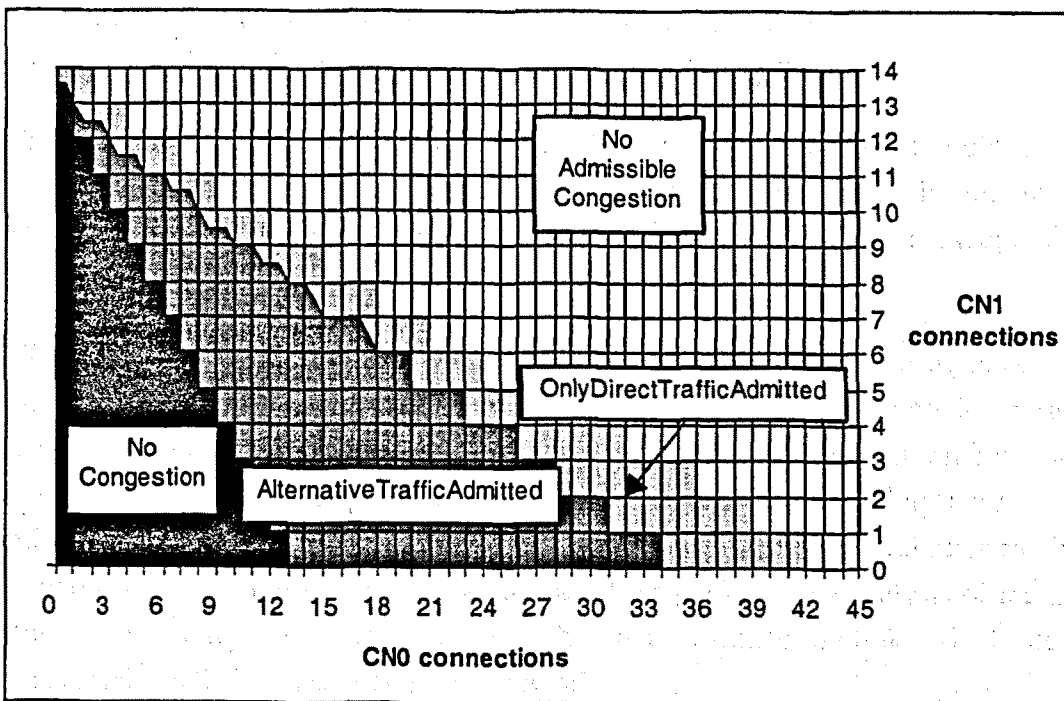


Fig. 15 : CP by CAC using (Individual CLR requirements) / 2.

Note : There are some states shadowed with two different colours, this is an effect of the program used to generate the figure; evidently all the state is in the same area.

3.5 CALL BLOCKING PROBABILITY

The GoS constraint requires that the percentage of calls blocked for each traffic demand should be less than a pre-specified number. Since the objectives of the routing algorithm are to achieve a satisfactory network resource utilization and to equalize Call Blocking Probability (CBP), different proposals to evaluate the CBP are presented.

In 1917, Erlang published a teletraffic dimensioning method for circuit switched networks. He developed a formula which expressed the call loss probability of a telephone system. The problem considered by Erlang can be phrased as follows. Calls arrive at a link as a Poisson process of rate v . The link comprises C circuits, and a call is blocked and lost if all C circuits are occupied. Otherwise the call is accepted and occupies a single circuit for the holding period of the call. Call holding periods are independent of each other and of arrival times and are identically distributed with unit mean. Then the Erlang's formula gives the proportion of calls that are lost, and for over eighty years this simple formula has helped telecommunication engineers determine the amount of capacity, C , that is required for a given level of offered traffic, v , if the loss probability is to be acceptable.

But, what happens if the system consists of many links, and if calls of different types (perhaps voice, video and conference call) require different resources ?

The difficulties to obtain the CBP arise from the combination of multiple service classes with an alternative or adaptive routing algorithm. The problem with the alternative and adaptive routing algorithms is difficulty or impossibility of finding an exact expression for the calculation of the CBP in the multiservice case.

The difficulty arises in the analysis of adaptive routing networks during the estimation of the offered load at every route. Note that in this case the parameter that could be estimated is the arrival rates of call offered to alternative route, because the arrival rates and the holding time of request offered to direct route is known and the holding time of request offered to alternative route does not vary. The evaluation of the link arrival rates can be done in two ways. One is to develop an analytical model for performance analysis of the network with the given routing policy. The second method is to estimate the link arrival rates based on some simple statistics measured in the network.

In the following subsections, the statistics of the offered, carried and overflowed traffic are explained.

3.5.1 Offered, carried and overflowed traffic characteristics

In this section an analytical model for the evaluation of the link arrival rates is explained. For a given source-destination pair, a user generates Poisson call requests with rate λ . The traffic load between pairs of nodes are measured in erlangs (the call arrival rate “ λ ” multiplied by the average call duration “ $1/\mu$ ”). Call requests are first offered to the direct VP. If the direct route is unavailable, the call is offered to one 2-VP alternative route. The traffic load to be carried in a dynamic call routing environment can be carried in two ways: on a direct link or on two links in case of alternate routing. The traffic overflowed from the direct link, called the overflowed traffic, intends to use an alternative route.

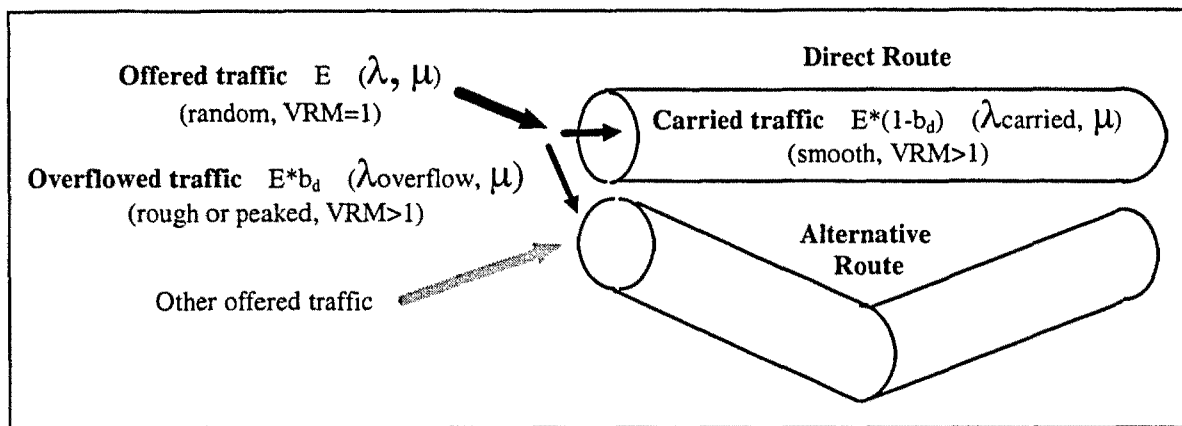


Fig. 16 : Offered, carried and overflowed traffic

If we estimate a blocking b_d of the load to be carried on the direct path, then the overflow traffic can use two links to complete the requirements. This overflow traffic shares capacity with other traffic pairs.

Offered traffic is a random traffic (Poisson) which has the characteristics that the variance of the arrival process is equal to its mean. The variance to mean ratio (VMR), also called peakedness factor, is defined as

$$VMR = \frac{\text{variance}}{\text{mean}}$$

Thus, random traffic has a VMR of 1. Traffic with VMR>1 is referred to as rough, and traffic with VMR <1 is called smooth.

Given the traffic load offered to a VP, the expected call blocking probability percentage (blocking probability) can be calculated by the famous Erlang-B formula or Wilkinson’s formula, depending upon whether the traffic is random or rough (see [KER93]). These two basic trunking formulas that will be used to formulate the GoS constraint are introduced in next sections.

3.5.2 Erlang-B formula: random traffic

The call blocking probability for a link with capacity z and a random traffic load $\rho = \lambda/\mu$ can be calculated by the well known **Erlang-B** formula as follows

$$B(z, \rho) = \frac{\frac{\rho^z}{z!}}{\sum_{k=0}^z \frac{\rho^k}{k!}}$$

This formula is numerically difficult to evaluate with a computer because it involves calculating very large numbers. Fortunately, it can be rearranged algebraically into a much more convenient form which allows us to iteratively compute as follows :

$$B(z, \rho) = \begin{cases} 1 & \text{if } z = 0; \\ \frac{\rho B(z-1, \rho)}{(\rho B(z-1, \rho) + z)} & \text{if } z = 1, 2, \dots \end{cases}$$

As stated earlier, the overflow from a high usage link will be rerouted on its alternate routing path. The statistics of the overflowed were established by [SYS60], and it was found that the carried traffic is smooth while the overflow traffic is rough (see previous figure).

Given the capacity z and a random traffic load ρ for a high usage link, the precise expressions for the mean and variance of the carried traffic and overflowed traffic $U_c(z, \rho)$, $V_c(z, \rho)$, $U_o(z, \rho)$ and $V_o(z, \rho)$ are :

$$\text{mean of carried traffic } U_c(z, \rho) = \rho (1 - B(z, \rho))$$

$$\text{variance of carried traffic } V_c(z, \rho) = U_c(z, \rho) [1 - L_c(z, \rho)]$$

$$\text{where } L_c = \rho (B(z-1, \rho) - B(z, \rho))$$

$$\text{mean of overflow traffic } U_o(z, \rho) = \rho B(z, \rho)$$

$$\text{variance of overflow traffic } V_o(z, \rho) = U_o(z, \rho) \left[1 - U_o(z, \rho) + \frac{\rho}{(z+1 + U_o(z, \rho) - \rho)} \right]$$

The overflow traffic is always rough, that is, the variance is greater than or equal to mean. The approach taken is to model the traffic with mean intensity and variance as another distribution for which we can analyze the blocking. These formulas must be evaluated

iteratively. Unlike the Erlang formulas, these formulas cannot be used incrementally to easily determine an appropriate valued z during a design. Instead, it must be evaluated over and over again for different z . For this reason, these formulas are not widely used. Instead, the Wilkinson Equivalent Random Theory [WIL56] is more widely used. This method outlined in [WIL56] proposed that instead of dealing directly with the analysis of non-random overflow traffic, that such traffic be modeled by an equivalent amount of random traffic offered to an appropriate group of lines.

3.5.3 Wilkinson's formula : rough traffic

The call blocking probability for a link with capacity z and rough traffic of mean U_0 and variance V_0 can be calculated by using **Wilkinson's formula**. Wilkinson showed that when random traffic is offered to a group of n trunks, the (non-random) overflow traffic is adequately described by two parameters, namely its mean and its variance.

$$W(z, U_0, V_0) = B(z + z', \rho')$$

Look at previous figure and think of any offered load, with mean ρ and variance v as overflow from a random load, ρ' , being offered to a group of z lines. ρ' is called the equivalent random load and z' the equivalent lines. If this overflow traffic is offered to another group of z lines, the probability of loss can be computed using the Erlang-B function.

Thus, we have an offered load with mean ρ and variance v , which may or may not be overflow from other groups of lines. Now, find the mean and variance of the overflow when this load is offered to a group of z lines. First determine ρ' and z' , using the methods described as follows, and then use the Erlang-B function to compute the mean, U_0 of the overflow traffic.

This approach relies on the observation that offering traffic to m_1 lines, and then offering the overflow to m_2 lines is the same as offering the original load to $m_1 + m_2$ lines. This is valid because we can think of the traffic being offered first to the group of m_1 lines and then, if necessary, to the rest. While this point of view affects the utilization of the lines in the individual groups, it does not affect the blocking probability for the traffic because from the point of view of the traffic, the lines are identical.

A method to determine z' and ρ' was developed by ([RAP64],)

$$\rho' = V_0 + 3r(r-1),$$

$$z' = \rho' \frac{(U_0 + r)}{(U_0 + r - 1)} - U_0 - 1 \quad \text{with} \quad r = \frac{V_0}{U_0}$$

Wilkinson's formula also includes the case of random traffic, since $V_0 = U_0$ (which is true for Poisson arrivals and exponential call holding times) results in $W(z, U_0, V_0) = B(z, U_0)$. For the rough traffic, where z' may not be an integer, the Erlang-B formula must be extended to handle the non-integer values ; it then becomes a gamma function, which can be evaluated using the approximation proposed by Farmer and Kaufman [FAR78] that calculates the $B(z+z', \rho')$.

$$B(z+z', \rho') = \begin{cases} 1/S & \text{if } 0 \leq z+z' < 1; \\ \frac{\rho' B(z+z'-1, \rho')}{(\rho' B(z+z'-1, \rho') + z+z')} & \text{if } z+z' \geq 1. \end{cases}$$

where

$$S = 0.711093 \left(1 + \frac{0.415775}{\rho'}\right)^{z+z'} + 0.278518 \left(1 + \frac{2.29428}{\rho'}\right)^{z+z'} + 0.010389 \left(1 + \frac{6.28995}{\rho'}\right)^{z+z'}$$

An alternative to this approach is to compute an integer estimate for z' and then adjust ρ' accordingly. Specifically,

$$z'' = \lfloor z' \rfloor$$

$$\rho'' = \frac{(z'' + \rho + 1)(r + \rho - 1)}{(r + \rho)}$$

3.5.4 Multiservice systems

Different models for the approximate calculation of the CBP in homogeneous and heterogeneous traffic environments on a single path without and with trunk reservation are presented in several works [AST95], [AZM94], [COST242], [DZI93b], [KEO96], [SIE95] and [VLA94].

When a single link is considered, the exact call blocking probabilities can be derived using two different algorithms: a product form solution described in [ENO73] and a recursive solution according to the algorithm proposed in [KAU81] and [ROB81].

When only one traffic case is considered, we have a blocked calls cleared situation in which there are available m server ($M/M/m/m^5$: m -server loss system). Each newly arriving customer is given his private server ; however, if a customer arrives when all servers are

⁵ (Input specification / service time distribuion / number of servers / number of sources). So an $M / M / m / m$ queue has call arriving from m sources at random intervals, lasting for varying periods (that follow an exponential curve. Other calls are queued in a queue with m places. M : Markov (purely random).

occupied, that customer is lost. We create this artifact as above by choosing the following birth and death coefficients :

$$\lambda(k) = \begin{cases} \lambda & k < m \\ 0 & k \geq m \end{cases} \quad \text{and} \quad \mu(k) = k * \mu \quad k = 1, 2, \dots, m$$

In this case the VP is described by a Markov chain with finite number of states S (see previous section) and using a product form solution the CBP is obtained. To derive the blocking probabilities for the different traffic classes we first focus on the unnormalized functions $p^*(n_1, \dots, n_N)$ given by

$$p^*(n_1, \dots, n_N) = \prod_{i=1}^N \frac{(\lambda_i / \mu_i)^{n_i}}{n_i!}$$

Note, that they only depend on the offered traffic $A_i = \lambda_i / \mu_i$ and not on the arrival and service rates individually. We derive the state probabilities by normalization:

$$p(n_1, \dots, n_N) = G(S)^{-1} p^*(n_1, \dots, n_N)$$

where the normalized constant $G(S)$ is the sum of the unnormalized functions over the allowed states S:

$$G(S) = \sum_{(n_1, \dots, n_N) \in S} p^*(n_1, \dots, n_N)$$

Using these state probabilities, the probability of blocking an arriving call of class i is

$$B_i = \sum_{(n_1, \dots, n_N) \in S_i} p(n_1, \dots, n_N)$$

where S_i is the set of blocking states.

The recursive solution of the model is based on a mapping of the multi-dimensional state space into a one dimensional state space in accordance with a proper bandwidth discretization. A brief description of the methods are given in [COST242] and [SIE95]. This recursive algorithm reduces the numerical complexity. It is also possible to calculate the

single service call blocking probability for different routing algorithms [15 de SIE95] and [16 de SIE95]. For networks without alternative routing the blocking probabilities generally satisfy a product form solution.

In [COST242] two simple algorithms for computing the exact blocking probabilities are mentioned. Thus it might look unnecessary to consider the prospect of an approximation. However, an exact solution might not be practical in case of the product form solution if a large number of different traffic classes is considered. If the granularity of the traffic mixture is high, say call bandwidths of some kbps and a transmission link with a capacity of some hundreds of Mbps, a solution using the two mentioned algorithms might not be practical, either. A first-shot approximation could also give a clear view of the importance of certain key parameters, which can be useful in network planning. Simple approximation are also explained in [COST242].

For networks with alternative routing a product form solution no longer exists. Due to the complexity involved, exact evaluation methods have not been found in literature.

While considering the case of trunk reservation, we are *leaving* the area of state spaces which can be solved by a product form solution. In this case, no product form solution exists, due to the fact that one-way transitions are present in the state space which destroy reversibility. Therefore, the expression obtained above is not correct, because it is not possible calculate the value of $p(x,y)$. In principle, at least for smaller state spaces, the state equation systems can be completely formulated and solved using e.g. an iterative algorithm. This possibility is however numerically intractable for more realistic parameter sets with larger state spaces. Approximate solutions are presented in [COST242].

3.6 SUMMARY

In this chapter Congestion Probability Routing algorithm has been presented. The principal characteristics of CPR algorithm is that Congestion Probability as the metric of the VP cost function and the Routing Control Parameter is defined as a protection mechanism. The Routing-CAC cycle and the set of allowed states of the proposed algorithm has been also explained. Finally, the difficulty to obtain exact evaluation methods is described. In the following chapter computer simulations to illustrate the behaviour of Congestion Probability Routing algorithms are presented.

4. CPR performance evaluation

The ability to compare several proposals for any network topology is fundamental to carry out a complete study of Congestion Probability Routing algorithms performance. Mathematical analysis is difficult when different Routing and CAC strategies are used. Analytical tools apply some approximations and assumptions on the models, so that the accuracy of the obtained performance is then reduced. Consequently, the proposed algorithms are implemented in a simulation environment. With simulations, we may illustrate the behaviour of the CPR algorithm proposed above.

The simulator developed can be considered as a tool to calculate (or, at least, to estimate) the stationary blocking probabilities in certain specific ATM network given traffic types, Connection Demand Class (CDC), Congestion Probability Routing (CPR) algorithms, Routing Control Parameter (RCP), network resources and the load on the network. The simulator has been written in ANSI C. This is designed for use in UNIX environments. Currently, the simulator runs in a SUN Sparc-20 workstation. The simulator can be configured for any topology and type of source. The Routing and CAC strategies are defined by the user and introduced into the simulator through a configuration file. The output results of the simulator are also configurable. Therefore, the desired network parameters are obtained in order to know the performance of the Congestion Probability Routing algorithms.

Let us now consider routing-call admission control in ATM networks where a call may be set up via a number of VPs and nodes. If the Congestion Probability of all possible combinations has been pre-calculated before starting the routing simulation (off-line evaluations), the connection set-up delay does not influence the results of the routing algorithms. In this chapter, the simulation trials planned and the results of these trials are reported. Results presented show different network performances by changing the network topology, the Routing Control Parameter and the load on the network.

4.1 TRAFFIC MODEL AND NETWORK TOPOLOGY

Throughout this dissertation we have considered heterogeneous traffic which needs different requirements (following table). There are **ST** traffic classes modelled by General Modulated Deterministic Process (GMDP) explained in [R1022]. This model describes the behaviour of a traffic source at cell and burst level. It consists of a finite number of states. In each state, cells are sent at a constant rate during a general distributed sojourn time. After the sojourn time has ended the process enters another state with a certain probability. In the GMDP model several traffic types are defined by varying the number of states, the bit rate of the state and its corresponding probability. The specification of the number of traffic types to be supported and their QoS requirements are beyond the scope of this paper.

Two different (albeit rather artificial) traffic classes were considered, one with a high bandwidth demand and the other with a low bandwidth demand. The constant parameters of the two classes are given in the table below.

Traffic Class	(rate; probability) state 0	(rate; probability) state 1	mean rate	burstiness	CLP Requirements	demand bandwidth
3	(0 Mbit/s; 0.8)	(1 Mbit/s; 0.2)	0.2 Mbit/s	5	1.0 E-5	0.3
4	(0 Mbit/s; 0.8)	(10 Mbit/s; 0.2)	2 Mbit/s	5	1.0 E-5	8

Table 9 : Traffic descriptor parameters of traffic class 3 and 4.

The statistical characteristics of connections (the interarrival time of connection requests and the expected duration of the connection, the mean holding time) are used for the generation of traffic. The VCC connection requests belonging to a CDC j are assumed to arrive according to a stationary Poisson process with rate λ_j . The connection holding time is assumed to have an independent and exponentially distributed function with mean $1/\mu_j$.

Each is CDC characterised by the traffic class, the required QoS and the origin-destination pair. Different system loads are obtained varying the number of CDC and their Inter-arrival Time (IT) (1/call arrival rate).

The network chosen for simulations (following figure) allows the study of the performance of each routing algorithm when different loads and RCP values are considered. The capacity of each VP has been set to 50 Mbits/s in order to decrease the simulation effort. In some trials, some VP's and nodes are ignored.

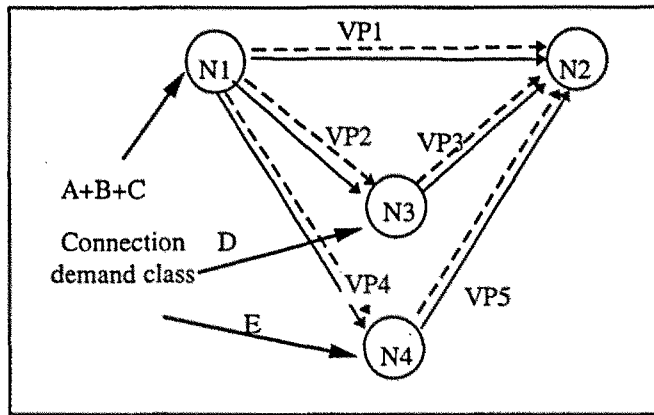


Fig. 17 : Virtual Path Network

Routing policies differ in how they choose from among the set of allowable alternative routes. We consider direct and alternative policies : in the *Direct Policy* calls are only allowed to be routed via a direct route, each call is allowed to use exactly the direct VP; and in the *Alternative Policies* the traffic overflow from the direct route, called the overflowed traffic, tries to use an alternative route. The number of possible alternative routes could be one or two. In the last case, a selection function is needed. We assume that when a call is denied access to the network, it does not retry and is considered lost.

Following table shows the direct route and the set of allowable alternative routes by each CDC considered.

CDC	Origin	Destination.	Traffic Class	Direct Route	set of allowable Alternative Routes
A _{tc}	N1	N2	tc	VP1	{ AR ₂₃ =(VP2+VP3) , AR ₄₅ =(VP4+VP5) }
B _{tc}	N1	N3	tc	VP2	(*)
C _{tc}	N1	N4	tc	VP4	(*)
D _{tc}	N3	N2	tc	VP3	(*)
E _{tc}	N4	N2	tc	VP5	(*)

Tabla 10 : Connection Demand Classes and Routing table.

Each CDC is labelled using a letter and a number, where the letter determines the origin-destination pair and the number the traffic class. For example, the origin-destination pair of CDC A₃ is N1-N2 and the traffic class is 3.

(*) To reduce the complexity the set of allowable alternative routes are not considered in these trials. In a real network, there should be alternative routes for these CDCs, and each VP of an alternative route is also the direct route of other CDCs which has another set of alternative routes, and so on.

4.2 SIMULATION RESULTS

In each test case, multiple simulation runs were performed varying the offered traffic load. Simulation allows us to obtain the number of requested, offered and rejected VCC for each VP and for each route. The following parameters are considered as a result of each simulation run:

- the Blocking Probability (BP) parameters.
- the probability of alternately routed calls (from the calls accepted) for each traffic class.

Different BP are calculated (from each CDC), for each route (direct route or alternative route) and for all possible routes. The Call Blocking Probability (CBP) for the CDC class j is evaluated by:

$$CBP_j = \frac{\text{Number of VCC}_j \text{ rejected}}{\text{Number of VCC}_j \text{ requested}}$$

The Network Call Blocking Probability (NCBP) is defined as the Blocking Probability from all CDCs for all possible routes, and is evaluated by:

$$NCBP = \frac{\sum_j \text{Number of VCC}_j \text{ rejected}}{\sum_j \text{Number of VCC}_j \text{ requested}}$$

The probability of alternately routed calls (ARP) for the CDC class j is evaluated by :

$$ARP_j = \frac{\text{Number of VCC}_j \text{ carried over alternative route}}{\text{Number of VCC}_j \text{ offered}}$$

In the figures which appear in the following subchapter, where the results of the simulation runs are given, these parameters are presented as a function of the offered traffic load. The traffic load for each traffic class we mean the product of the holding time and the call arrival rate. Note that the same load value for two CDCs could represent different load if the demanded bandwidth value by each traffic type is different.

4.2.1 Homogeneous traffic with no loaded alternative routes

The performance of homogeneous traffic by different types of traffic, loads, set of allowable alternative routes and values of the Routing Control Parameter is studied in these experiments. The performance is studied in terms of blocking probabilities.

The most simple case is presented in this experiment because there is only one CDC. The basic network topology is shown in the following figure :

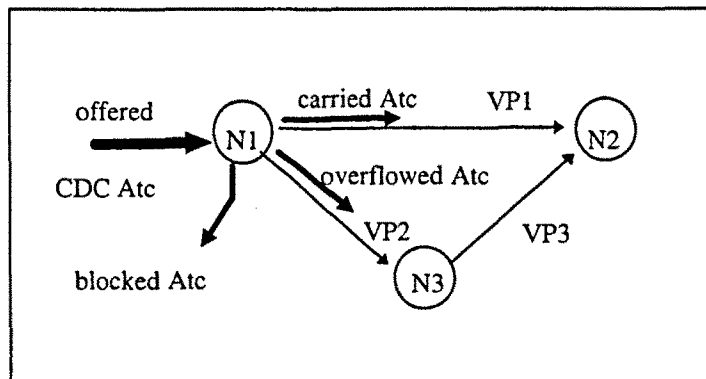


Fig. 18 : VPN and CDCs of experiments 1 and 2

Note that overflowed traffic in the DR1 is named alternative traffic when it is carried by the alternative route.

The direct route and the set of allowable alternative routes by the CDC considered are:

CDC	Origin	Destination	Traffic Class	Direct Route	set of allowable Alternative Routes
Atc	N1	N2	tc	DR1	{ AR23=(VP2+VP3) }

Tabla 11 : Connection Demand Classes and Routing table of experiments 1 and 2.

As the blocking probability only depend on the offered traffic and not on the inter arrival time and holding times individually, to vary the load of the network, the interarrival time is fixed and different values of the holding time are considered. In this case, the mean number of demand CDCs to the system is the same in all the simulations. Different system loads are obtained varying the holding time (*ht*). The CDC Atc have an interarrival time of 0.1 time units ($ia_{Atc}=0.1$) and the period of each simulation is equal to 1500 time units and the mean number of demand calls are approximately 15000. A simulation is run 5 times for each set of parameters.

To probe that the blocking probability only depends on the offered traffic and not on the inter arrival time and holding times individually, the same experiments are run with $ia_{tc}=0.2$. There are no differences with results obtained by $ia_{tc}=0.1$.

Experiment 1

The traffic of the CDC which origin-destination pair is N1-N2 is belongs to class 3 ; therefore the CDC is named A3. In this experiment the ht_{A3} values are $\{10, 20, \dots, 100\}$; therefore, the load offered by the CDC A3 are $load_{A3} = \{100, 200, \dots, 1000\}$ units of "load of traffic class 3". Remember that the unit load considered depends of the traffic class of the CDC.

CBP in AR23 and in DR1

The following figure plots the CBP varying the set of allowable routes, the RCP and the load of the CDC A4. It shows the CBP, in the Alternative Route (AR23) and in all possible routes (CDC A3), by two values of the RCP : $1.0E-0$ and $1.0E-6$. It also shows the CBP in the Direct Route (DR1). Note that the value of the RCP is chosen as 1 when the protection mechanism is not used, because the PC is always less that 1. In this table all results are obtained by simulations.

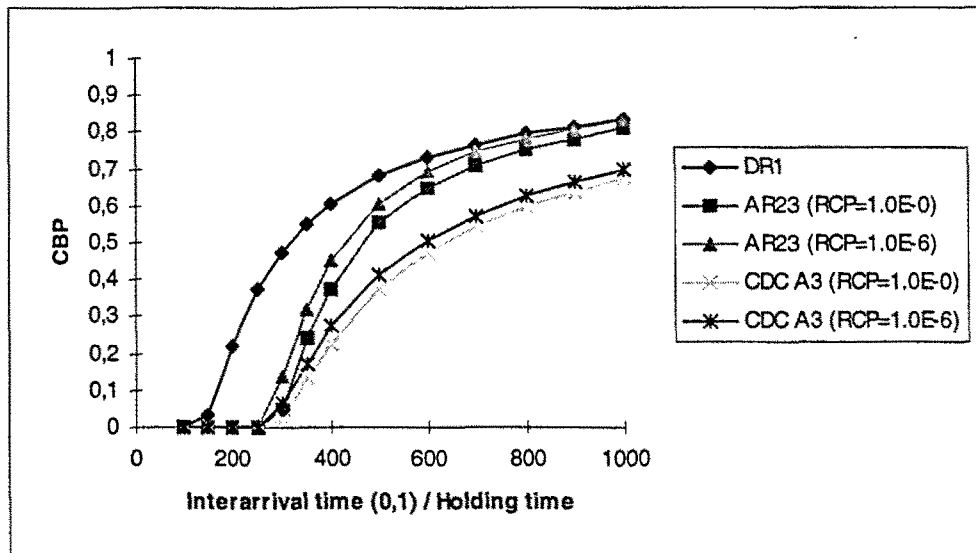


Fig. 19 : CBP in AR23 and in DR1 (experiment 1)

Remarks :

- The DR1 values, which correspond with the *Direct Policy*, are independent of the RCP considered because the protection mechanism is only used in alternative routes.
- The AR23 values corresponds with the CBP of the overflowed traffic on the direct route. This value is very close to 0 until a load of 250 because the traffic is carried by direct route. When the load increases, this value tends towards the DR1 values.
- Comparing AR23 with and without protection mechanism, the CBP increases when the protection mechanism is used ($RCP=1.0E-6$) because some Congestion Probability is reserved in the alternative route.

- d) As the reserved Congestion Probability is not used because there is no direct traffic in this route, the NCBP also increases when the protection mechanism is used.
- e) The CDC A3 values corresponds to the *Alternative Policies*. In this experiment the DR1 values are always higher than the CDC A3 values because two routes are dedicated exclusively to carrying the CDC A3. Remember that there is only one CDC.
- f) Comparing the *Alternative Policies* with the *Direct Policy* values we can observe that the distance between the two values is similar when the load is high.

Simulations versus analytical models

The following figure plots the CBP - in the direct route, in the alternative route and in all possible routes - obtained via simulations and the corresponding analytical model - Erlang-B formula and Wilkinson formula.

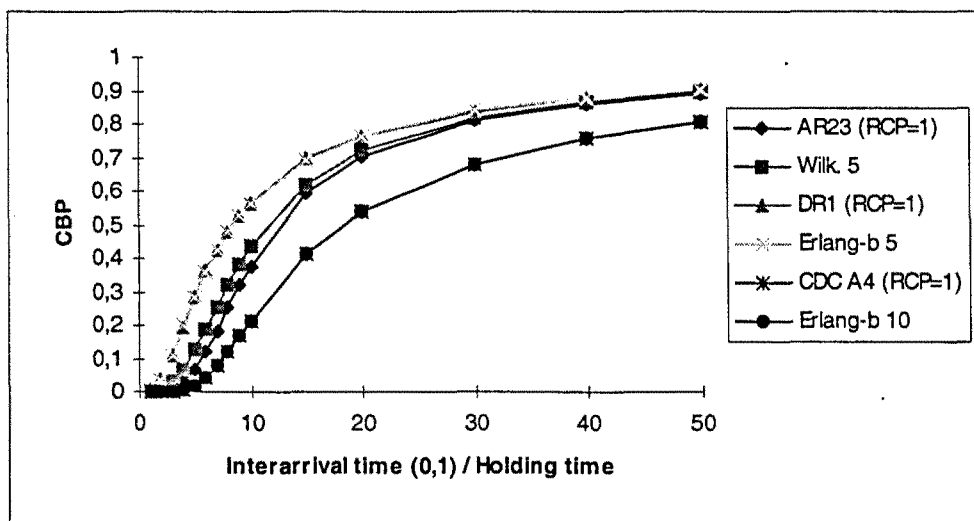


Fig. 20 : Simulations versus analytical models (experiment 1)

Remarks :

- a) The CBP values of the DR1 obtained via simulation are very close to the values obtained by the Erlang-B formula to 157. The number 157 correspond with the maximum number of connections that could be accepted in the VP to ensure that the QoS requirements are met.
- b) The CBP values of the AR23 obtained via simulation are very close to the values obtained by Wilkinson formula to 157.
- c) The CBP values of the CDC A3 obtained via simulation are very close to the values obtained by Erlang-B to 314.
- d) The values obtained by simulations are always less than that obtained by the analytical model.

Alternated / Offered

The following figure plots the relation between the alternated traffic carried over the alternative route R23 and the traffic offered by the CDC A3.

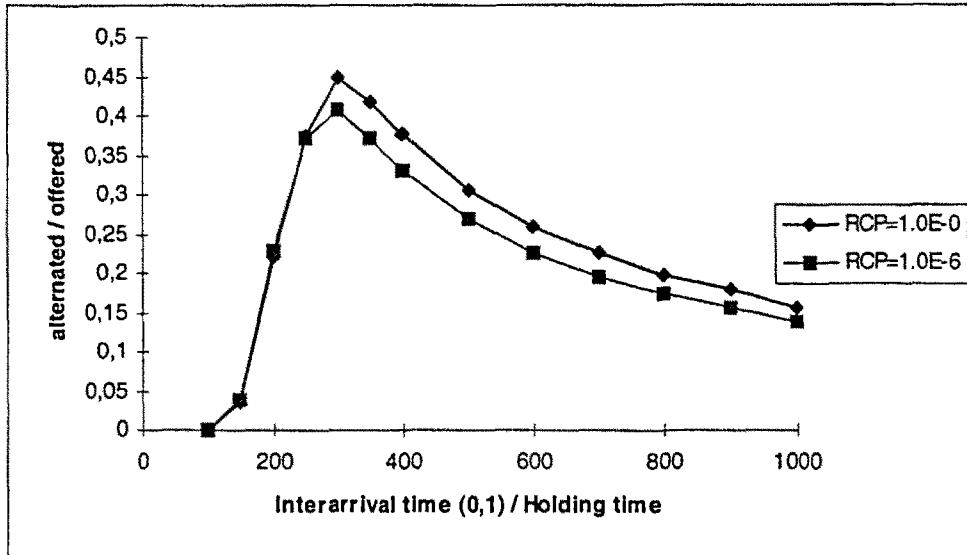


Fig. 21 : Alternated / Offered (experiment 1)

Remarks :

- While the load offered by the CDC is small (for example, less than 50), all the traffic is carried by the direct route and there is no overflowed traffic, and therefore either alternative traffic is allowed.
- When the load increases, all offered traffic cannot be carried by the direct route and the overflowed traffic is offered to the alternative route. While this route is lightly loaded all alternative traffic is accepted and the relation increases.
- This behaviour is present while the alternative route can carry all the alternative traffic. When this is not true, as the alternatively routed traffic is constant, if the offered load increases the relation decreases. In this case, the relation decreases when the protection mechanism is used ($RCP=1.0E-6$) because some Congestion Probability is reserved in the alternative route.

Experiment 2

In this experiment, the traffic of the CDC A belongs to class 4 and the ht_{A4} values are $\{0.1, 0.2, \dots, 1, 1.5, 2, 3, 4, 5\}$; therefore, the load offered by the CDC A4 are $load_{A4} = \{1, 2, \dots, 10, 15, 20, 30, 40, 50\}$ units of "load of traffic class 4". Remember that the unit load considered depends on the traffic class of the CDC.

CBP in AR23 and in DR1

The following figure plots the CBP varying the set of allowable routes, the RCP and the load of the CDC A4. It shows the CBP, in the Alternative Route (AR23) and in all possible routes (CDC A4), by two values of the RCP : $1.0E-0$ and $1.0E-6$. It also shows the CBP in the Direct Route (DR1). Note that the value of the RCP is chosen as 1 when the protection mechanism is not used, because the PC is always less than 1.

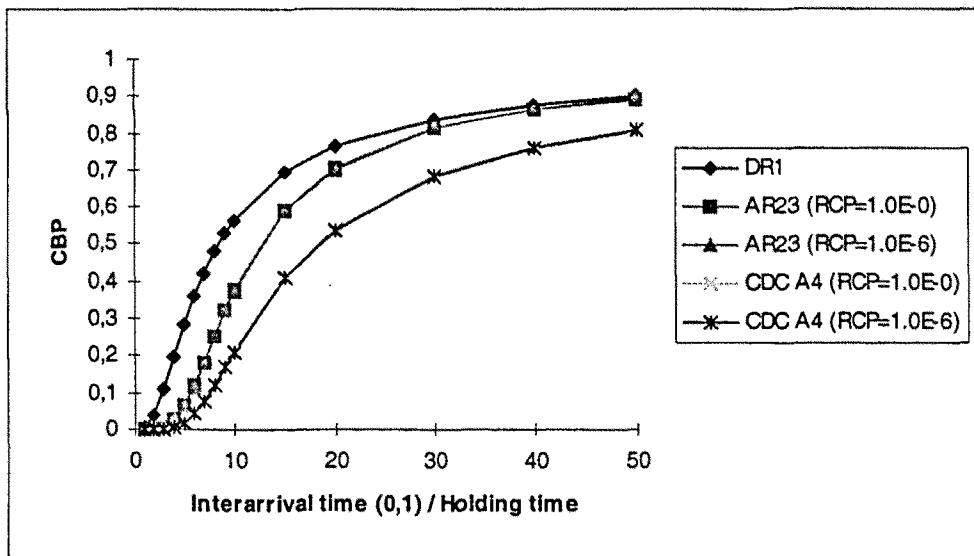


Fig. 22 : CBP in AR23 and in DR1 (experiment 2)

Remark :

- In this case, if the value of the RCP considered is $1.0E-6$, the Congestion Probability obtained is independent of protection mechanism.

Simulations versus analytical models

The following figure plots the CBP obtained via simulations and the corresponding analytical model. The CBP of the DR1 obtained via simulation are compared with the values obtained by the Erlang-B formula to 5, the CBP of the AR23 with Wilkinson formula to 5 and the NCBP with Erlang-B to 10.

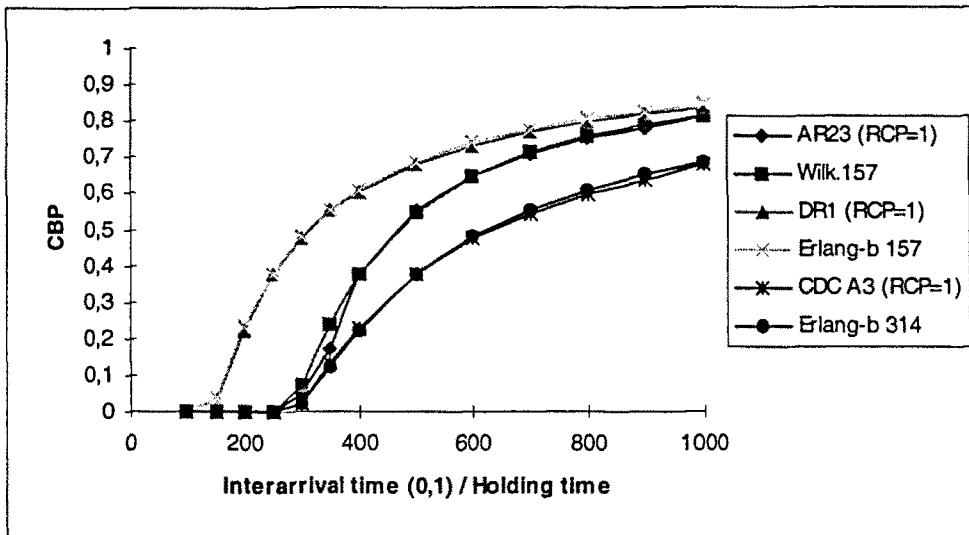


Fig. 23 : Simulations versus analytical models

Remark :

- a) In this case, when the system has a low load there is a little difference in the CBP of the traffic offered to the alternative route, (AR23 and Wilk. 5).

Alternated / Offered

The following figure plots the relation between the alternated traffic carried over the alternative route R23 and the traffic offered by the CDC A4.

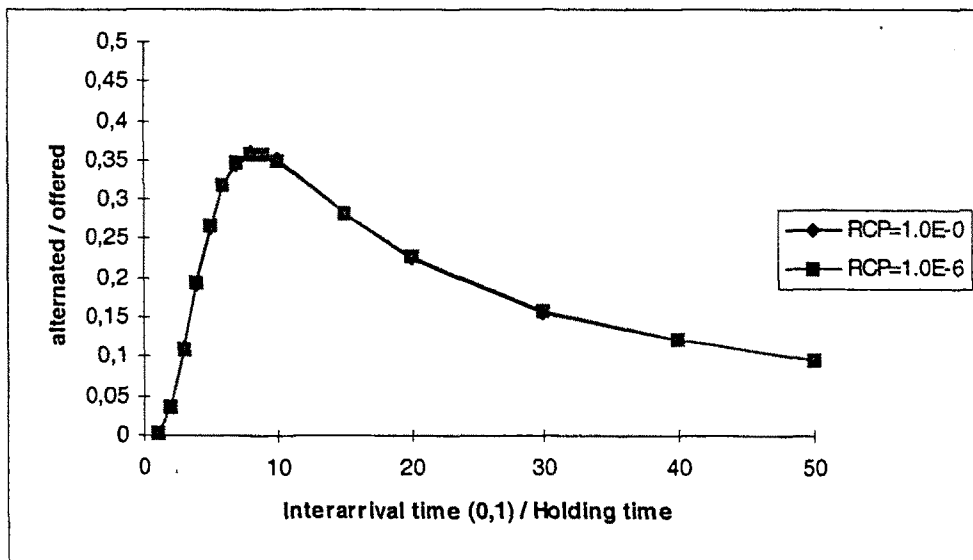


Fig. 24 : Alternated / Offered (experiment 2)

Remark :

- a) As the Congestion Probability obtained is independent of protection mechanism, the same overflowed traffic is carried in both cases.

4.2.2 Heterogeneous traffic with no loaded alternative routes

The performance of heterogeneous traffic with different types of traffic, loads, set of allowable alternative routes and values of the Routing Control Parameter is studied.

Therefore, three routing algorithms are considered : the *Direct Policy* (the set of allowable alternative routes is not considered), the *Alternative Policy without protection mechanism* (the RCP is equal to 1.0E-0) and the *Alternative Policy with protection mechanism* (in this case, the value considered by the RCP is 1.0E-6).

Moreover, the relationship between the CBP of CDCs with different traffic class are also studied.

In this case, the basic network topology is shown in the following figure :

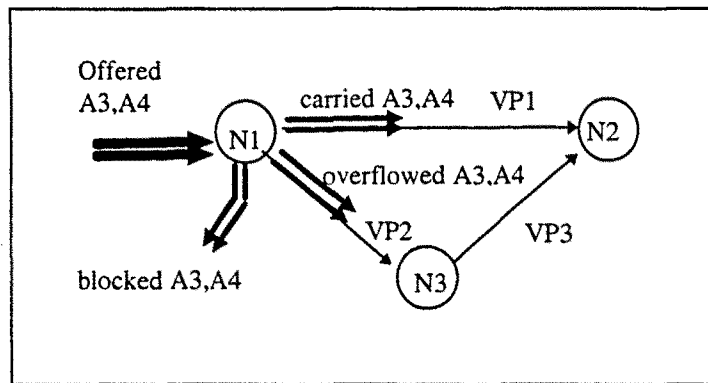


Fig. 25 : VPN and CDCs of experiment 3

The direct route and the set of allowable alternative routes by the CDC considered are:

CDC	Origin	Destination	Traffic Class	Direct Route	set of allowable Alternative Routes
A3	N1	N2	3	VP1	{ AR23=(VP2+VP3) }
A4	N1	N2	4	VP1	{ AR23=(VP2+VP3) }

Tabla 12 : Connection Demand Classes and Routing table of experiment 3.

The only difference between CDC A3 and CDC A4 is the traffic class of each CDC.

In this trial, the period of each simulation is equal to 7500 time units and the mean number of demand calls are approximately 75000. A simulation is run 5 times for each set of parameters.

Experiment 3

Two CDCs of type A are considered: A3 and A4, where the number means the traffic class of the CDC. In this experiment the ht_{A3} values are $\{5, 10, \dots, 35, 40, 50, 60, 70\}$ and the ht_{A4} are $\{0.1, 0.2, \dots, 0.8, 1.4, 2\}$; and therefore, the load offered by the CDC A3 are $load_{A3} = \{50, 100, \dots, 350, 400, 500, 600, 700\}$ units of "load of traffic class 3" and the load offered by the CDC A4 are $load_{A4} = \{1, 2, \dots, 8, 14, 20\}$ units of "load of traffic class 4". Remember that the unit load considered depends of the traffic class of the CDC.

Different load scenarios are studied which has assigned a name corresponding with the load of each CDC. In this case the name is $load_{A3_load_{A4}}$, for example, in this experiment, the scenario 50_xx corresponds with a $load_{A3}$ equal a 50 units of "load of traffic class 3". The xx of $load_{A4}$ indicates that this value is varied.

By each scenario, different figures plot the CBP, varying the set of allowable routes (the routing policy) and the value of the RCP (1.0E-0 and 1.0E-6). For simplicity the legend on the following figures is modified, the label (0) means RCP=1.0E-0 and (-6) means RCP=1.0E-6.

To reduce the number of figures the values corresponding to CDC A3 and to CDC A4 are plotted in the same figure.

CBP in AR23 and in DR1

The following figures plot the CBP in the Alternative Route (AR23) and in the Direct Route (DR1), as function of the offered load. The figures corresponding with the scenarios 100_xx, 200_xx and 300_xx are drawn.

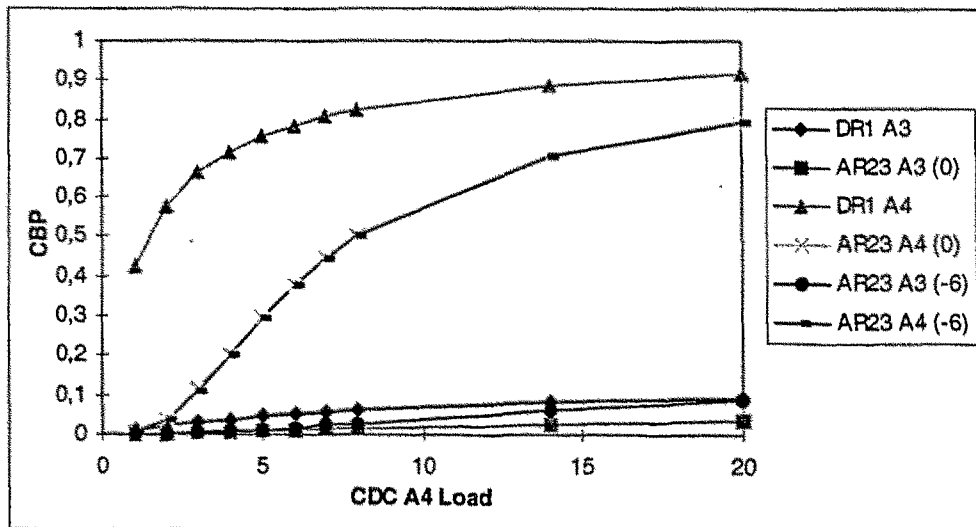


Fig. 26 : CBP in AR23 and in DR1 (experiment 3 - scenario 100_xx)

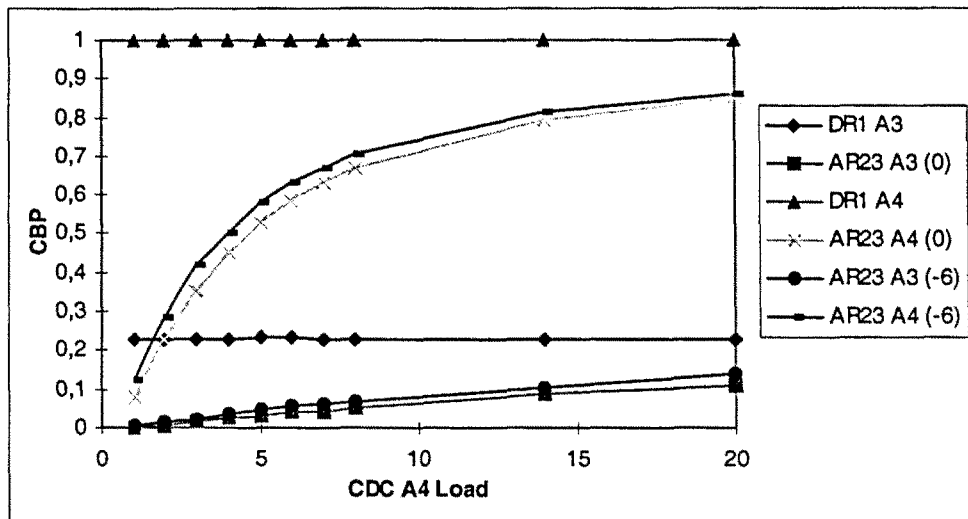


Fig. 27 : CBP in AR23 and in DR1 (experiment 3 - scenario 200_xx)

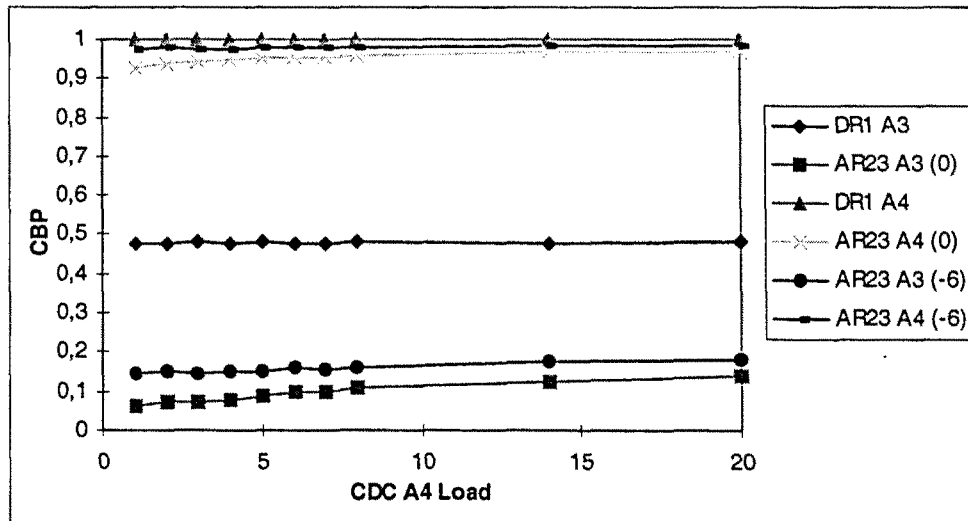


Fig. 28 : CBP in AR23 and in DR1 (experiment 3 - scenario 300_xx)

Remarks :

- In all the figures, it is obvious that the CBP for calls with higher bandwidth requirements (DR1 A4) are always higher than for calls which require less bandwidth (DR1 A3).
- Comparing the values obtained by the *Direct Policy* (DR1 A3 and DR1 A4) in the different scenarios, these CBPs increases if the load of the system increases.
- Comparing the values obtained by the *Alternative Policies* the protection mechanism has a little influence when the system has a low load.
- When the load of the system increases, all AR23 values, CDC A3 and CDCA4, increases if the protection mechanism is used (RCP=1.0E-6). This influence is greater if the load of each CDC increases.

NCBP and CBP of CDCs

When there is more than one CDCs, the Network Call Blocking Probability (NCBP) is studied. The following figures plot the CBP of the CDC A3, the CBP of the CDC A4 and the NCBP, with the same scenarios presented previously : 100_xx, 200_xx and 300_xx.

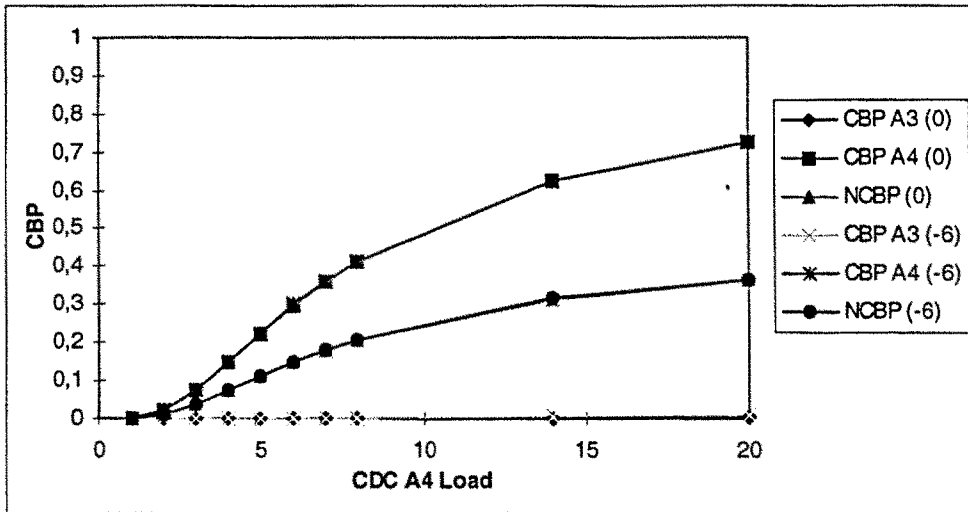


Fig. 29 : NCBP and CBP of CDCs (experiment 3 - scenario 100_xx)

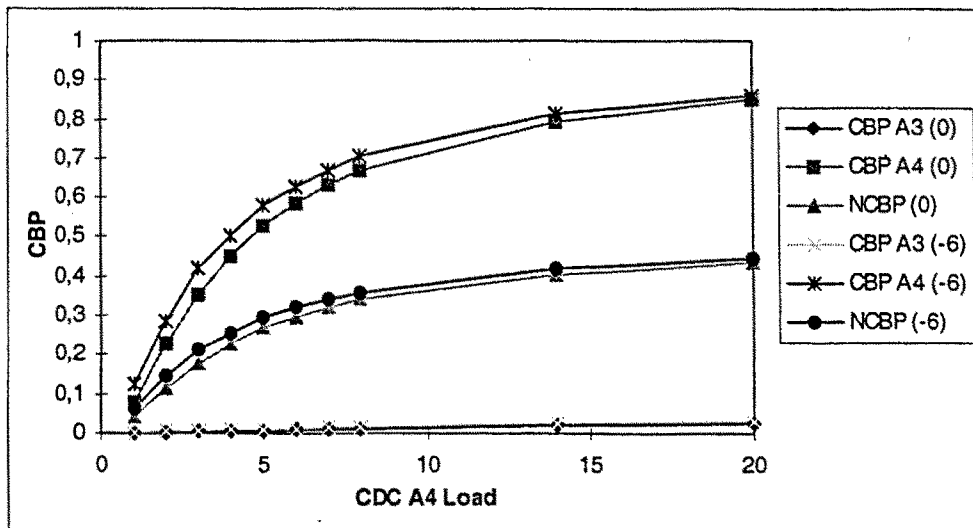


Fig. 30 : NCBP and CBP of CDCs (experiment 3 - scenario 200_xx)

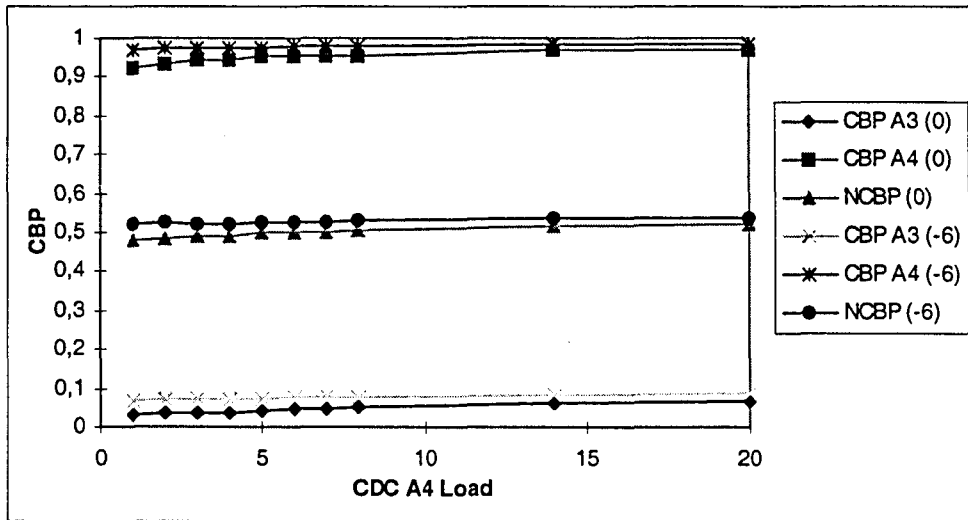


Fig. 31 : NCBP and CBP of CDCs (experiment 3 - scenario 300_xx)

Remark :

- a) As the CBP of CDC A3 and CDC A4 increases when the load of the system increases, and this CDCs are the only CDCs considered, the NCBP also increases.

Alternated / Offered

The following figure plots the relation between the alternated traffic carried over the alternative route R23 and the traffic offered by the CDC A3 and CDC A4.

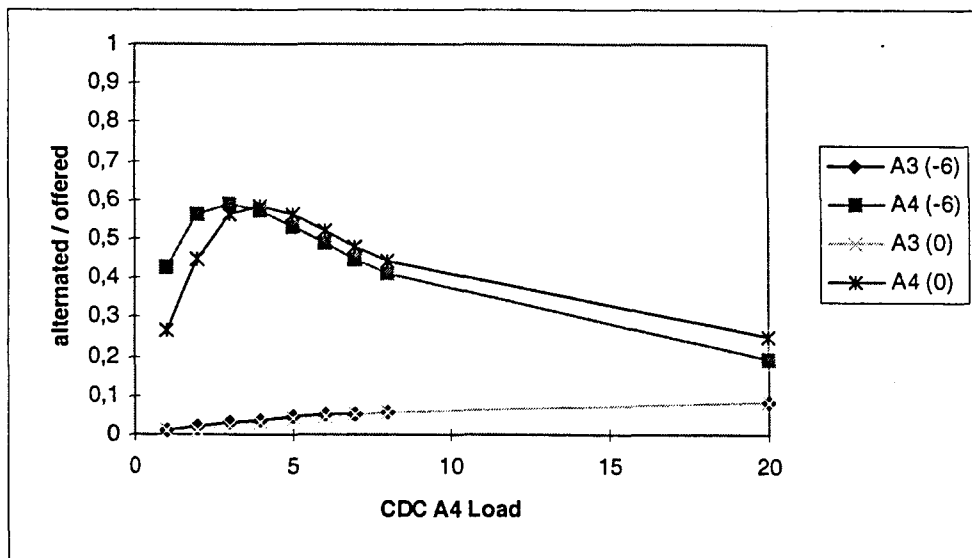


Fig. 32 : Alternated / Offered (experiment 3 - scenario xx_100)

Remark :

- a) The values of CDC A3 are less than the CDC A4 because the overflowed traffic of CDC A3 are less than the overflowed traffic of CDC A4.

4.2.3 Influence of heterogeneous alternative traffic in a homogeneously loaded route.

The influence of heterogeneous traffic in a homogeneously loaded route by different types of traffic, loads and values of the Routing Control Parameter is studied in this experiment.

In this case, the basic network topology is shown in the following figure:

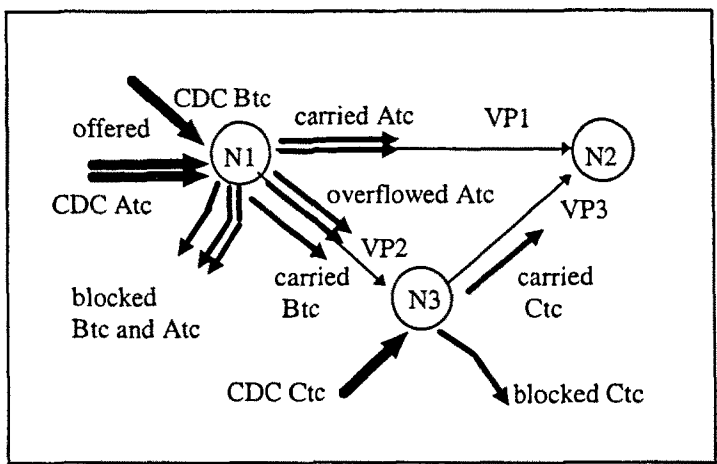


Fig. 33 : VPN and CDCs of experiment 4.

The direct route and the set of allowable alternative routes by the CDC considered are:

CDC	Origin	Destination	Traffic Class	Direct Route	set of allowable Alternative Routes
Atc	N1	N2	3 and 4	VP1	{ AR23=(VP2+VP3) }
Btc	N1	N3	3	VP2	--
Ctc	N3	N2	3	VP3	--

Tabla 13 : Connection Demand Classes and Routing table of experiment 4.

Remember that the letter of the CDC represents the origin-destination pair and the number the traffic class.

In this trial, the period of each simulation is equal to 7500 time units and the mean number of demand calls are approximately 75000. A simulation is run 5 times for each set of parameters.

Different load scenarios are studied which has assigned a name, $load_{A3_load_{A4_load_B}$, corresponding with the load of each CDC. For example, in experiment 4, the scenario 100_xx_100 corresponds with a $load_{A3}$ equal a 100 and a $load_{B3}$ equal a 100 units of “load of traffic class 3”. The $load_{A4}$ is represented by xx when it varies in the scenario. Note that $load_C$ is omitted because coincides with $load_B$. By each scenario, different figures plot the CBP in the Alternative Route (AR23), varying the set of allowable routes, the RCP and the load of the system.

Experiment 4

In this experiment, {A3, A4, B3, B4, C3, C4} is the set of CDCs considered. The load of the two CDCs B3 and C is the same in all the scenarios. The ht_{B3} and ht_{C3} values are {5, 10, 20, 30, 40} and therefore, the load offered are $load_{B3} = load_{C3} = \{50, 100, 200, 300, 400\}$ units of "load of traffic class 3". The variation on the CBP of the CDCs of type B and C are studied when alternated traffic is also offered in the Direct Route of CDC B3 and CDC C3.

This alternated traffic is generated by two CDCs of type A (CDC A3 and CDC A4). In this experiment the ht_{A3} values are {10, 20} and the ht_{A4} are {0.1, 0.2, ..., 0.8, 1.4, 2}; and therefore, the load offered by the CDC A3 are $load_{A3} = \{100, 200\}$ units of "load of traffic class 3" and the load offered by the CDC A4 are $load_{A4} = \{1, 2, ..., 8, 14, 20\}$ units of "load of traffic class 4". Remember that the unit load considered depends of the traffic class of the CDC.

The following figures show the results of the scenario 100_xx_100.

CBP of alternative traffic in VP2

The following figure plots the CBP of the CDCs A3 and A4 in the VP2, by two values of the RCP : 1.0E-0 and 1.0E-6.

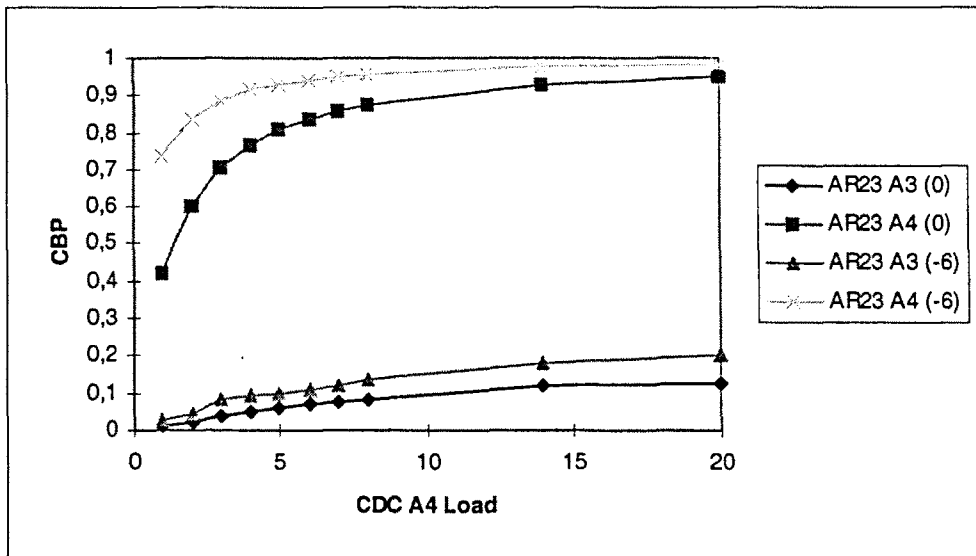


Fig. 34 : CBP of alternated traffic in the VP2 (experiment 4 - scenario 100_xx_100)

Remarks :

- The CBP for connection with higher bandwidth (CDC A4) is always greater than for connections which require less bandwidth (CDC A3).
- In both cases, the CBP increases when the RCP (1.0E-6) is used.

NCBP and CBP of CDCs

The following set of figures plot the CBP of CDC A3 and CDC A4 varying the set of allowable routes and the RCP.

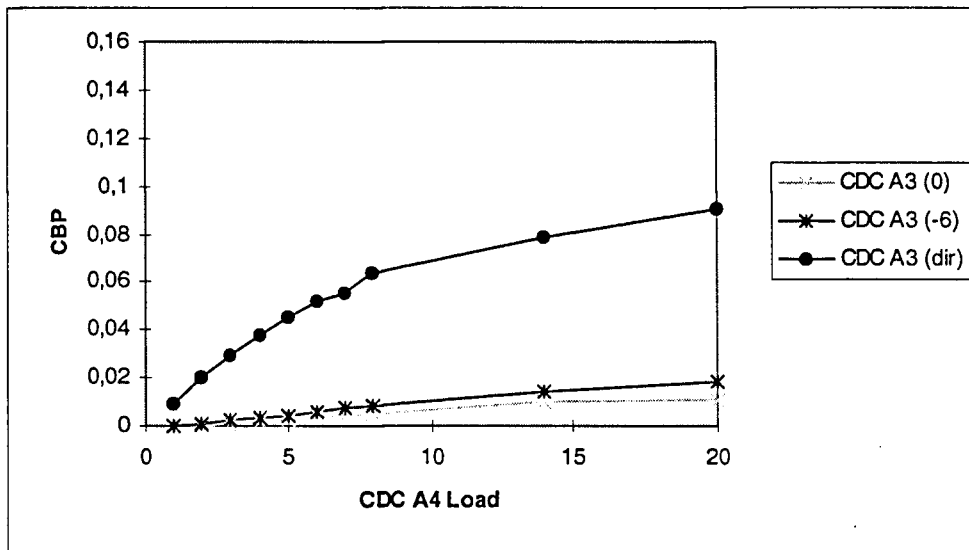


Fig. 35 : CBP of CDC A3 (experiment 4 - scenario 100_xx_100)

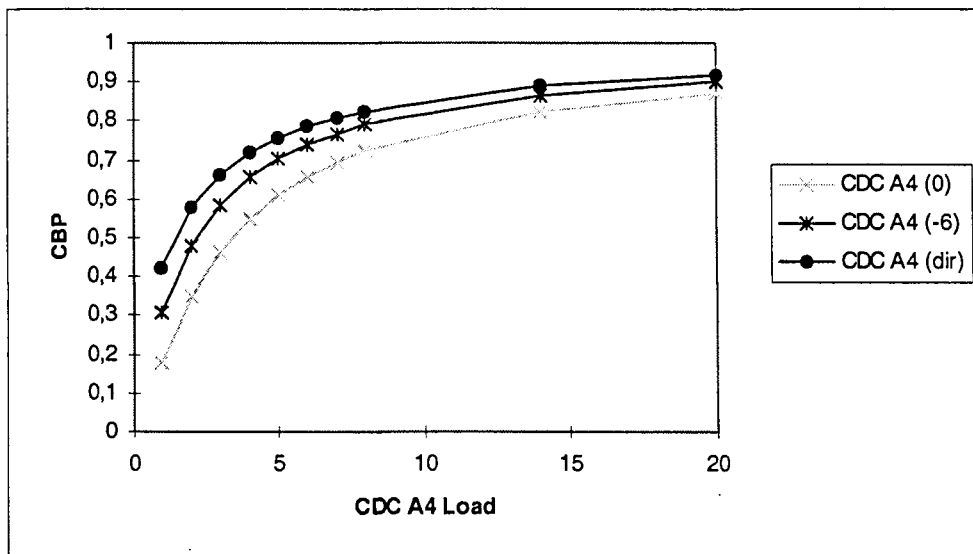


Fig. 36 : CBP of CDC A4 (experiment 4 - scenario 100_xx_100)

Remarks :

- a) In this scenario, the CBP obtained by the *Direct Policy* is always greater than the values obtained by the *Alternative Policies*.
- b) The CBP of CDC A3 and CDC A4 decreases if the RCP is considered.

The following figure plots the CBP of CDC B3 varying the set of allowable routes and the RCP.

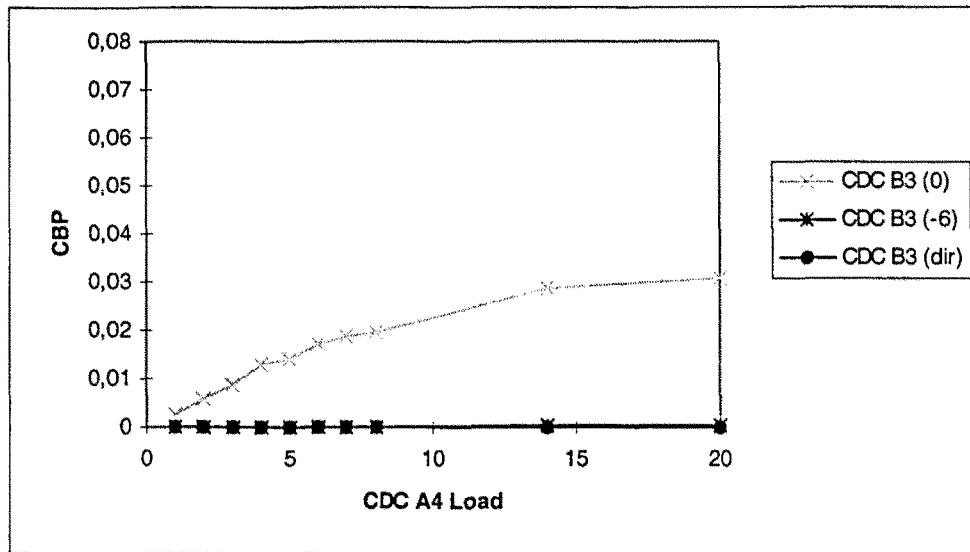


Fig. 37 : CBP of CDC B3 (experiment 4 - scenario 100_xx_100)

Remarks :

- a) Comparing the results obtained by the *Alternative Policies (with and without protection mechanism)*, when the RCP is considered (RCP=1.0E-6) the CBP of CDC B3 decreases.
- b) When the RCP is considered, the CDC of B3 are equal to the values obtained by the *Direct Policy*.
- c) When the RCP is considered, the CDC of B3 is insensitive to variations in the load offered by other CDCs.

The following figure plots the NCBP varying the set of allowable routes and the RCP.

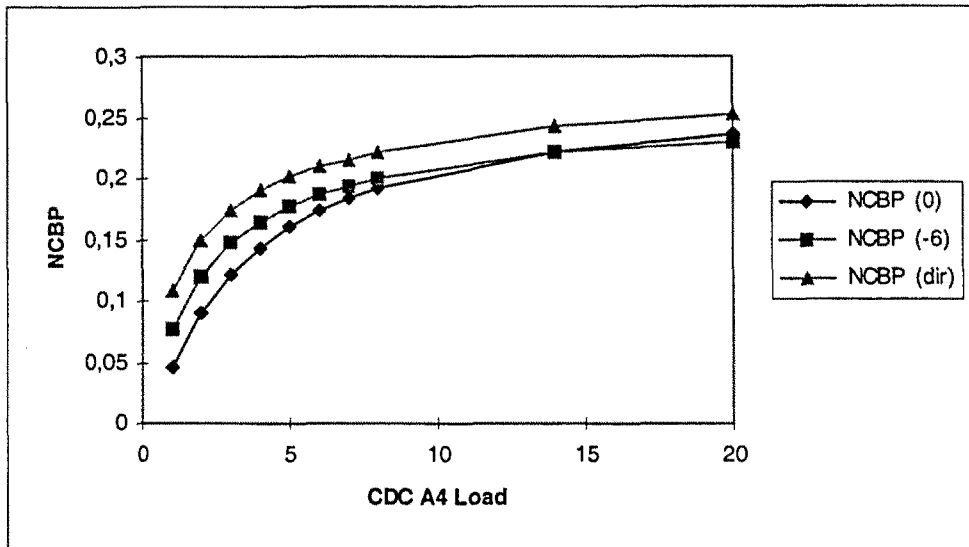


Fig. 38 : NCBP (experiment 4 - scenario 100_xx_100)

Remarks :

- a) In this case, the NCBP obtained by the *Direct Policy* (dir) is always greater than the values obtained by the *Alternative Policies* with and without protection mechanism, label (0) and (-6) respectively.
- b) Comparing the NCBP of both *Alternative Policies*, when the system is low loaded the NCBP of the no-protection case is greater than the NCBP of the protection case, because the reserved Congestion Probability is not used by direct traffic. When the system is more loaded, the NCBP of protection case is lower.

4.2.4 Route cost function and alternative route selection scheme

The performance of different route cost and alternative route selection functions are compared. To study the selection alternative route function, almost two alternative routes could be considered. The network topology is shown in the following figure :

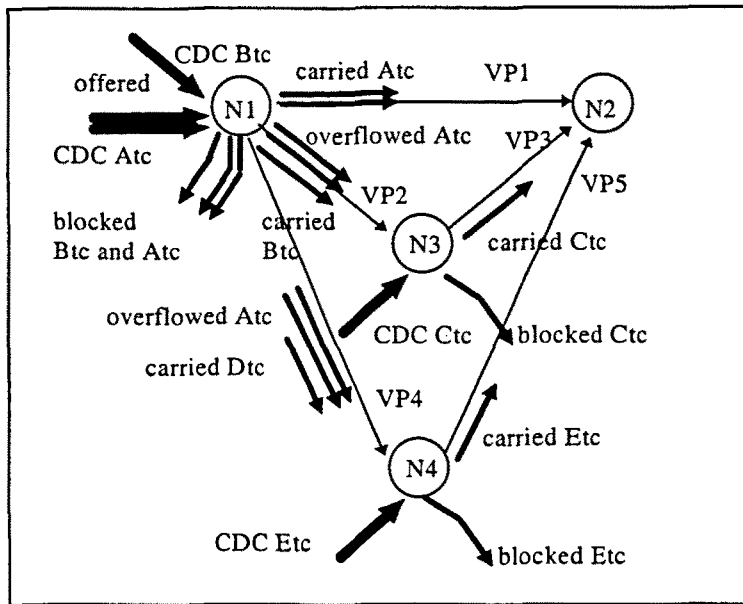


Fig. 39 : VPN and CDCs of experiment 5.

The direct route and the set of allowable alternative routes by the CDC considered are:

CDC	Origin	Destination	Traffic Class	Direct Route	set of allowable Alternative Routes
Atc	N1	N2	3 and 4	VP1	{ AR23=(VP2+VP3) and AR45=(VP4+VP5) }
Btc	N1	N3	3	VP2	--
Ctc	N3	N2	3	VP3	--
Dtc	N4	N2	3	VP4	--
Etc	N4	N2	3	VP5	--

Tabla 14 : Connection Demand Classes and Routing table of experiment 5.

Experiment 5

In this experiment, the holding time of all CDCs is 10 and the load of each CDC is shown in the following table :

Connection Demmand Class	Load
A3	200
A4	6.25
B3, C3, D3, E3	8, 10, 13.3, 20, 40

Tabla 15 : CDC load (experiment 5).

Note that in this experiment the load of CDCs A3 and A4 is fixed and the load of CDCs B3, C3, D3 and E3 varies.

Numerical results

The following table shows the NCBP of the different routing algorithms considered :

	80	100	133	200	400
directe	0,099	0,086	0,075	0,234	0,567
min_add (0)	0,018	0,023	0,065	0,273	0,567
min_add (-6)	0,015	0,022	0,069	0,233	0,567
db_max (0)	0,018	0,025	0,065	0,270	0,568
db_min (0)	0,022	0,026	0,070	0,274	0,567
db_add (0)	0,017	0,024	0,068	0,274	0,567
fifa (0)	0,034	0,031	0,074	0,274	0,569
max_max (0)	0,042	0,059	0,076	0,272	0,567
max_min (0)	0,043	0,047	0,076	0,275	0,565
max_add (0)	0,043	0,054	0,074	0,272	0,566
min_max (0)	0,018	0,025	0,068	0,273	0,566
min_min (0)	0,023	0,026	0,068	0,271	0,567
rall (0)	0,029	0,042	0,073	0,276	0,568
ravai (0)	0,031	0,041	0,073	0,275	0,569
db_max (-6)	0,015	0,023	0,068	0,234	0,565
db_min (-6)	0,016	0,024	0,069	0,234	0,566
db_add (-6)	0,016	0,023	0,069	0,234	0,567
fifa (-6)	0,016	0,023	0,069	0,236	0,568
max_max (-6)	0,015	0,023	0,070	0,234	0,567
max_min (-6)	0,015	0,024	0,071	0,233	0,566
max_add (-6)	0,015	0,022	0,067	0,234	0,567
min_max (-6)	0,015	0,022	0,068	0,235	0,568
min_min (-6)	0,017	0,023	0,069	0,234	0,565
rall (-6)	0,019	0,022	0,069	0,234	0,567
ravai (-6)	0,017	0,023	0,069	0,234	0,567

Tabla 16 : Numerical results (experiment 5)

Remarks :

- a) In this experiment, the performance of the different algorithms proposed are similar.
- b) When alternative routing without protection mechanism is considered, there are very small variations depending on the composition rule of the alternative route cost and the selection alternative route scheme.
- c) Comparing the values varying the composition rule of the alternative route cost, these variations are more appreciable.
- d) Comparing the values varying the selection alternative route scheme these variations are lower.
- e) If the load increases, the difference decreases.

f) When the protection mechanism ($RCP=1.0E-6$) is considered, these differences between the different algorithms are inappreciable.

NCBP of CDCs

The following figure plots the NCBP varying the set of allowable routes. The *Direct Policy* and the *alternative policy without protection mechanism* ($RCP=1.0E-0$) are considered.

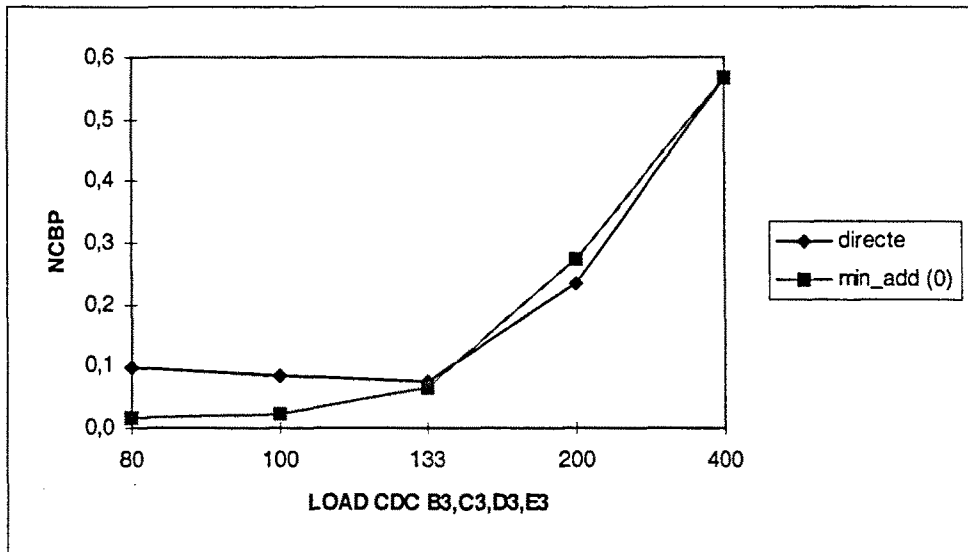


Fig. 40 : NCBP of CDCs (experiment 5).

Remarks :

- When the load offered by CDCs B, C, D and E is high (400), the NCBP obtained by different routing algorithm are similar because the whole network is heavily loaded so the connection cannot be accepted on alternative routes.
- When the load decreases (200) and the *Alternative Policy* is used the NCBP increases. The CBP of overflowed traffic (CDCs A) increases because the VPs are loaded with direct traffic offered by CDCs (B, C, D and E). This occurs because traffic of CDCs A rejected on direct route (VP1) is accepted by alternative routes.
- When the load decreases to (100, 80) the VPs of the alternative routes are lightly loaded, so they can perfectly accept the overflowed traffic and the NCBP decreases.

The following figure plots the NCBP varying the set of allowable routes. The *Direct Policy* and the *alternative policy with protection mechanism* ($RCP=1.0E-6$) are considered.

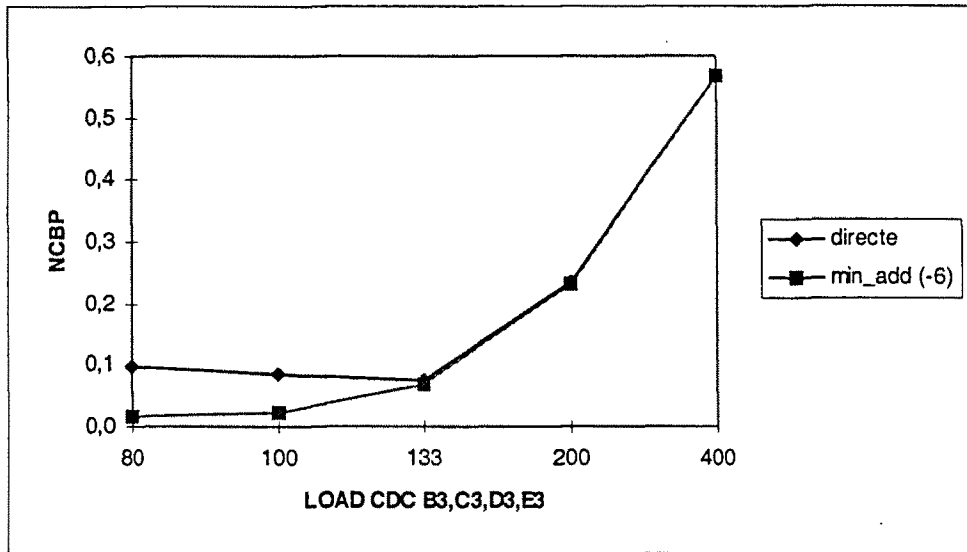


Fig. 41 : NCBP and CBP of CDCs (experiment 5).

Remarks :

- When the load offered by CDCs B, C, D and E is high (400), the whole network is heavily loaded so the connection cannot be accepted on alternative routes, therefore the protection mechanism would be useless.
- When the load offered decreases, the NCBP of the *Alternative Policy* decreases and it is very similar to the value obtained by the *Direct Policy*.
- When the load is less than 133, the NCBP of the *alternative policy with protection mechanism* ($RCP=1.0E-6$) is greater than the value obtained when RCP is ignored, but it is always smaller than the NCBP of the *Direct Policy*.

4.3 SUMMARY

In this chapter, computer simulations are run to illustrate the behaviour of the CPR algorithms. First experiments (1, 2 and 3) show the influence of the routing policy and of the RCP in simple topologies which are chosen to compare the obtained results with analytical methods. These experiments also prove the correct behaviour of the simulator. The results of experiments 3, 4 and 5 also show that better performance may be achieved by using *alternative policies* when the traffic load is light or medium. However, with heavy traffic loads, the *direct policy* performs better. The utilization of RCP varies the performance of the CDC traffic depending on the route selected. The CBP of traffic carried by an alternative

route increases when the RCP is used, but the traffic carried by the direct route is insensitive to the use of alternative policies (fig 37). Moreover, the RCP prevents the network from excessive blocking when the *alternative policies* are considered (fig 40). Table 16 shows that the influence of the protection mechanism in the network performance is more than the composition rule of the alternative route cost and the selection alternative route scheme.

5. Multipoint Routing

New applications – such as audio and video conferencing, replicated database updating, distributed resource discovery and shared workspaces - involve data delivery from multiple sources to multiple destinations, all members of the same “communication group”. The term multipoint are used in this dissertation to refer in general to all forms of communications with multiple participants, regardless of semantics. The term “multicast” has been used almost synonymously, even though it is often used to denote point-to-multipoint communication. The term “multipoint” is preferred because of its more general connotations. For example, “multicast” will be used to characterize the routing tree, whereas multipoint communication will be used to describe any type of communication within a group. Multicasting is the ability of an application to simultaneously and efficiently transmit a single data packet to a set of receivers that are members of a “communication group”.

The problem of the multipoint routing protocols is to construct a minimum cost graph (tree or ring⁶ topology) that spans the source node to each destination node. To discuss the establishment of point-to-multipoint and multipoint-to-multipoint virtual channel connection (VCC) in a fully connected VP-based ATM networks is the purpose of this section. Also, different aspects of multipoint connection routing are studied.

5.1 MEMBERSHIP CHANGES : STATIC AND DYNAMIC

One of the important distinctions between the point to point and multipoint connections is the possible connection dynamism. It is quite likely that in some applications the group membership can vary during the connection’s lifetime. This variability adds additional complexity to the already difficult problem of CAC and routing of multipoint connections.

Multipoint routing protocols are classified into two categories depending on the membership changes [WAX88], static and dynamic. In the **static version**, the group of destination nodes is fixed during the connection set-up phase and the identities of all destination nodes are available to the multipoint routing protocol at once. Once a static

group has been set up, a membership remains unmodified until it is discarded. Paths from the source to all destinations are computed at the same time. Video-conference with a fixed number of participants falls under the static version. In the **dynamic version**, the group of destinations nodes can change during the connection and the identities of the destination nodes are revealed to the routing protocol one by one. Video-conferencing applications with large groups usually fall under this category. On the routing point of view, note that the dynamic problem can be reduced to the static problem if the multicast tree is recomputed each time a membership change. But, such mechanisms are computationally expensive, especially when the membership changes frequently.

5.2 ROUTING COST FUNCTIONS

5.2.1 Shortest Path algorithm and Minimum Steiner algorithm

The objective of a multipoint routing protocol is to find a path from the source to each destination minimising a routing cost function. Two cost terms could be defined to determine the graph: *the destination cost*, a measure of the cost of each path to connect the source with each destination, which is the sum of all the edges of the path, and *the network cost*, a measure of the utilization of the network resources, which is simply the sum of the costs of all the edges in the tree [BHA83].

From this point of view, a multipoint routing can be classified into:

- **Shortest Path algorithms**, which attempt to *minimise the cost of each path* (the destination cost) from the source node, S, to each destination node D_i

$$\min(\text{cost}(S, D_i) \forall i$$

- **Minimum Steiner algorithms** [HAK71], which attempt to *minimise the total cost of the multicast tree* (the network cost) from the source node, S, to the set of destination nodes {D}, and were shown to be NP-complete [KAR72]

$$\min(\text{cost of multicast tree } T)$$

where the cost of the multicast tree is the addition of all the edges of the tree

⁶ Ring or circuit: A path in which the initial node coincides with the final node.

The equivalent graph of a theoretic solution to this problem would be to find a minimal Steiner tree for the graph given a set of destinations. The associated problem, the Steiner problem in networks (SPN), was originally formulated by Hakimi [HAK71] and may be stated as follows.

Given:

- a weighted, undirected graph $G = (V, E, c)$, $c: E \rightarrow \mathbb{R}$, where V is the set of vertices, E is the set of edges and c is the function cost;
- a source vertex $S \in V$ and a set of destination vertices $D \subseteq V$.

To find :

- a tree $T=(S \cup D, E_T)$ of minimum cost such that there is a path between the source vertex S and each destination vertices in D . E_T is the set of edges of the tree.

A sub-tree of G including all the nodes in D which is of minimum total weight is called a minimal Steiner tree for G and D . The vertices in T which are not in D are known as Steiner vertices or Steiner points. The problem in general is NP-complete even if all the edges have the same weight [GAR72]. For the case where $|D|=1$, the problem reduces to that of finding the shortest path between two vertices, while the case of $|D|+|S|=|V|$ requires finding a minimum spanning tree of G . Both the above reductions, the algorithms of Dijkstra [DIJ59] and Prim [PRI57], respectively.

The Steiner algorithm is a monolithic algorithm. It has to be run each time there is a change in the group membership or in the network topology. The inefficiency of a Steiner tree increases dramatically each time the group changes or the network changes [DOA93].

Different optimisation goals can be used in the multicast tree problem to determine what constitutes a good tree. One such goal is providing a minimum cost by each source. Another optimisation is making use of the network resources as efficiently as possible; two interesting variants of this objective are: minimising the total cost of the tree and distributing bandwidth utilisation in the tree in order to minimise congestion along links.

5.2.2 Constrained Steiner tree algorithms

In some cases, the network resource utilisation can be maximised under the constraint that an end-to-end Quality of Service (QoS) must be satisfied from the source to each destination node (multipoint group). These are called constrained Steiner tree algorithms to distinguish them from other algorithms which have not this constraint. These are presented

when it is necessary and sufficient for the network to satisfy a given limit, i.e. it is not necessary to minimise the cost of each path.

- **Constrained Steiner tree algorithms**, which attempt to construct a minimum cost multicast tree without violating the constraint implied by the upper limit.

5.2.3 Example

The following figure shows the Shortest Path, the Minimum Steiner and the Constrained Steiner solution in a fully VP based network. N1 is the origin node and N2, N3, N4 and N5 are the destination nodes. Multicast capabilities are assumed in all nodes. The VP_{ij} from N_i to N_j and the VP_{ji} from N_j to N_i are drawn as a single line with two arrows which has a label with two numbers. The first number corresponds to the cost VP_{ij} (i<j) and the second to the cost from N_j to N_i (j>i). For example, the cost of the VP₃₄ is 10 and the cost of VP₄₃ is 1. The label x corresponds with number sufficiently high to ignore VPs with this cost.

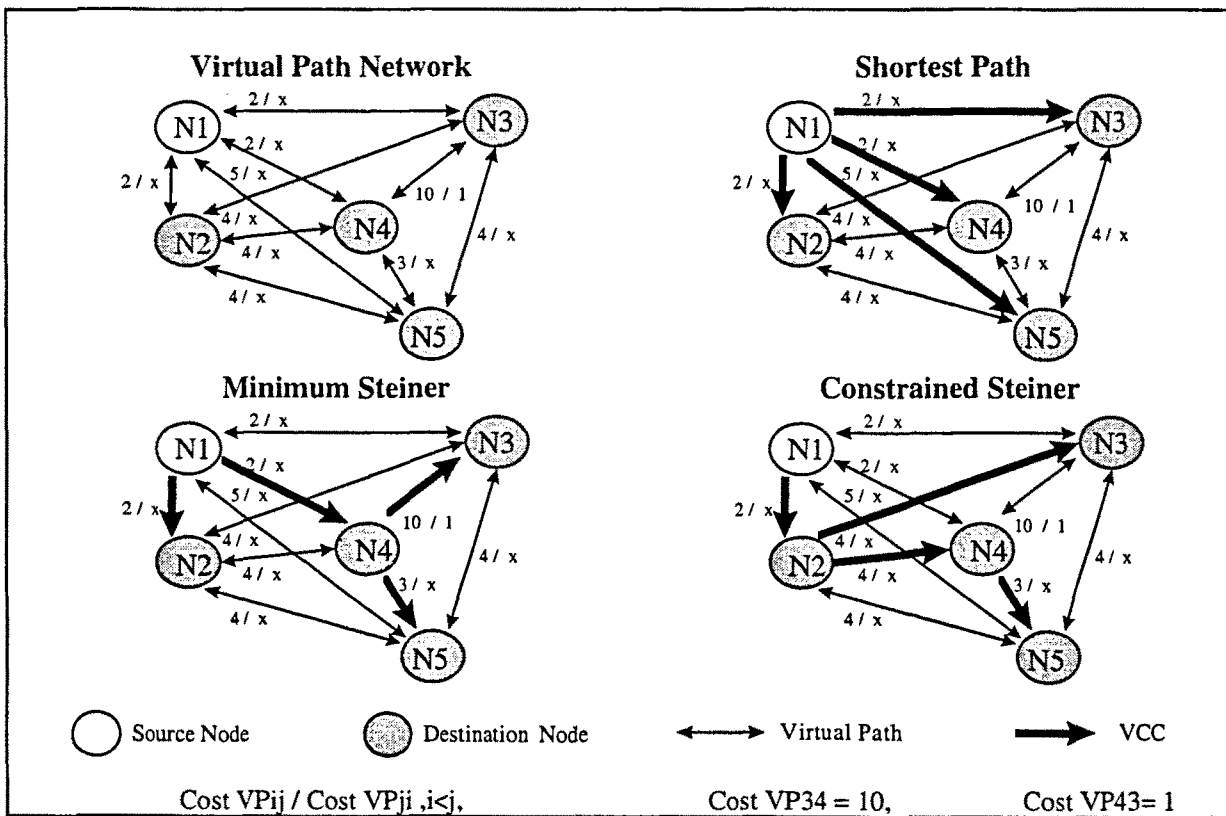


Fig. 42: Shortest path algorithm and Minimum Steiner algorithms

The following table shows the destination cost form each source node to destination node and the network cost obtained by each algorithm.

	Destination cost					Network cost (a)
	N1-N2	N1-N3	N1-N4	N1-N5		
Shortest path	2	2	2	5 (b)		11 (c)
Minimum Steiner tree	2	3 (d)	2 (e)	5 (f)	(g)	7 (h)
Constrained Steiner tree (i)	2	7	6	9	(j)	9 (k)

Tabla 17: Destination cost and network cost

- (a) This value is calculated adding the cost of all VPs of the solution.
- (b) There are two possible routes from N1 to N5 : the direct route (VP15) and the alternative route N1-N4-N5 (VP14 and VP45). The first case is considered.
- (c) Note that the network cost is not the function that could be minimized in this algorithm.
- (d) In this case the route from N1 to N3 is the alternative route N1-N4-N3, which is not the shortest path from N1 to N3, but the destination cost is not the function that could be minimized in this algorithm. Note in this case, that the cost of VP43 is 1.
- (e) The VP14 (direct route from N1 to N4) is also used in the alternative route considered from N1 to N3.
- (f) There are two possible routes from N1 to N5 with the same cost: the direct route (VP15) and the alternative route N1-N4-N5 (VP14 and VP45). In point-to-point routing, direct route will be selected before that alternative route, but in this case, the second one is selected to reduce the network cost.
- (g) Note that there are two routes from N1 in the tree solution obtained and from N4 too.
- (h) This value is the minimum between all the possible tree solutions. In the Minimum Steiner tree algorithm, the network cost is minimised as the expense of destination cost between N1 and N2.
- (i) Suppose that the limit considered is 15 and the value of x is 10. One possible algorithm to construct the tree, adds sequentially each node i with the previous node $i-1$ using the $VP_{i-1,i}$ if the cost from N1 to N_i does not violate the limit. In this case N4 is not added using the VP34 because the destination cost of N4 is 16 which is greater than the limit.
- (j) All destination cost are less than the limit.
- (k) This value is not the minimum. Moreover, the value obtained using the algorithm explained in (i) is higher than the obtained using the shortest path algorithm. Note that is not always true, the tree VP12, VP13, VP14 and VP45 is the solution obtained using another constrained algorithm and their network cost is 9.

5.3 EXACT ALGORITHMS AND HEURISTICS FOR THE STEINER TREE PROBLEM

Previous authors have established that determining an optimal multicast tree for a static multicast group may be modelled as the NP-complete Steiner problem in networks [BEA89], [BHA83], [HWA92b] and [WIN87]. Consequently, its explicit solutions are prohibitively expensive. Two popular explicit algorithms are the spanning tree enumeration algorithm and the dynamic programming algorithm [WIN87]

Hakimi [HAK71] provided a spanning tree enumeration algorithm where the Steiner tree for a given graph G may be found by enumeration of all minimum spanning trees of subgraphs of G induced by X , where $D \subseteq X \subseteq V$. The time complexity of this algorithm is $O(2^{(|V|-|D|)})^7$. It is thus efficient for problem instances where $|D| \approx |V|$.

Dreyfus and Wagner [DRE72] present a dynamic programming algorithm which uses the optimal decomposition method. The complexity of the algorithm is $O(|V| \cdot 3^{|D|} + |V|^2 \cdot 2^{|D|} + |V|^3)$ [HWA92b]. Since it is exponential in the number of destination vertices, this algorithm is best suited for instances where $|D| \ll |V|$ and is polynomially solvable if $|D|$ is fixed. There are other exact algorithms for this problem which are discussed in [HWA92b].

5.3.1 Heuristics

It is clear that because of the computational complexity, these algorithms are not practical for solving real-life problems. However, there are several polynomial-time heuristics, which can find good solutions to this problem very efficiently. Moreover, most of these heuristics can guarantee that the cost of their solution is within a factor of two times the cost of the optimal solution.

⁷ $O(|D|^2 \cdot 2^{(|V|-|D|)} + |V|)$ in [BAU97]

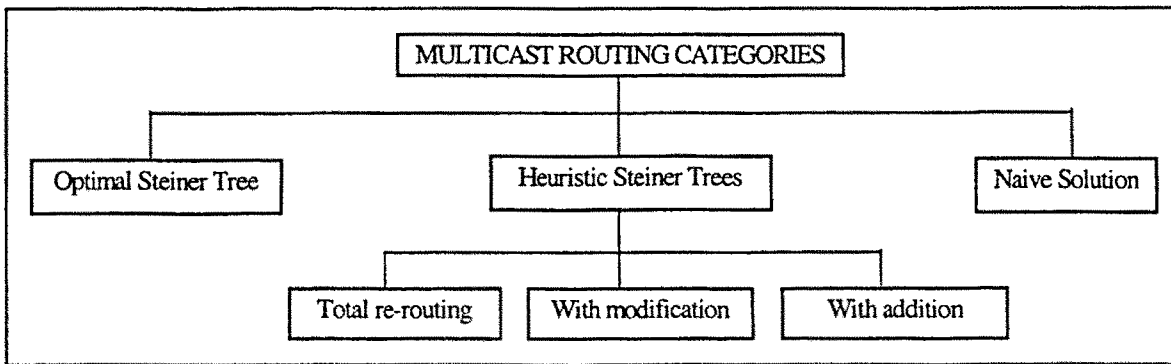


Fig. 43: Multicast routing categories.

As shown in figure, [DOA93th] pp. 124, there are three ways in which heuristic Steiner tree may be used for routing multicast groups whose membership is dynamic. One is to re-route the whole tree whenever the group membership changes. This may have repercussions for members who remain in the group, since there may be a disturbance in the communication, and in an ATM network, such a change may allow cells to arrive out of order at the destination. A variation of this method is to permit partial or local rearrangement of the tree when modifications to the membership occur. This would appear to be the same as reordering drawback as total re-routing.

Yet another approach is to begin with an optimal (or near optimal) tree and make minimal changes to it as group membership changes, in the extreme causing no disruption to members who remain in the group. This is consequential to the approach described by Waxman [WAX88]. As membership in the group changes, one would expect the inefficiency of this method to degrade and indeed simulation studies have shown occasional "spikes" of very high inefficiency.

A third category of multicast routing is shown in the right in figure. This is to choose a sub-optimal tree which will be resilient (strong and not damaged easily by changes. In the extreme case, finding the minimum source to destination path for all destinations independently and taking the union of these paths produces trees which will be resilient to changes, but which may be suboptimal.

A number of good, inexpensive heuristics methods exist for the Steiner problem in networks and have been reviewed extensively elsewhere [HWA92b], [BAU95], [BHA83], [HWA92b], [WIN87], [SMI92], [TAK80], [VOS92]. There are numerous heuristics, that have been proposed to construct Steiner trees [CIM87], [NOR94], [RAY86], [TAK80], [WIN87]. The one that is still considered the most optimal is the one described in [KOU81].

Among more recent research works, the following remarks are noted [DIO97]:

1) Reference [DOA93] shows that the most complex heuristic is not the best, and in most of the cases, a sub-optimal tree can keep its properties after modification. The naive

heuristics consists of designing a sub-optimal tree which is resilient to change. Member and node movement are achieved by joining or leaving the resilient tree.

2) In the degree constrained problem [BAU95], the design of the multicast tree is constrained by the multicast capabilities of nodes. This type of problem becomes important in ATM environments where the connectivity of switches is an important issued in the efficiency of the network technology. The degree constrained problem is then to find a minimum Steiner tree constrained by the multicast capability of nodes, which is also the number of interfaces on which a message can be duplicated. Simulations made by [BAU95] show that a fanout to two for node (or three interfaces) is enough to find acceptable solutions. Reference [BAU95] converges with [DOA93] in the sense that they both confirm that the naive heuristic works quite well and produces more stable trees when networks and groups are dynamic.

5.4 ESTABLISHMENT OF POINT TO MULTIPOINT CONNECTIONS

5.4.1 Naïve approach and Multicast tree

Because the ATM network is connection oriented, a path has to be established between the source and the destinations before information can be exchanged. There are two basic ways of establishing point to multipoint connections in ATM networks: **Naïve Approach** and **Multicast Tree**.

- **Naïve Approach.** A point to point virtual channel connection (VCC) from the source to each destination is established in this case. This approach leads to a simple implementation but clearly produces a non-optimal solution. The VVC set to each destination is known as a source-specific tree. The drawback is that it can require a large amount of network resources due to the duplication of data and the cost quickly becomes unacceptable.
- **Multicast tree.** A multicast tree, is a ring-free connected subnetwork spanning the source node and the group of destination nodes. Using such trees, common copies of data are transmitted over the multicast tree; “duplications of data” in the same path are avoided and therefore network resources are used efficiently. However, finding an optimal multicast tree, called the multicast tree problem, is not easy, and more efficient algorithms are needed.

5.4.2 Example

The following figure shows the naïve approach and the multicast tree obtained in the establishment of the point-to-multipoint connection from {N1} to {N3, N4, N5} in the 5-node fully VP based network (VPN).

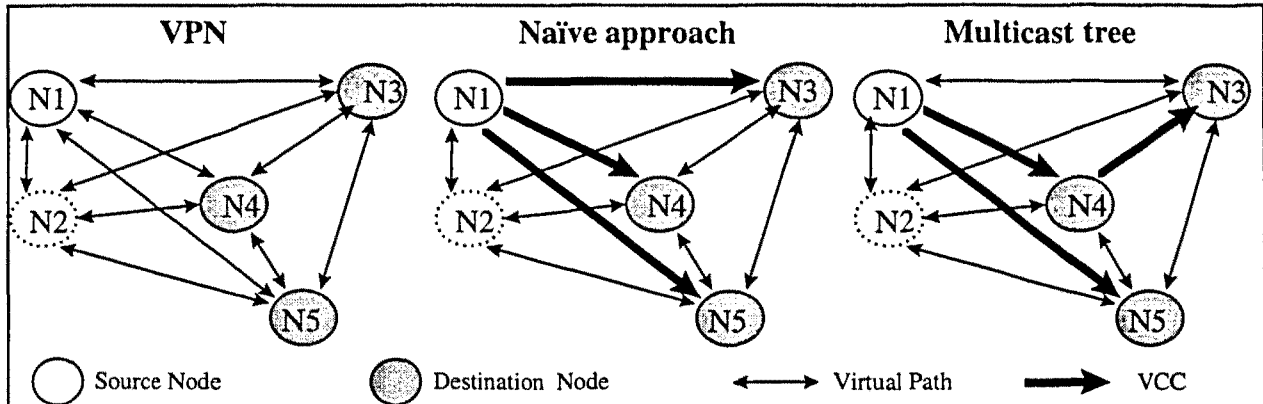


Fig. 44 : Point to multi-point connections establishment.

In the multicast tree, the route considered to establish the VCC from N1 to N3 is the alternative route VP14+VP43. Note that VP14 is also the direct route to establish the VCC from N1 to N4. Therefore the node N4 is simultaneously a destination node and an intermediate node.

5.5 ESTABLISHMENT OF MULTIPOINT TO MULTIPOINT CONNECTIONS

5.5.1 Separate Tree and Single Shared Tree

In the current standards for ATM, the “communication group” address abstraction does not exist. The sender should be aware of all the members of the “communication group”. Multipoint-to-multipoint is supported through point-to-multipoint VCC’s.

There are two approaches to establish the multipoint-to-multipoint connection: **Separate Tree and Single Shared Tree:**

- The simplest way is to establish a **separate tree** from each source to all destinations. Traffic addressed to a multicast group may be routed on a tree that is specific to the particular sender and group. The main problem with this method is the complexity. There are as many point-to-multipoint VCC’s as sources, as they all have to be controlled and managed.
- The other way is to establish a **single tree shared** by all of the source nodes to send traffic for all destination nodes. We can distinguish this from the Steiner problem by

observing that this family of algorithms is aimed at multiple sources / multiple destinations, as opposed to the single source / multiple destinations scenario addressed by the Steiner tree. Designing a shared tree is like designing a tree for group. The shared approach does, however, suffer from traffic concentration, as the traffic from all sources of a given group will converge to the root of the tree.

5.5.2 Examples

The following figures show three examples of the multipoint to multipoint connection establishment.

Multipoint to multipoint connection establishment from {N1, N2} to {N3, N4, N5}.

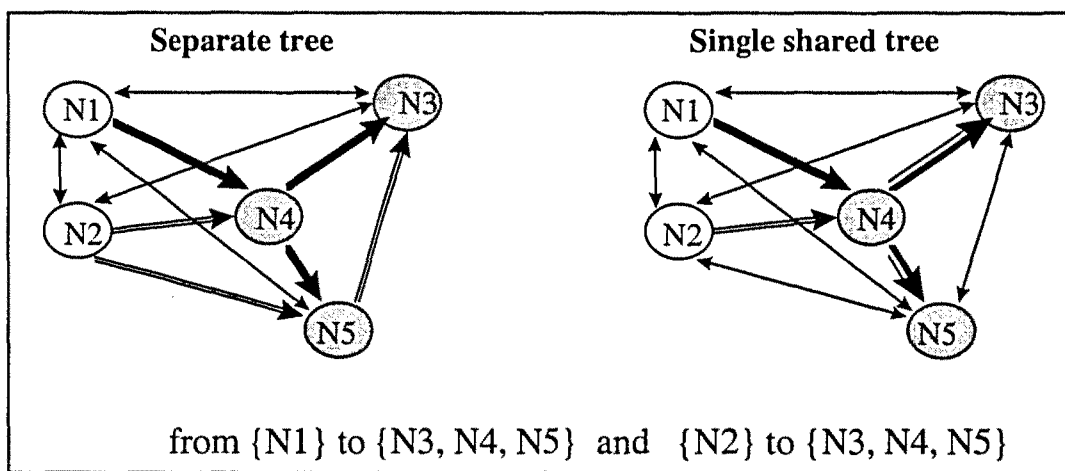


Fig. 45 : Multipoint to multipoint connection establishment from {N1, N2} to {N3, N4, N5}.

Trees obtained with the tree Separate Tree solution are: from N1 to destination nodes {N3, N4, N5} the tree formed by {VP14, VP43, VP45}; and from N2 to {N3, N4, N5} the tree formed by {VP24, VP25, VP53}.

In the Single Shared tree solution, the root of the tree is N4 and the tree is formed by {VP43, VP45}. Moreover, the VP14 and VP24 connect nodes N1 and N2 with the root of the tree respectively.

Multipoint to multipoint connection establishment from {N1} and to {N2, N3, N4, N5}.and {N2} and to {N1, N3, N4, N5}.

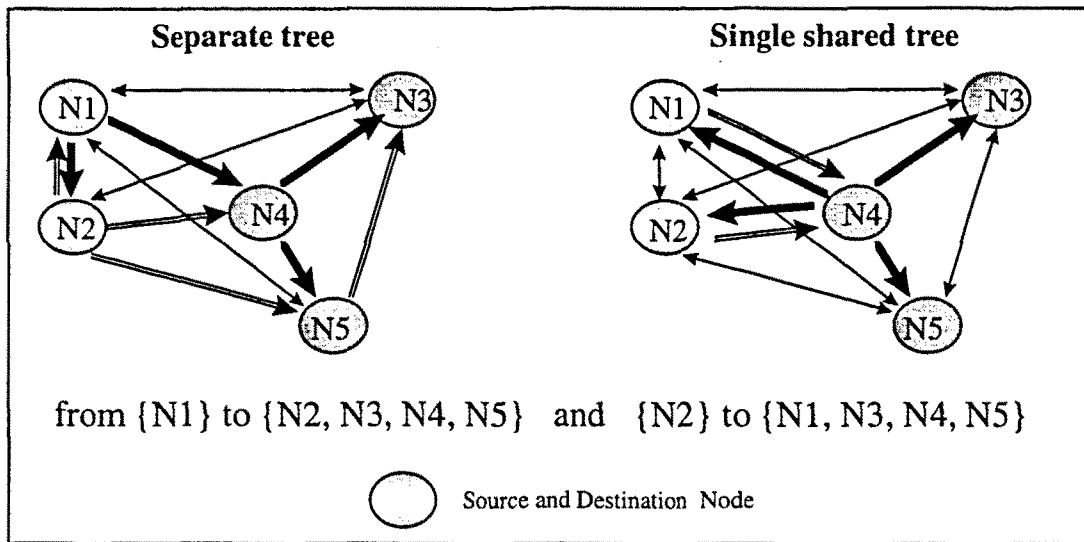


Fig. 46: Multipoint to multipoint connection establishment from {N1} and to {N2, N3, N4, N5}.and {N2} and to {N1, N3, N4, N5}.

Trees obtained with the tree Separate Tree solution are : {VP12, VP14, VP43, VP53} when the source node is N1; and {VP21, VP24, VP25, VP53} when the source node is N2.

In the Single Shared tree solution, the root of the tree is N4 and the tree is formed by {VP41, VP42, VP43, VP45}. Moreover, the VP14 and VP24 connect nodes N1 and N2 with the root of the tree respectively.

Multipoint to multipoint connection establishment from each node to all others.

From $\{N_i\}$ to $\{\{N_1, N_2, N_3, N_4, N_5\} - \{N_i\}\} \forall i=1,2,3,4,5$. All nodes are source and destination node simultaneously.

In this case, to clarify the figure of the separate tree solution, each tree is drawn separately.

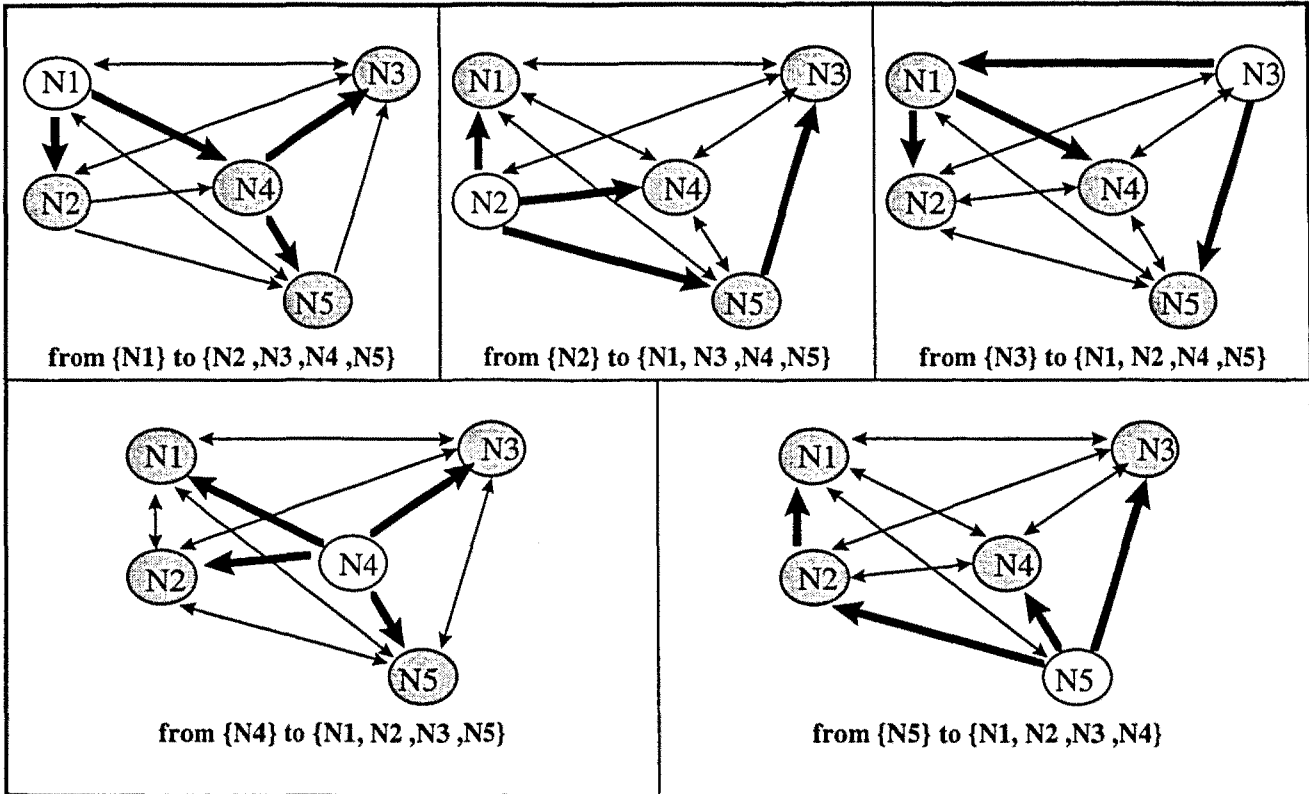


Fig. 47 : Multipoint to multipoint connection establishment. Separate tree Approach

To obtain the solution, all trees could be joined. Note that VP12, VP14 and VP21 are used in more than one tree. For example, the VP12 is used when N1 is the source node and also when the source node is N3.

In the Shared Tree approach, the point-to-point of each figure could be considered in the solution, but the tree could be considered only one time.

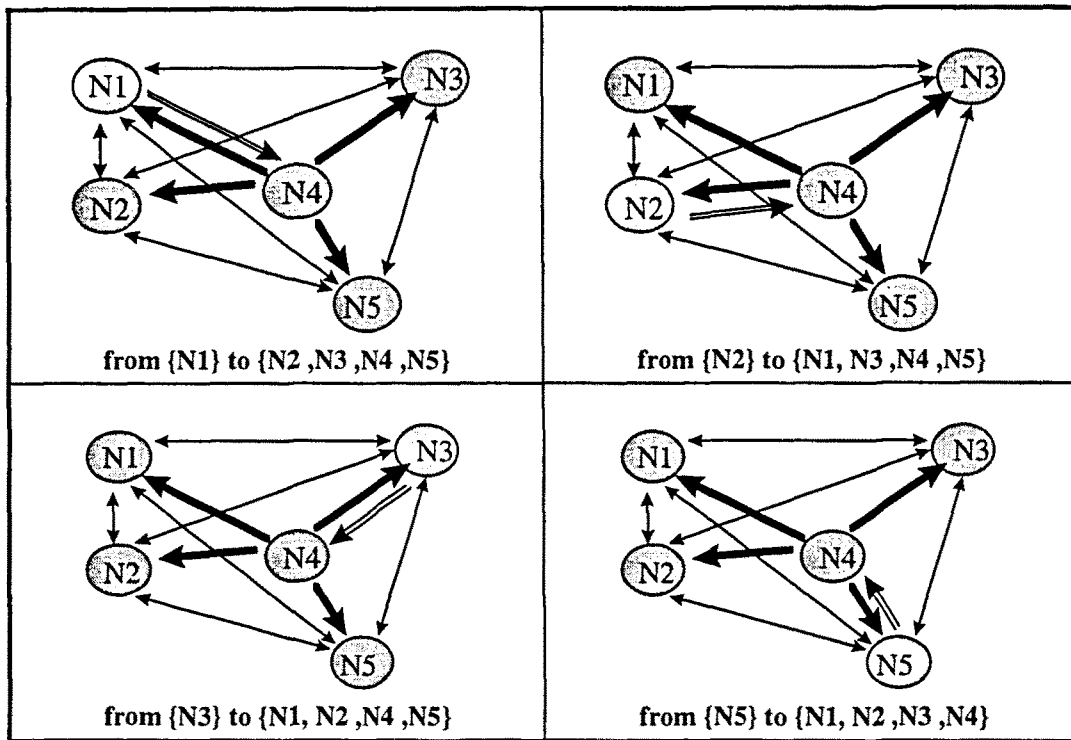


Fig. 48 : Multipoint to multipoint connection establishment. Shared Tree Approach.

The root of the Single Shared tree is N4 and the tree is formed by {VP41, VP42, VP43, VP45}. The VP14, VP24, VP34 and VP54 connects N1, N2, N3 and N5, respectively, with the root of the tree.

5.5.3 Comparing multipoint-to-multipoint approaches

The table compares some quantitative parameters needed for supporting a single group while using the Separate Tree and the Shared Single Tree approaches.

Different values are obtained if the root of the shared tree is or not a destination node. The second row of the Single Shared Tree is evaluated if the root of the shared tree is a destination node.

	Separate Tree	Single Shared Tree	
		n+m	(n-1) + (m-1)
total VCCs terminated at cluster members	$n*m$	$n+m$	$(n-1) + (m-1)$
point-to-multipoint VCCs	n	1	1
point-to-point VCCs	0	n	$(n-1)$
VCCs terminated at the root of the shared tree	-	n	$(n-1)$
VCCs terminated at each group member	n	1	1 (a)
signalling requests generated due to a single membership change	n	2	2

Tabla 18 : Comparing multipoint-to-multipoint approaches. Separate tree and single shared tree.

n = Number of source nodes multicasting to group. m = Number of group members in the “communication group”.

(a) Note that if the root of the shared tree is a group member, the number of VCCs terminated in this node is $(n-1)$.

The most attractive feature of the Single Shared Tree approach is its simplicity. From the network control point of view, there are only one point-to-multipoint and n point-to-point VCCs to be managed, instead of n point-to-multipoint VCCs in the former case.

Also, at a join or removal, there is only one point-to-point VCC to be established/released (the VCC from the joined/removed node to the root of the shared tree) and only one point-to-multipoint VCC to be modified in the Single Shared Tree approach (the shared tree), instead of the point-to-multipoint VCC to be established/released and $(n-1)$ ⁸ point-to-multipoint VCCs (trees routed in the other nodes) to be modified in the former case.

Furthermore, it puts little connection management burden on the nodes, because each of them has to manage only two VCCs instead of n . However, like the connectionless server approach, the Single Shared Tree approach has the disadvantage of becoming a potential throughput bottleneck and a single point of failure.

⁸ Note that for the case with one point-to-multipoint VCC for source we do not consider the additional VCCs and functions that may be needed to exchange control information between the stations (e.g., address of new member, list of addresses of existing members, etc.).

The following table summarizes the advantages and disadvantages of both approaches.

Separate Tree		Single Shared Tree	
higher data path performance	✓	consume less connection resources	✓
lower packet latency	✓	groups stabilise quicker after membership change	✓
heavy consumption of connection resources	✗	higher packet latency	✗
heavy signalling traffic for dynamic groups	✗	possible data path bottleneck : could lead to congestion and considerable demand for resources (buffer space and CPU time) to store incoming cells	✗
there would be no sharing of resources by the point-to-multipoint VCs even though they belong to same "communication group"	✗	reflected packet problem	✗

Tabla 19 : Advantages and disadvantages of separate tree and single shared tree.

5.6 RING BASED APPROACHES

5.6.1 Euler tour on the multicast tree and Travelling Salesman Problem

When all (or several) nodes are simultaneously source and destination nodes the amount of resources required is reduced using a ring-based approach. In contrast with tree-based approaches, ring-based approaches are considered to build a tour for obtaining a ring for all nodes of the "communication group". There are two basic approaches: to construct a tree and build a **Euler** tour on this tree or to find a minimum cost tour to visit each node exactly once (i.e. a simple ring). This last approach is known as the **Travelling Salesman Problem**.

The first approach is to construct a Euler tour by joining the multipoint-to-multipoint connections of the previous shared tree solution. In the second case a single ring is constructed.

Given a graph, an Eulerian circuit is a circuit which traverses every link of the graph once and only once. A graph contains a Eulerian tour if and only if the number of nodes of odd degree is 0.

A Hamiltonian circuit of a graph has been defined as an elementary circuit passing once and only one through every node. The problem of finding the least cost Hamiltonian circuit is widely known in the literature as the Travelling Salesman Problem (TSP). It can be stated very simply :

A salesman spends his time visiting n cities (or nodes). In one tour he visits each city just once, and finishes up where he started. In what order should he visit them to minimise the distance travelled ?.

If there are only 2 cities then the problem is trivial, since only one tour is possible. If all links are presented then there are $(n-1)!$ different tours for an n city asymmetric TSP. To see why this is so, pick any city as the first - then there are $n-1$ choices for the second city visited, $n-2$ choices for the third, and so on. It should be noted that if the graph is not complete, it can be considered as a complete graph with infinite value inserted as the cost of non-existent links.

The second approach has an advantage since each link is visited only once, whereas in the first approach the virtual ring results visiting each direction of a link. However, the maintenance of a ring is more complicated than of a tree. Thus, there is a trade off between constructing a ring and a tree to connect the nodes in a “communication group”.

5.6.2 Example

The following figures show the ring solutions by the multipoint-to-multipoint connection establishment from $\{N_i\}$ to $\{\{N_1, N_2, N_3, N_4, N_5\} - \{N_i\}\} \forall i=1,2,3,4,5$. All nodes are source and destination node simultaneously.

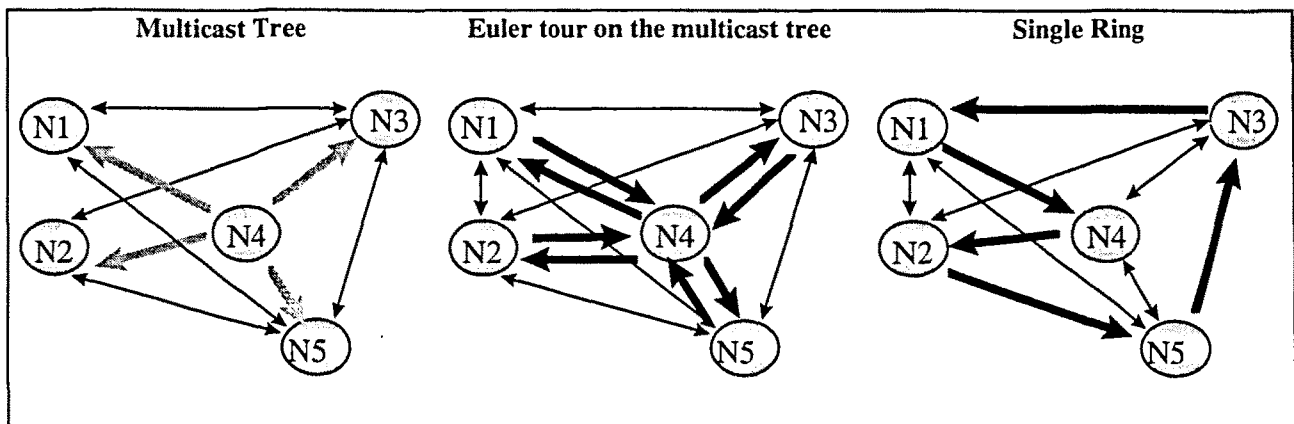


Fig. 49 : Multipoint to multipoint connection : Ring Based approach

Given the multicast tree $\{VP41, VP42, VP43, VP45\}$ a possible Euler tour built on the multicast tree is formed by $\{VP41, VP14, VP42, VP24, VP43, VP34, VP45, VP54\}$. A single ring to connect all nodes is formed by $\{VP14, VP42, VP25, VP53, VP31\}$.

5.6.3 Comparing ring bases approaches

The table below compares some quantitative parameters needed for supporting a single group while using the Euler tour on the single shared tree and the Single Ring approaches.

Row with Single Shared Tree values if the root of the shared tree is a destination node is done to facilitate the comparison with tree approaches.

	Single Shared Tree	Euler Tour	Single Ring
total VCCs terminated at cluster members	$2 * (m-1)$	$2 * (m-1)$	m
point-to-multipoint VCCs	1	0	0
point-to-point VCCs	$(m-1)$	$2 * m$	m
VCCs terminated at the root of the shared tree	$(m-1)$	$(m-1)$	-
VCCs terminated at each group member	1 (a)	1	1
signalling requests generated due to a single membership change	2	2	3

Tabla 20 : Comparing multipoint-to-multipoint approaches. Separate tree and single shared tree.

m = Number of group members in the "communication group"
 = Number of source nodes multicasting to group.
 (all nodes are source and destination simultaneously)

(a) Remember that if the root of the shared tree is a group member, the number of VCCs terminated in this node is $(n-1)$.

The most attractive feature of the Single Ring approach is that any point-to-multipoint is considered and the number of point-to-point only increases in 1. The major drawback is the more complicated maintenance of a single ring that of a tree. This drawback is explained more in detail in the next chapter.

5.7 RELATED WORKS

In [HWA95], Hwang proposed a new approach toward point to multipoint routing in single rate loss in which destination nodes join or leave the multicast tree dynamically. Based on the maximum free circuits routing concept, two algorithms are proposed for the **dynamic multicast routing** problem and an algorithm is designed for the "**static multicast routing**" problem. The dynamic version is based on the shortest path model with minimum path cost, and the static version is designed based on the minimum spanning tree concept. A new performance metric, referred to as the "*fractional reward loss*", is proposed for evaluating these three routing algorithms.

In [HWA96], Hwang and Huang focus on designing point to multipoint routing algorithms for ATM networks. They limit the study to the point to multipoint routing

problem in homogeneous VP networks. They are interested in developing adaptive point to multipoint routing algorithms in which routing decision is made based on network state information. Four point to multipoint routing algorithms are proposed in this paper : i) “the deterministic reservation *multicast* algorithm”, ii) “the deterministic reservation *multicast* algorithm with dynamic VP capacity sharing”, iii) “the deterministic reservation *multicast* algorithm with intermediate exits” and iv) “the deterministic reservation *multicast* algorithm with dynamic VP capacity sharing and intermediate exits”.

Ofek in [OFE97] constructs a tree to connect the nodes of the “communication group” and builds an Euler tour on this tree to obtain the virtual ring.

5.8 SUMMARY

In this section the main issues associated with routing of multipoint connections are explained. two different categories of multipoint protocols depending on the membership changes (static and dynamic), the shortest path algorithm and Steiner algorithms (minimum, constrained, exact and heuristic), the establishment of point to multipoint connections (naïve approach and multicast tree) and the establishment of multipoint to multipoint connections (separate tree, single tree and ring based approaches). Finally some works related with multipoint routing algorithms for ATM networks are provided.

6. Dynamic multipoint routing based on Congestion Probability

Some drawbacks appear when a multicast tree is established. It has been shown that the computation of a multicast tree can be reduced to the well-known Minimal Steiner Tree (MST) problem in graphs which are known to be *NP-Complete*[KAR72]. For some applications, the multicast group cannot be determined a priori because the *group membership changes* during the course of the multipoint session after new members join the group or existing members leave the connection. Thus, the routing protocol needs to build a multicast tree with partial information. Under these conditions, the computation of an “optimal” spanning tree for each new “communication group” may not be the best way to process. To support a dynamically changing “communication group”, it is necessary to recompute the multicast tree after each change. As this can be computationally expensive, it makes sense to compute a near-optimal multicast tree which is minimally disturbed after each change in group membership. In this case, the number of connections that could be established after a membership change is reduced, as is the amount of signalling traffic.

If designing an optimal tree is a complex problem, maintaining this tree optimality after changes in the membership group may be even more so. The optimal solution obtained is only ephemeral, due to the dynamic nature of multipoint applications. Consequently the challenge is to find a good compromise between the efficiency of the obtained tree and the dynamic of the group.

In formulating the multipoint routing problem as a Steiner tree problem, several researchers have assumed that each link has a pre-defined cost. The development of multipoint routing algorithms in VP networks is more complicated than these previous papers because there is *no fixed cost of a VP incurred by a connection*; the cost of using a link is usually based on the knowledge of the current network load, on the traffic descriptors of each connection and on the QoS requirements (in terms of the cell loss probability, cell delay variation and maximum cell delay) of the new connection and of the connections already involved in the VP.

The practical use of multicast Steiner tree based algorithms in B-ISDN is questionable because :

- The minimum Steiner algorithms [HAK71] were shown to be NP-complete [KAR72];
- There are clearly some applications for which the set of destinations will be dynamic [WAX88], [DOA93th], [ZHU95] and [RAM96];
- Adding or removing destinations to an existing Steiner tree may lead to a totally different Steiner tree. This may have repercussions on members who remain in the group, since there may be a disturbance in the communication, because several VCC may be torn down and rerouted.
- The point to multipoint connection establishment procedure defined in the ITU-T draft recommendation protocol for call set up, e.g. [Q.93B], [Q.2931], [UNI-3.0] and [UNI-3.1], requires setting up the destination nodes sequentially. A point to multipoint connection is first set up by establishing a point-to-point connection between the source node and the first destination node. After this set up is complete, additional destination nodes can be added sequentially.

In this chapter some consideration about how the Congestion Probability Routing (CPR) algorithm can be extended to routing dynamic multipoint connections are explained. Two classes of adaptive multipoint routing algorithms with constrained end-to-end cell loss probability are proposed in following sections: the “**Shortest Path Additive from the Partially formed Tree**” solution (SPA-Tree solution) and the “**Ring**” solution which is considered when all (or several) nodes are simultaneously source and destination.

6.1 TREE SOLUTION

In this subsection, to establish a dynamic point-to-multipoint VCC a constrained multicast tree is proposed. The solution is named “**The Shortest Path Additive Solution from the partially formed tree**”. These multipoint routing algorithms are based on adding the destination nodes one by one to the tree. To connect a destination node to a partially-formed multicast tree, the route with minimum cost from the node to the partially-formed tree is chosen. The cost of a route is the sum of VP costs on the route, which is computed as shown before. Since alternative routes consist of two VP’s in the CPR algorithm, in the routing protocol presented in this section, the length of each path is also limited to two VP’s. The reason for such constraint is that the larger the path the more stringent QoS, and thus more capacity, is required to set up the call on each VP on the path.

As Hwang in [HWA95], we assume that the VP network is fully connected and the number of VPs to source from destination is limited to two, that the multicast tree is non-rearrangeable, (i.e., the routing algorithms are not allowed to modify the existing multicast tree except to add new nodes and links) and that removal of a destination node from a multicast tree dynamically is not considered.

There are some differences between our proposal and related works, [HWA95] and [HWA96]. We study the multipoint routing problem in heterogeneous VP Networks, (e.g. in multimedia applications, a call could consist of a number of connections of different traffic types which make it necessary to consider heterogeneous VP Networks). It can yield a better solution than homogeneous VP Networks because it facilitates media synchronisation and simplifies traffic management. On the other hand, the performance criteria by the CAC are Individual CLP requirements. The objective of the algorithm is to minimise the Probability of Congestion (PC) from the source to each destination node. The PC is applied as a route selection parameter. Traffic classes are not limited to on-off sources in our work, multi-state sources are also allowed. Finally, we consider that the Routing Control Parameter is used to restrict alternative traffic and prevent direct traffic when the VP is very busy.

Different algorithms based on the SPA solution from the partially formed tree (SPA-Tree) are presented, varying the types and the precedence of the considered routes: these may be direct routes from the partially formed tree, alternative routes through an implicated node or alternative routes.

6.1.1 Only Direct Routes

This algorithm considers the partially formed tree, but only direct routes are allowed. In this case, at each step a single node is added to the tree.

We propose to subdivide the set of direct routes from the partially formed tree to the new node depending on the QoS guaranteed by each direct route.

Solution	Precedence	
	(first)	(last)
Only Direct Routes	Direct Routes from the partially formed tree with Route Cost < Individual_CLP / 2	Direct Routes from the partially formed tree with Route Cost < Individual_CLP

Tabla 21 :Tree Solution. Only Direct Routes.

If one “Direct Route from the partially formed tree with Route Cost < Individual_CLP / 2” is selected, the destination node of this route can be considered as the origin node of other direct routes with the same route cost characteristics (Route Cost < Individual_CLP / 2) when the posterior nodes will be added to the tree.

Otherwise, if one “Direct Route from the partially formed tree with Route Cost < Individual_CLP” is selected, the Route Cost is > Individual_CLP / 2, and therefore, the destination node is always a leaf of the tree.

To maximize the network resource utilization first are considered “direct routes from the partially formed tree with Route Cost < Individual_CLP / 2”.

The following table explains the “Shortest Path Additive solution from the partially formed tree” when only direct routes are considered.

EXAMPLE : SPA-Tree-Only Direct Routes

Origin Node : N1 Destination Nodes: N5, N3, N6 No Destination Nodes : N2, N4

From N1 to N5:
a) QoS/2 or Direct = {R15}

From the partially formed tree (N1, N5) to N3:
aa) QoS/2 = {R53 (if QoS(R15)<QoS/2 and QoS(R53)<QoS/2), R13 (if QoS(R13)<QoS/2)}
ab) Direct = {R13}

If the route R53 has been selected, the routes from the partially formed tree (N1, N5, N3) to N6 are:
aaa) QoS/2 = {R56 (if QoS(R15)<QoS/2 and QoS(R56)<QoS/2)}
aab) Direct = {R16}

1) The figure shows the possible routes {aa, ab} that can be selected to connect the node N3, whenever route a) is selected to connect N1 to N5.

2) If aa) is selected in previous step, routes {aaa, aab} are available to connect N6

3) This figure shows the adopted solution when the route aab) is selected.

Tabla 22 : SPA-Tree-Only Direct Routes.

6.1.2 Alternative routes through an implicated node

The following algorithms combine the partially formed tree and the use of direct and alternative routes. When there are two or more destination nodes, the transit node of an alternative route can be one of the destination nodes. In this case, this node is known as an implicated node and the route is known as an “alternative route through an implicated node”. The remainder of alternative routes are known as alternatives routes through a no-destination node or simply “alternative routes”.

In algorithms presented in this section, we propose:

- alternative routes through an implicated node are considered before “alternative routes”.
- the precedence of the “alternative routes through an implicated node” in relation with direct routes varies: after all direct routes, between “direct routes” and “direct routes with QoS/2”, and finally before all direct routes.

The different possibilities to combine the previous proposals are shown in the following table :

Algorithm	Precedence			
	(first)	—————>		(last)
after direct routes	Direct Routes from the partially formed tree with Route Cost < Individual_CLP / 2	Direct Routes from the partially formed tree with Route Cost < Individual_CLP	Alternative Routes through an Implicated Node	Alternative Routes
between direct routes	Direct Routes from the partially formed tree with Route Cost < Individual_CLP / 2	Alternative Routes through an Implicated Node	Direct Routes from the partially formed tree with Route Cost < Individual_CLP	Alternative Routes
before direct routes	Alternative Routes through an Implicated Node	Direct Routes from the partially formed tree with Route Cost < Individual_CLP / 2	Direct Routes with Route Cost < Individual_CLP	Alternative Routes

Tabla 23 : SPA-Tree-Alternative Routes algorithms.

If “*alternative routes through an implicated node*” are considered first, the complexity of the algorithm is reduced. This is because two destination nodes, instead of just one, are added in a single step; obviously, the destination node considered in this step, and the implicated node which would be added in further steps.

When the posterior nodes will be added to the tree, the implicated node of the “alternative route with route cost < Individual_CLP / 2” would be considered as an origin node of direct routes with route cost < Individual_CLP / 2, because the cost of each VP of the alternative route is less that the Individual_CLP / 2.

The following table explains the establishment of point-to-multipoint VCC when the Shortest Path Additive algorithm from the partially formed tree when “alternatives routes through an implicated node” are considered after direct routes :

EXAMPLE : SPA-Tree-Alternative Routes through an implicated node after direct routes

Origin Node : N1

Destination Nodes: N5, N3, N6

No Destination Nodes : N2, N4

From N1 to N5:

- a) QoS/2 or Direct = {R15} (*)
- b) Implicated = {R135, R165} (**)
- c) Alternative = {R125, R145}

From the partially formed tree (N1, N5) to N3:

- aa) QoS/2 = {R53 (if $QoS(R15) < QoS/2$ and $QoS(R53) < QoS/2$), R13 (if $QoS(R13) < QoS/2$)}
- ab) Direct = {R13}
- ac) Implicated = {R163}
- ad) Alternative = {R123, R143}

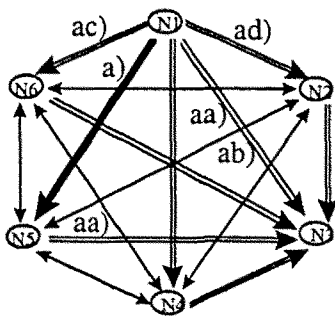
From the partially formed tree (N1, N3, N5) to N6:

- aaa) QoS/2 = {R56 (if $QoS(R15) < QoS/2$ and $QoS(R56) < QoS/2$), R16 (if $QoS(R16) < QoS/2$)}
- aab) Direct = {R16},
- aac) Implicated = {}
- aad) Alternative = {R126, R146}

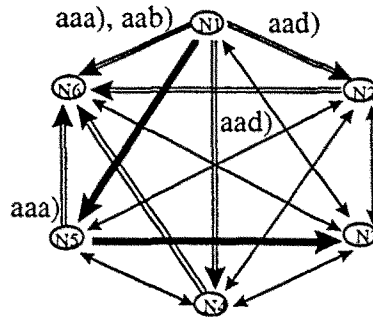
(*) QoS/2 or Direct = {Rod}, route from node Origin "o" to node destination "d"
The Cost of the route {Rod} could be : $< Individual_CLP / 2$ or $< Individual_CLP$ ("direct")

(**) Implicated or Alternative Route = {Roid}
The cost of the route {Roi} is $< Individual_CLP / 2$ and the cost of the route {Rid} is $< Individual_CLP / 2$

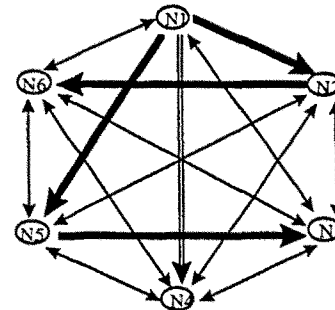
(***) The underlined condition is unnecessary because R53 are been selected.



1) The figure shows the possible routes, {aa), ab), ac), ad}), that could be selected to connect the node N3, whenever route a) is selected to connect N1 to N5.



2) If aa) is selected in previous step, four routes {aaa), aab), aac), aad)} are available, to connect N6.



3) This figure shows the adopted solution when the route aad) is selected.

Tabla 24 : SPA-Tree-Alternative Routes through an implicated node after direct routes

6.1.3 Pseudo-code of SPA algorithms

In this section, the pseudo-code of the different Shortest Path Additive algorithms, presented previously, are described :

Only Direct Routes

```

Given a point to multipoint connection demand (s,D)
D={d1, d2, ..., dN}          /* destination's order is relevant */
Initially: T2={NT2, VPT2}={s}, ∅}
T:={NT, VPT}={∅, ∅}

/* Try to connect each destination via direct route (direct VP) with QoS/2 */
i:=1
while i ≤ N
    D=D-{di}                /* remove di */

    /* from the partially formed multicast tree*/
    Let ADR(NT2, di) = { (vp(NT1, di) ∨ NT1 ∈ NT2; PC2(vp(NT1, di) < 1 ) } be the set of available direct routes connecting the partially
    formed multicast tree with di

    Select dr(NT1, di) ⊂ ADR(NT2, di) the route with minimum PC
    if dr(NT1, di) ≠ ∅
        T2:=T2 + dr(NT1, di)          /* NT2= NT2 ∪ { di} and VPT2 = VPT2 ∪ {vp(NT1, di)} */
        D=D-{di}                        /* remove di */
    else
        Let vp(s, di) be the direct virtual path connecting s with di
        if PC(vp(s, di)) < 1
            T:=T + vp(s, di)          /* NT = NT ∪ {di} and VPT = VPT ∪ {vp(s, di)} */
            D=D-{di}                  /* remove di */
        else
            block the connection
            free all the VCC established
            abort the point to multipoint connection demand setup procedure
        end if
    end if
    i:=i+1
end while

T:=T + T2}          /* NT= NT ∪ NT2 and VPT = VPT ∪ VPT2 */

```

Tabla 25 : Only Direct Routes

Alternative Routes through an implicated node after direct routes

```

Given a point to multipoint connection demand (s,D)
D={d1, d2, ..., dN}      /* destination's order is relevant */
Initially: T2={NT2,VPT2}={s},∅}
T:={NT,VPT}={∅, ∅}

/* Try to connect each destination via direct route (direct VP) with QoS/2 */
i:=1
while i ≤ N
  D=D-{di}                /* remove di */

  /* from the partially formed multicast tree*/
  Let ADR(NT2,di):= { (vp(NT1,di) ∨ NT1 ∈ NT2; PC2(vp(NT1,di) < 1 ) be the set of available direct routes connecting the partially
  formed multicast tree with di
  Select dr(NT1,di) ⊂ ADR(NT2,di) the direct route with minimum PC
  if dr(NT1,di) ≠ ∅
    T2:={T2 + dr(NT1, di)}      /* NT2= NT2 ∪ { di} and VPT2= VPT2 ∪ {vp(NT1,di)} */
    D=D-{di}                    /* remove di */
  else
    3
    /*from the source node*/
    Let vp(s,di) be the direct virtual path connecting s with di
    if PC(vp(s,di)) < 1
      T:=T + vp(s,di)    /* NT = NT ∪ {di} and VPT = VPT ∪ {vp(s,di)} */
    else
      /*We prioritise alternative routes through destination nodes*/
      Let AIR(s,di):= { (vp(s,s-di*) + vp(s-di*,di); di* ∈ D and PC2(vp(s,s-di*) < RCP and PC2(vp(s-di*,di) < RCP ) be the
      set of available alternative routes connecting s with di
      /* PC2 denotes that the Individual_CLP over the VP are (end-to-end Individual_CLP)/2 */
      Select ir(s,di) ⊂ AIR(s,di) the alternative route with minimum PC among all alternatives routes of AIR(s,di)
      if ir(s,di) ≠ ∅
        T:=T + ir(s,di)      /* NT = NT ∪ {di, di} and VPTD = VPT ∪ {vp(s,di), vp(di,s)} */
        D=D-{di}            /* remove di */
      else
        /*Alternative routes through no destination node.*/
        Let AAR(s,di):= { (vp(s,s-di*) + vp(s-di*,di); di* ∈ N-{NT}, PC2(vp(s,s-di*) < RCP and PC2(vp(s-di*,di) < RCP )
        be the set of available alternative routes connecting s with di
        /* PC2 denotes that the Individual_CLP over the VP are (end-to-end Individual_CLP)/2 */
        Select ar(s,di) ⊂ AAR(s,di) the alternative route with minimum PC
        if ar(s,di) ≠ ∅
          T:=T + ar(s,di)    /* NT = NT ∪ {di, di} and VPTD = VPT ∪ {vp(s,di), vp(di,s)} */
          D=D-{di}          /* remove di */
        else
          block the connection
          free all the VCC established
          abort the point to multipoint connection demand setup procedure
        end if
      end if
    end if
  end if
  i:=i+1
end while

T:=T + T2                  /* NT = NT ∪ NT2 and VPT = VPT ∪ VPT2 */

```

Tabla 26 : Alternative Routes through an implicated node after direct routes

Alternative Routes through an implicated node between direct routes

```

Given a point to multipoint connection demand (s,D)
D={d1, d2, ..., dN}      /* destination's order is relevant */
Initially: T2={NT2,VPT2}={s},∅}
T:={NT,VPT}={∅, ∅}

/* Try to connect each destination via direct route (direct VP) with QoS/2 */
i:=1
while i ≤ N
  D=D-{di}                /* remove di */

  /* from the partially formed multicast tree - {s} */
  Let ADR(NT2,di):= { (vp(NT1,di) ∨ NT1 ∈ NT2 -{s}; PC2(vp(NT1,di) < 1 } be the set of available direct routes connecting the
  partially formed multicast tree with di
  Select dr(NT1,di) ⊂ ADR(NT2,di) the direct route with minimum PC among all direct routes of ADR(s,di)
  if dr(NT1,di) ≠ ∅
    T2:={T2 + dr(NT1, di) /* NT2= NT2 ∪ { di} and VPT2= VPT2 ∪ {vp(NT1,di)} */
    D=D-{di}                /* remove di */
  else

    /*We prioritise alternative routes through destination node.*/
    Let AIR(s,di):= { (vp(s,s-di*) + vp(s-di*,di); di* ⊂ D and PC2(vp(s,s-di*) < RCP and PC2(vp(s-di*,di) < RCP } be the set of
    available alternative routes connecting s with di
    /* PC2 denotes that the Individual_CLP over the VP are (end-to-end Individual_CLP)/2 */
    Select ir(s,di) ⊂ AIR(s,di) the alternative route with minimum PC among all alternatives routes of AIR(s,di)
    if ir(s,di) ≠ ∅
      T:=T + ir(s,di)        /* NT= NT ∪ {di, di} and VPTD = VPT ∪ {vp(s,di), vp(di,s)} */
      D=D-{di}                /* remove di */
    else

      /*from the source node*/
      Let vp(s,di) be the direct virtual path connecting s with di
      if PC2(vp(s,di)) < 1    /* VCC from s to di can be accepted. */
        T2:={T2 + vp(s,di) /* NT2= NT2 ∪ {di} and VPT2= VPT2 ∪ {vp(s,di)} */
      else
        if PC(vp(s,di)) < 1
          T:=T + vp(s,di) /* NT = NT ∪ {di} and VPT = VPT ∪ {vp(s,di)} */
        else

          /*Alternative routes through no destination node.*/
          Let AAR(s,di):= { (vp(s,s-di*) + vp(s-di*,di); di* ⊂ N-{NT}, PC2(vp(s,s-di*) < RCP and PC2(vp(s-di*,di)
          < RCP } be the set of available alternative routes connecting s with di
          /* PC2 denotes that the Individual_CLP over the VP are (end-to-end Individual_CLP) /2 */
          Select ar(s,di) ⊂ AAR(s,di) the alternative route with minimum PC among all alternatives routes of
          AAR(s,di)
          if ar(s,di) ≠ ∅
            T:=T + ar(s,di) /* NT= NT ∪ {di, di} and VPTD = VPT ∪ {vp(s,di), vp(di,s)} */
            D=D-{di}        /* remove di */
          else
            block the connection
            free all the VCC established
            abort the point to multipoint connection demand setup procedure
          endif
        endif
      endif
    endif
  end if
  i:=i+1
end while

T:=T + T2                    /* NT= NT ∪ NT2 and VPT = VPT ∪ VPT2 */

```

Tabla 27 : Alternative Routes through an implicated node between direct routes

Alternative Routes through an implicated node before direct routes

```

Given a point to multipoint connection demand (s,D)
D={d1, d2, ..., dN}      /* destination's order is relevant */
Initially: T2={NT2, VPT2}={s, ∅}
T:={NT, VPT}={∅, ∅}

/* Try to connect each destination via direct route (direct VP) with QoS/2 */
i:=1
while i ≤ N
  D=D-{di}                /* remove di */

  /* from the partially formed multicast tree*/
  Let ADR(NT2, di):= { (vp(NT1, di) ∨ NT1 ∈ NT2; PC2(vp(NT1, di) < 1 } be the set of available direct routes connecting the partially
  formed multicast tree with di;
  Select dr(NT1, di) ∈ ADR(NT2, di) the direct route with minimum PC
  if dr(NT1, di) ≠ ∅
    T2:={T2 + dr(NT1, di)}          /* NT2 = NT2 ∪ { di } and VPT2 = VPT2 ∪ {vp(NT1, di)} */
    D=D-{di}                          /* remove di */
  else

    /*We prioritise alternative routes through destination node.*/
    Let AIR(s, di):= { (vp(s, s-di*) + vp(s-di*, di); di* ∈ D and PC2(vp(s, s-di*) < RCP and PC2(vp(s-di*, di) < RCP } be the set of
    available alternative routes connecting s with di;
    /* PC2 denotes that the Individual_CLP over the VP are (end-to-end Individual_CLP)/2 */
    Select ir(s, di) ∈ AIR(s, di) the alternative route with minimum PC among all alternatives routes of AIR(s, di)
    if ir(s, di) ≠ ∅
      T:=T + ir(s, di)                /* NT = NT ∪ {di, di} and VPTD = VPT ∪ {vp(s, di), vp(di, s)} */
      D=D-{di}                        /* remove di */
    else

      /*from the source node*/
      Let vp(s, di) be the direct virtual path connecting s with di;
      if PC(vp(s, di)) < 1
        T:=T + vp(s, di)             /* NT = NT ∪ {di} and VPT = VPT ∪ {vp(s, di)} */
      else

        /*Alternative routes through no destination node.*/
        Let AAR(s, di):= { (vp(s, s-di*) + vp(s-di*, di); di* ∈ N-{NT}, PC2(vp(s, s-di*) < RCP and PC2(vp(s-di*, di) <
        RCP } be the set of available alternative routes connecting s with di;
        /* PC2 denotes that the Individual_CLP over the VP are (end-to-end Individual_CLP) /2 */
        Select ar(s, di) ∈ AAR(s, di) the alternative route with minimum PC among all alternatives routes of AAR(s, di)
        if ar(s, di) ≠ ∅
          T:=T + ar(s, di) /* NT = NT ∪ {di, di} and VPTD = VPT ∪ {vp(s, di), vp(di, s)} */
          D=D-{di}          /* remove di */
        else
          block the connection
          free all the VCC established
          abort the point to multipoint connection demand setup procedure
        endif
      endif
    end if
  end if
  i:=i+1
end while

T:=T + T2                /* NT = NT ∪ NT2 and VPT = VPT ∪ VPT2 */

```

Tabla 28 : Alternative Routes through an implicated node before direct routes

6.1.4 Deletion process

When a node is added, two operations are involved : the selection of a path and the connection setup. The deletion process is the reverse process of addition, but in this case it is not necessary to select the path. The leaf node that wants to leave does the following : prune itself and removes the VP between the node and its neighbour.

Deletion process algorithm of node d_d

```

Initially:  $T := \{N_T, VP_T\}$  and  $T_2 := \{N_{T_2}, VP_{T_2}\}$ 

if  $d_d \in N_{T_2}$ 
     $T_2 := T_2 - dr(\text{neighbour}, d_d) /* N_{T_2} = N_{T_2} - \{d_d\}$  and  $VP_{T_2} = VP_{T_2} - \{vp(\text{neighbour}, d_d)\} */$ 
else
     $T := T - dr(\text{neighbour}, d_d) /* N_T = N_T - \{d_d\}$  and  $VP_T = VP_T - \{vp(\text{neighbour}, d_d)\} */$ 
endif

```

Tabla 29 : Deletion process algorithm of node d_d

If nodes can leave the “communication group” at any moment, the presented SPA solutions could be slightly modified. When a node is added, it may be added to an existing tree. However, when a node is deleted, the same connection may stay because other nodes are still connected to the tree through the same node; therefore, the VP between the node and its neighbour could not be removed. When a node is deleted, the degree of this neighbour node decreases to 1. The neighbour node is pruned if it is not a connected node and their degree is 0. When a non-leaf node leaves a “communication group”, it remains on the tree as a no-connected node, its degree is also decreased to 1.

Modification of the deletion process algorithm of node d_d

```

Initially:  $T := \{N_T, VP_T\}$  and  $T_2 := \{N_{T_2}, VP_{T_2}\}$ 

if  $degree(d_d) = 0$  /*if  $d_d$  is a leaf node*/
    if  $d_d \in N_{T_2}$ 
         $T_2 := T_2 - dr(\text{neighbour}, d_d) /* N_{T_2} = N_{T_2} - \{d_d\}$  and  $VP_{T_2} = VP_{T_2} - \{vp(\text{neighbour}, d_d)\} */$ 
    else
         $T := T - dr(\text{neighbour}, d_d) /* N_T = N_T - \{d_d\}$  and  $VP_T = VP_T - \{vp(\text{neighbour}, d_d)\} */$ 
    endif
     $degree(\text{neighbour}) := degree(\text{neighbour}) - 1$ 
endif

```

Tabla 30 : Modification of the deletion process algorithm of node d_d

6.1.5 Finite state machine and messages types if only direct routes are considered

For each “communication group”, the nodes, which are involved in the tree building process maintain a finite state machine associated with that “communication group”. This state machine allows us to know the state of each node at any moment.

If SPA-Tree Only Direct Route solution is considered, the finite state machine consists of the following states :

- **VPN-NODES (S0):** All nodes are initially in this state, where the node has no information pertaining to the multicast tree. All nodes stay in this state until a point-to-multipoint VCC is demanded.
- **ROOT (S1):** The origin node enters this state when a point to multipoint VCC is demanded. Origin node stays in this state until a point-to-point connection between the source and the first destination node is established or until the point to multipoint VCC is finished.
- **DESTINATION NO-TREE (S2):** The set of possible destination nodes enter this state when a point-to-multipoint VCC is demanded. In this state, destination nodes are not yet added to the multicast tree. A destination node stays in this state until it is joined to the multicast tree or until the point to multipoint VCC is finished.
- **LEAF (S3):** A destination node enters this state when it is joined to the multicast tree (it is connected because the connection has been established). Initially, this node is a leaf of the multicast tree. It stays in this state until another destination node is connected to the multicast tree from it or until it leaves the multicast tree.
- **ROOT DEGREE N (S4.n):** The origin node enters this state when a destination node join the multicast tree. In this case, the origin node is a no-leaf node. The origin node stays in this state while any destination node will be connected to the multicast tree from it. N indicates the number of destination nodes that are connected to the multicast tree from the origin node. When all destination nodes have left the multicast tree, the origin node enters in ROOT state (S0).
- **NO-LEAF NO-CONNECTED (S5.n):** When a no-leaf node leaves a “communication group”, it remains on the tree as a no-connected node. A destination node that is a no-leaf node, enters in NO-LEAF NO-CONNECTED state if it leaves

the “communication group”. N indicates the number of destination nodes that are connected to the multicast tree from this node.

- **NO-LEAF CONNECTED (S6.n):** A destination node which is in LEAF state enters this state when a destination node is connected to the multicast tree from it. A node enters in NO-LEAF NO-CONNECTED state when it is joined to the “communication group”. N indicates the number of destination nodes that are connected to the multicast tree from this node. The only difference between this state (NO-LEAF CONNECTED state) and the previous state (NO-LEAF NO-CONNECTED state) is that the destination node is on the “communication group”.

In the following table the characteristics of each state are explained:

STATE	STATUS				NEIGHBOUR
S0 :VPN Nodes		No-Tree			Unknown
S1 :Root	Origin	Tree	Leaf	Connected	N.A.
S2 :Destination No-Tree	Destination	No-Tree			Unknown
S3 :Leaf	Destination	Tree	Leaf	Connected	Known
S4 :Root Connected (degree n)	Origin	Tree	No-Leaf	Connected	Known
S5 :No-Leaf-No-Connected (degree n)	Destination	Tree	No-Leaf	No-Connected	Known
S6 :No-Leaf-Connected (degree n)	Destination	Tree	No-Leaf	Connected	Known

Tabla 31 : State characteristics if only direct routes are considered

Each node makes a transition from one state to another whenever it receives a message pertaining to the “communication group”. A point to multipoint connection has a source node and several destination nodes. To establish the connection the following messages are used by the nodes :

- **DEMANDED CONNECTION (origin node, {destination nodes}) :** This message is sent when a new point-to-multipoint VCC is demanded. This message includes the origin node and the set of possible destination nodes. When the origin node receives this message, it changes to ROOT state and sends a DESTINATION NODE MESSAGE to each possible destination node.

- **DESTINATION NODE (destination node) :** This message is sent by the origin node to the possible destination nodes when the origin node receives a DEMANDED CONNECTION message or a FINISH CONNECTION message.

- **FINISH CONNECTION (origin node, {destination nodes})** : This message is sent when a point-to-multipoint VCC is finished. We assume that FINISH CONNECTION message is sent when all destination nodes are in the DESTINATION NO-TREE state.

- **ADDITION NODE (join node, neighbour)** : This message is sent when a destination node, *join node*, joins the “communication group”. The *join node* will be connected to the multicast tree from the *neighbour node*. When the *join node* receives this message it sends a INCREASING DEGREE message to the *neighbour node*.

- **DELETION NODE (leave node, neighbour)** : This message is sent when a destination node, *leave node*, leaves the “communication group”. The *leave node* is connected to the multicast tree from the *neighbour node*. When the *leave node* receives this message it sends a DECREASING DEGREE message to the *neighbour node*.

- **INCREASING DEGREE (node)** : This message is received by the *node* to count the number of destination nodes which are connected to the multicast tree from the *node*.

- **DECREASING DEGREE (node)** : This message is received by the *node* to count the number of destination nodes which are connected to the multicast tree from it. When the *node* is in NO-LEAF NO-CONNECTED state and receives this message it changes to DESTINATION NO-TREE state and sends a DECREASING DEGREE message to the *neighbour node*.

The following figures show state machine and transitions between the states if only direct routes are considered :

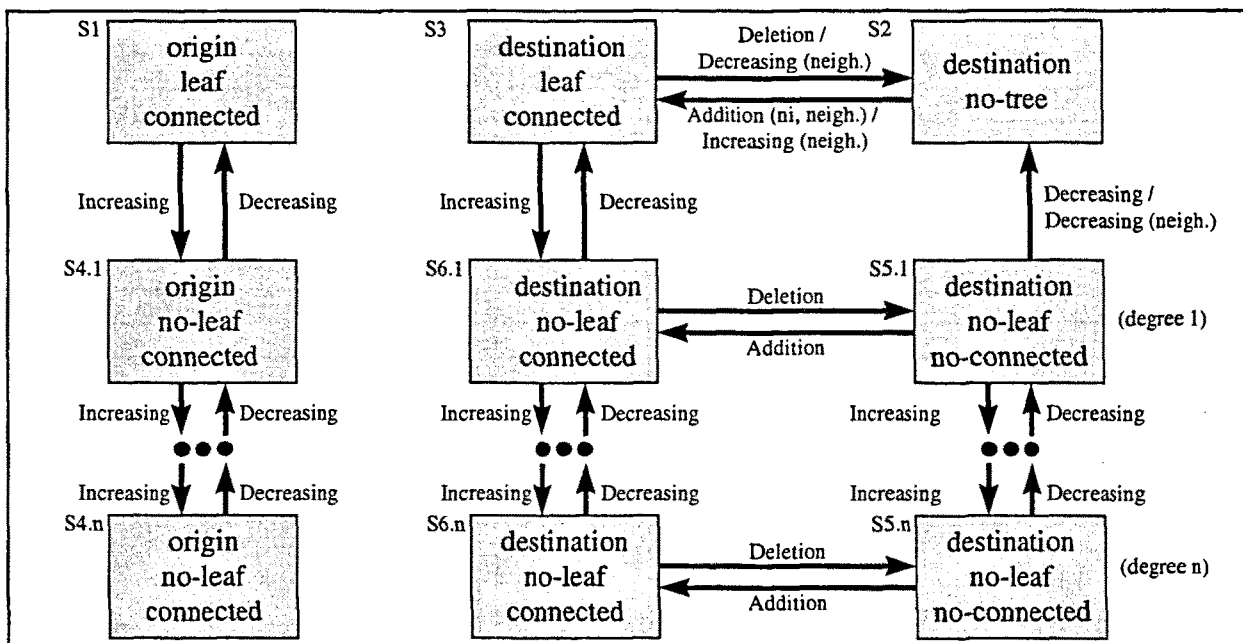
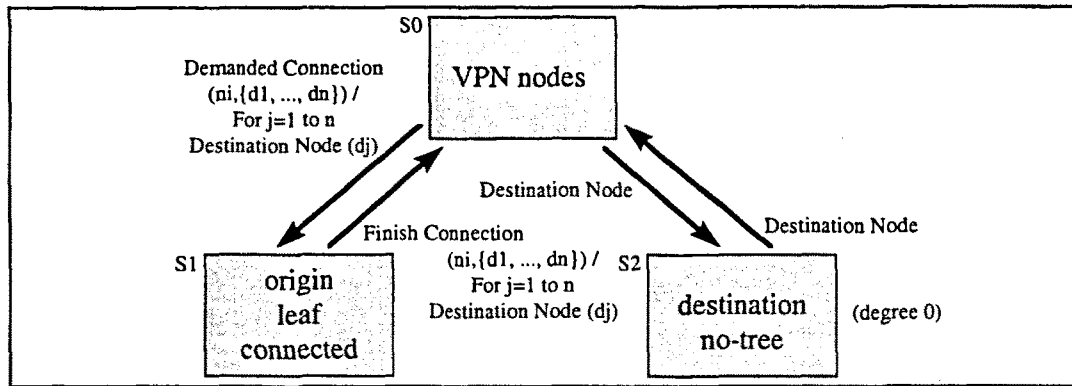


Fig. 51 : State machine of node i when Only Direct Routes are considered

Each arrow has two labels, the first is the message received by node i and the second is the message sent to specified node. To simplify the figure, the parameters ni and neighbour of the received message are omitted. To transit from state S2 to state S3 the neighbour is specified because the value is done in this message.

Example:

This example explains a dynamic point-to-multipoint VCC establishment if only direct routes are considered.

Origen Node : N1

Set of Destination Nodes : {N3, N5, N6}

Dynamic Destination Nodes : Add (N5), Add (N3), Add (N6), Deletion (N5), Deletion (N6), Deletion (N3)

ACTION	N1	N3	N5	N6	send MESSAGE to
	State/Neigh	State/Neigh	State/Neigh	State/Neigh	
Initially	S0 / ---	S0 / ---	S0 / ---	S0 / ---	
Demanded Connection (N1, {N3, N5, N6})	S1 / N.A.				Destination (N3) Destination (N5) Destination (N6)
Destination (N3)			S2 / ---		
Destination (N5)		S2 / ---			
Destination (N6)				S2 / ---	
Addition (N5, N1)			S3 / N1		Increasing (N1)*
Increasing (N1)	S41 / N.A.				
Addition (N3, N5)		S3 / N5			Increasing (N5)
Increasing (N5)			S61 / N1		
Addition (N6, N1)				S3 / N1	Increasing (N1)
Increasing (N1)	S42 / N.A.				
Deletion (N5)			S51 / N1		
Deletion (N6)				S2 / ---	Decreasing (N1)**
Decreasing (N1)	S41 / N.A.				
Deletion (N3)		S2 / ---			Decreasing (N5)
Decreasing (N5)			S2 / ---		Decreasing (N1)
Decreasing (N1)	S1 / N.A.				
Finish Connection (N1, {N3, N5, N6})	S0 / ---				Destination (N3) Destination (N5) Destination (N6)
Destination (N3)		S1 / ---			
Destination (N5)			S1 / ---		
Destination (N6)				S1 / ---	

Tabla 32 : Dynamic point-to-multipoint VCC establishment. Only direct routes.

(*) N5 is connect from N1
(**) The neighbour of N6 is N1

The following figures show the multicast tree evolution.

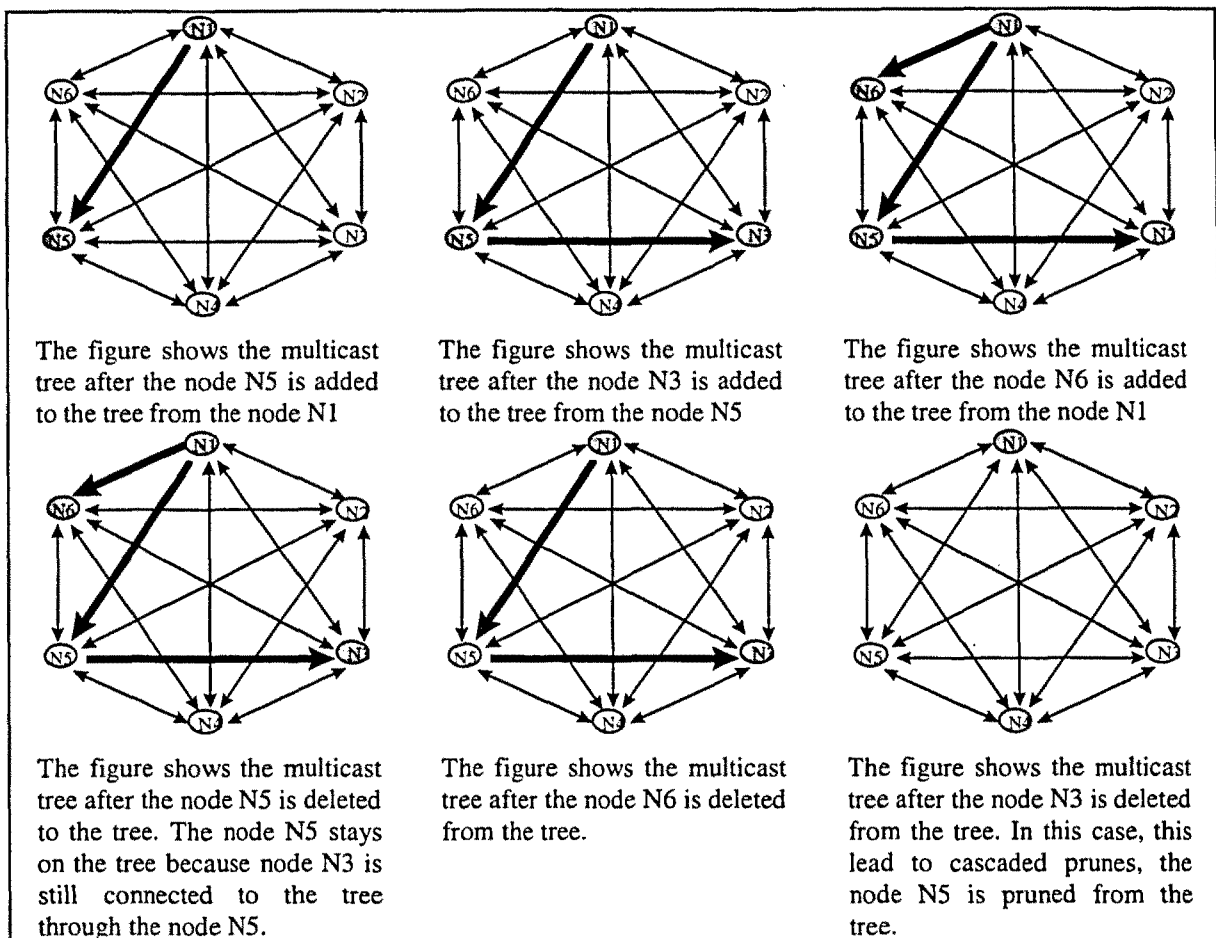


Fig. 52 : Multicast tree evolution

6.1.6 Finite state machine and messages types when alternative routes are considered

When alternative routes are possible, SPA-Tree-Alternative Routes solution, no-destination nodes could be on the tree. In this case, no-destination nodes are dealt with as no-connected nodes. In this case the following states are used:

- **NO-DESTINATION NO-TREE (S7).** The nodes of the VPN that do not pertain to the set of possible destination nodes enter this state when a point-to-multipoint VCC is demanded. In this state, no-destination nodes are not yet added to the multicast tree. A destination node stays in this state until it is joined to the multicast tree as a no-implicated node of an alternative route, or until the point to multipoint VCC is finished.

- **NO-DESTINATION TREE (S8.n)**. A no-destination node which is in **NO-DESTINATION NO-TREE** state enters in this state when a destination node is connected to the multicast tree using an alternative route that through it. N indicates the number of destination nodes that are connected to the multicast tree through this node. The only difference between **NO-DESTINATION TREE** state and the **NO-LEAF NO-CONNECTED** state is that the node is a no-destination node.

In the following table the characteristics of each state are explained:

STATE	STATUS				NEIGHBOUR
S7 :No-Destination No-Tree	No destination	No Tree			Unknown
S8 : No-Destination Tree (degree n)	No destination	Tree	No-Leaf	No-Connected	Known

Tabla 33 : State characteristics if only direct routes are considered

A new message is considered if alternative routes are possible:

- **NO-DESTINATION NODE (no destination node)**. This message is sent by the origin node to each one of the no-destination nodes when the origin node receives a **DEMANDED CONNECTION** message or a **FINISH CONNECTION** message.

Moreover, two messages are modified. The first message modified is the **ADDITION NODE** message, which has a new parameter with the transit node of the alternative route. The second message modified is the **DEMANDED CONNECTION** message which includes the set of no-destination nodes as a new parameter.

- **ADDITION ALTERNATIVE NODE (join node, tree node, alternative node)**. This message is sent when a destination node, *join node*, joins the "communication group". If the node is connect using a direct route, the *alternative node* parameter is empty and this message is treated as an **ADDITION NODE (join node, tree node)** message. If an alternative route is used to connect the join node from the multicast tree, the message includes the intermediate node of this alternative route and the node of the multicast tree from the join node will be connected. The *join node* will be connected to the multicast tree from the *tree node* using an alternative route through the *alternative node*. When the *join node* receives this message it sends an **INCREASING DEGREE (tree node)** message and an **INCREASING DEGREE (alternative node)** message.

- DEMANDED CONNECTION (origin node, {destination nodes}, {no-destination nodes})

New state transitions are also possible:

- A node in DESTINATION NO-TREE state changes to NO-LEAF NO-CONNECTED state if it receives an INCREASING DEGREE message. This (implicated) node is added to the tree because it is a transit node of the alternative route.
- Similarly, a node in NO-DESTINATION NO-TREE state changes to NO-DESTINATION TREE state if it receives an INCREASING DEGREE message. This (no-implicated or no-destination) node is added to the tree because it is a transit node of the alternative route.

The following figures show state machine and transitions between the states when alternative routes are considered :

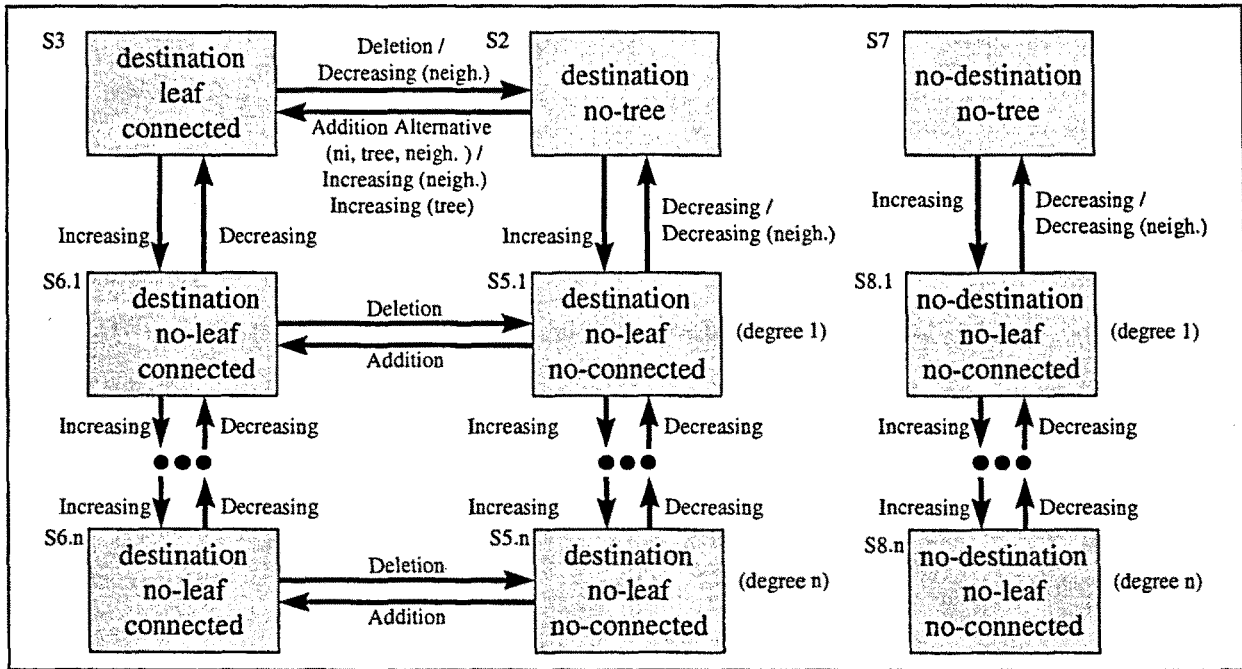


Fig. 53 : State machine of node *i* when Alternative Routes are considered

Each arrow has two labels, the first is the message received by node *i* and the second is the message sent to specified node. To simplify the figure, the parameters *ni* and neighbour of the received message are omitted. To transit from state S2 to state S3 the neighbour and the tree would be specified because the values are contained in this message.

Example:

This example explains a dynamic point-to-multipoint VCC establishment if alternative routes are considered.

Origin Node N1. Set of Destination Nodes {N3, N5, N6}. Set of No-Destination Node {N2, N4}.

Dynamic Destination Nodes: Add (N5), Add (N3), Add (N6), Deletion (N5), Deletion (N6), Deletion (N3).

ACTION	N1	N2	N3	N4	N5	N6	
	S0 / ---	S0 / ---	S0 / ---	S0 / ---	S0 / ---	S0 / ---	
Demanded Connection (N1, {N3, N5, N6}, {N2, N4})	S1/na						Destination (N3) Destination (N5) Destination (N6) No Destination (N2) No Destination (N4)
Destination (N3)			S2 / ---				
Destination (N5)					S2 / ---		
Destination (N6)						S2 / ---	
No Destination (N2)		S7 / ---					
No Destination (N4)				S7 / ---			
Addition (N5,N1)					S3/N1		Increasing (N1)
Increasing Degree (N1)	S41/na						
Addition (N3,N5)			S3/N5				Increasing (N5)
Increasing Degree (N5)					S61/N1		
Addition Alternative (N6,N1,N2)		--- / N2				S3/N1	Increasing (N1) Increasing (N2)
Increasing Degree (N1)	S42/na						
Increasing Degree (N2)		S81/N2					
Deletion (N5)					S51/N1		
Deletion (N6)						S2 / ---	Decreasing (N2)
Decreasing (N2)		S7 / ---					Decreasing (N1)
Decreasing (N1)	S41/na						
Deletion (N3)			S2 / ---				Decreasing (N5)
Decreasing (N5)					S2 / ---		Decreasing (N1)
Decreasing (N1)	S1 / ---						
Finish Connection (N1, {N3, N5, N6}, {N2, N4})	S0 / ---						Destination (N3) Destination (N5) Destination (N6) No Destination (N2) No Destination (N4)
Destination (N3)			S0 / ---				
Destination (N5)					S0 / ---		
Destination (N6)						S0 / ---	
No Destination (N2)		S0 / ---					
No Destination (N4)				S0 / ---			

Tabla 34 : Dynamic point-to-multipoint VCC establishment. Only direct routes.

The following figures show the multicast tree evolution.

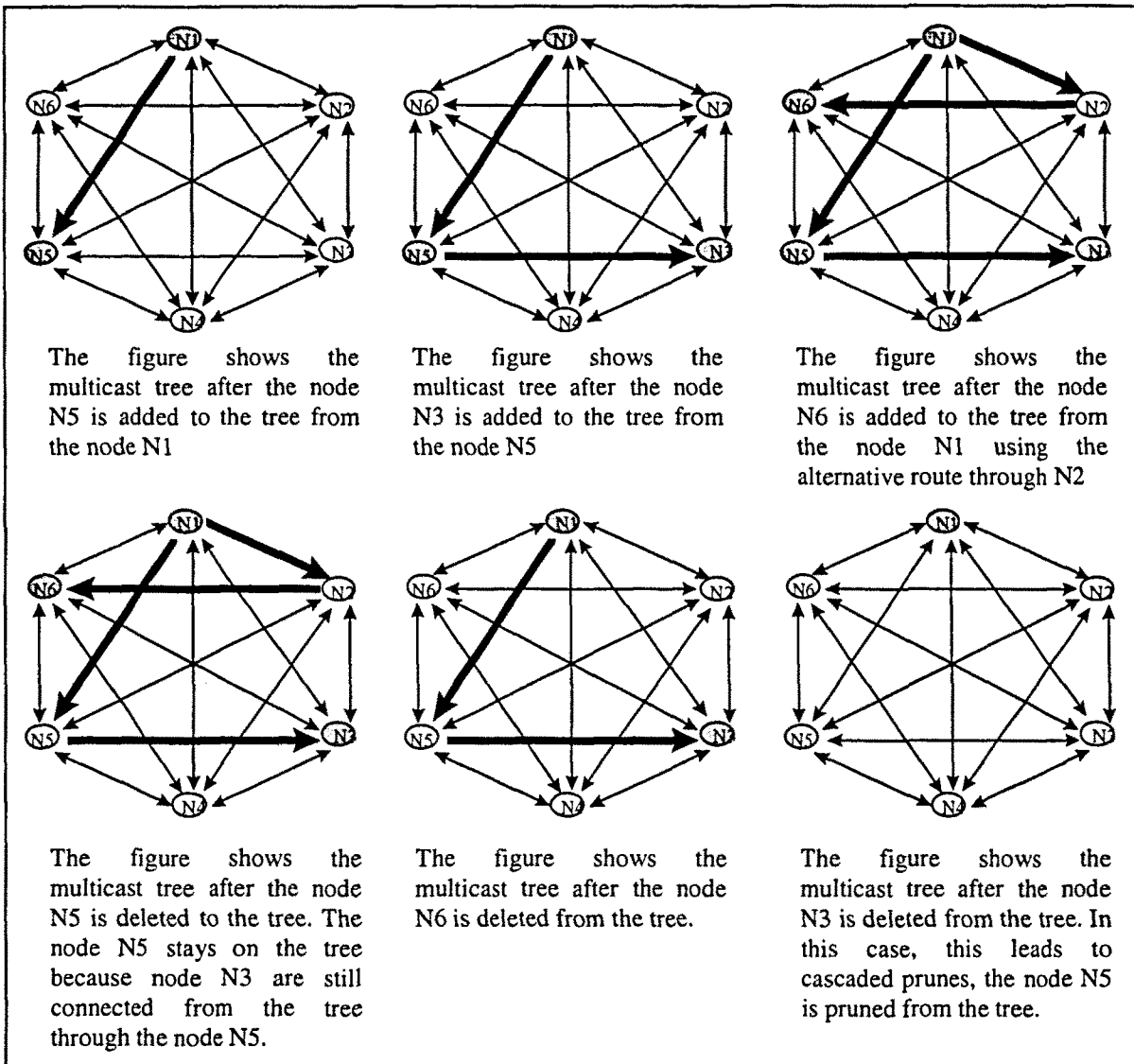


Fig. 54 : Multicast tree evolution

6.1.7 Static version

On the other hand, the static version of the multicast tree problem will be considered as a particular case of the dynamic version where the available identities of the destination nodes are revealed one by one in a random order. In this case, the solution obtained is not optimal. Different solutions are obtained depending on the order in which the nodes are added. The order in which nodes are added is a way of improving results. The optimal solution could be obtained if all possible orders are considered and the best solution can be selected.

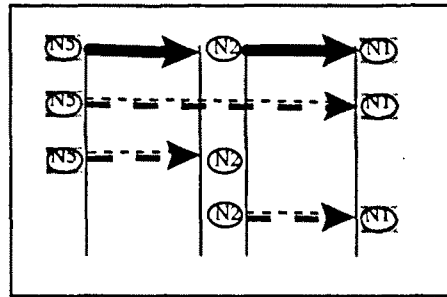


Fig. 56 : Types of routes

Given two nodes on a ring, an arc is defined as the portion of the ring connecting these nodes without passing through membership nodes. Note that if alternative routes through non-implicated node are considered, there will be no-membership nodes in the ring and in the arc. Moreover, an arc could be divided into sub-arcs (for simplicity, also called arcs), if their length is two or more. With nodes N5 and N1 completed, the figure shows the different arcs {Arc51, Arc52 and Arc21} that could be defined.

Different Ring algorithms are proposed depending on the type and the precedence of the route or the arc that could be replaced and the type and the precedence of routes that can be added to ring.

6.2.1 A route of the ring is replaced only with direct routes.

In this case, only direct routes are permitted to connect the new node with the ring. In this case, a single solution is available to build up the ring to connect the two initial nodes.

EXAMPLE : Ring solution- Only Direct Routes

Origin and Destination Nodes: N1, N5, N3, N6

From N1 to N5 and N5 to N1:

a) Direct = {R15}+{R51}. This is a single solution.

Two insertion routes, R135 and R531, are possible to add N3 to the ring formed by {R15 + R51}.

aa) $\{-R15 + R13 + R35 + R51\} = \{R13 + R35 + R51\}$

ab) $\{R15 - R51 + R53 + R31\} = \{R15 + R53 + R31\}$

If the R15 has been replaced in the previous step, three insertion routes are available to add N6 to the ring formed by {R13 + R35 + R51},

aaa) $\{-R13 + R16 + R63 + R35 + R51\} = \{R16 + R63 + R35 + R51\}$

aab) $\{R13 - R35 + R36 + R65 + R51\} = \{R13 + R36 + R65 + R51\}$

aac) $\{R13 + R35 - R51 + R56 + R61\} = \{R13 + R35 + R56 + R61\}$

If the R51 has been replaced, the insertion routes to add N6 to the ring formed by {R15 + R53 + R31} are:

aba) $\{-R15 + R16 + R65 + R53 + R31\} = \{R16 + R65 + R53 + R31\}$

abb) $\{R15 - R53 + R56 + R63 + R31\} = \{R15 + R56 + R63 + R31\}$

abc) $\{R15 + R53 - R31 + R36 + R61\} = \{R15 + R53 + R36 + R61\}$

Previous figures show the process to connect N6 to the ring {R13 + R35 + R51} whenever the solution aaa) is selected. In this case, the route R13 is replaced by the routes R16 and R63 and the final ring is {R16 + R63 + R35 + R51}

Tabla 35 : Ring solution- Only Direct Routes

6.2.2 A route of the ring is replaced with alternative routes.

In this case, direct and alternative routes are permitted to connect the new node with the ring. Different algorithms are proposed varying the precedence of the alternative routes through an implicated node in relation with direct routes: after direct routes and before direct routes.

Algorithm	Precedence		
	(first)	—————→	(last)
after direct routes	Direct Routes from the ring	Alternative Routes through an Implicated Node	Alternative Routes
before direct routes	Alternative Routes through an Implicated Node	Direct Routes from the ring	Alternative Routes

Tabla 36 : Ring algorithms using Alternative Routes.

In this case, several solutions to build up the first ring connecting the two initial nodes are considered.

EXAMPLE : Ring solution- Alternative Routes through an implicated node after direct routes

Origin and Destination Nodes: N1, N5, N3, N6

From N1 to N5:

Direct = {R15}
 Implicated = {R135} and {R165}
 Alternative = {R125} and {R145}

From N5 to N1:

Direct = {R51}
 Implicated = {R531} and {R561}
 Alternative = {R521} and {R541}
 (continue in the following table ...)

Tabla 37 : Ring solution- Alternative Routes through an implicated node after direct routes

This figure shows the obtained ring if the implicated route {R135} from N1 to N5 and the alternative route {R521} from N5 to N1 are selected.

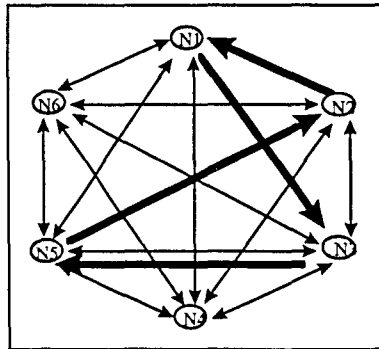


Fig. 57 : Ring obtained to connect N1 and N5

To add the next node to the ring, a route is replaced by two routes. Depending upon the criterion used for selecting the routes to be replaced, the set and the precedence of routes, different algorithms are proposed. Note that an alternative route through implicated node is considered as a concatenation of direct routes.

Solution	Precedence of routes to be replaced	
	(first)	(last)
first direct routes	Direct Routes from the ring	Alternative Routes
first alternative routes	Alternative Routes	Direct Routes from the ring
all routes	Direct Routes and Alternative Routes are simultaneously considered.	

Tabla 38 : Ring algorithms using Alternative Routes depending on precedence of routes to be replaced

As mentioned above, the added routes could be of different types,

(... continuation of the EXAMPLE)

Add N3 to ring $(N1, N5) = \{R13 + R35 + R521\}$.
The node N3 is already in the ring.

Add N6 to ring $(N1, N5, N1) = \{R13 + R35 + R521\}$.

Routes to be replace :

First **direct** routes = $\{R13, R35\} + \{R521\}$

First **alternative** routes = $\{R521\} + \{R13, R35\}$

All routes = $\{R13, R35, R521\}$

Each route could be replaced by different pair of routes, e.g., the set of possible routes to replace the route R13 are:

Direct-Direct : $\{-R13 + R16 + R63\}$

Direct-Implicated : there are not implicated nodes

Direct-Alternative : $\{-R13 + R16 + R643\}$

Alternative-Direct : $\{-R13 + R146 + R63\}$

Alternative-Implicated : there are not implicated nodes

Alternative-Alternative : $\{-R13 + R146 + R641\}$ (*)

(*) This solution is not available because the ring passes twice times through the node N4.

The following figures show the process of adding the node N6 to the ring. The route R13 is replaced by R16 and R63.

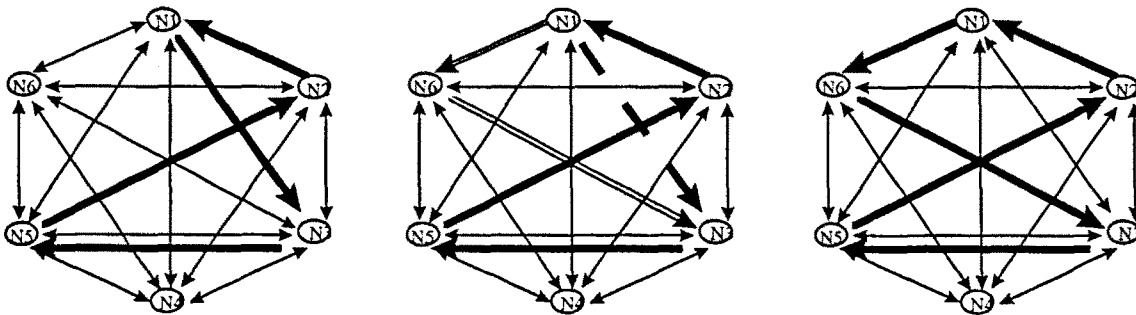


Tabla 39 : Ring solution- Alternative Routes through an implicated node after direct routes (continuation)

6.2.3 Ring Solution - An arc of the ring is replaced with alternative routes.

In this case, direct and alternative routes are allowed to connect the new node with the ring and the portion of the ring replaced could be an arc.

6.2.4 Static version

As on the static version of the tree solution, the static version of the ring problem will be considered as a particular case of the dynamic version where the available identities of the destination nodes are revealed one by one in a random order.

6.3 SUMMARY

In this chapter the Congestion Probability Routing algorithm is extended to dynamic multipoint connections. Algorithms with constrained end-to-end cell loss probability are introduced. Different tree solutions are proposed varying the precedence of the considered routes and depending on the QoS requirements guaranteed in each route. Ring solutions are based on the precedence of the route selected to be replaced when a new node is added to the ring. The objective of all algorithms proposed is to find a good compromise between the efficiency of the obtained graph (tree or ring) and the dynamic of the group.

7. Conclusions and future research

The main focus of this dissertation has been to provide an adaptive connection routing scheme with alternative routing in fully connected VP-based ATM networks. We assume a semi-permanent VPN topology that can be updated periodically if changing traffic demands make it necessary.

By providing alternative routes, the direct route would be able to achieve lower Call Blocking Probability (CBP) and higher network throughput. However, the use of alternative routes entails the utilization of other VPs and, therefore, a reduction of their capacity and an increasing of their blocking probabilities. VP congestion can occur at any VP along the route and more stringent QoS requirements must be considered. Therefore, the CBP increases, because connections that could be accepted on these VPs along a direct route are rejected with the new QoS requirements.

The principal characteristics of the Congestion Probability Routing (CPR) algorithm are that Congestion Probability (CP) is the metric parameter of the VP cost function and that a threshold of the Congestion Probability of the VP is defined, the Routing Control Parameter (RCP). This single metric, the CP, models the characteristics of the network accurately, because it mixes the CLP of the current VCCs and the residual bandwidth that is available for the new VCC. The protective mechanism determines the set of available alternative routes and it inhibits alternative routing when the VP becomes too loaded. Therefore, it increases the probability that direct calls are set up.

Experimental results show that better performance may be achieved by using *alternative policies* when the traffic load is light or medium. However, with heavy traffic loads, the *direct policy* performs better. Using alternative routes does not always decrease the network call blocking probability (NCBP). The RCP despite this drawback. The utilization of RCP varies the performance of the CDC traffic depending on the route selected. The CBP of traffic carried by an alternative route increases when the RCP is used, but the traffic carried by the direct route is insensitive to the use of alternative policies. Moreover, the RCP prevents the network from excessive blocking when the *alternative policies* are considered. Moreover, the influence

of the protection mechanism in the network performance is more than the composition rule of the alternative route cost and the selection alternative route scheme.

New applications – such as audio and video conferencing, replicated database updating, distributed resource discovery and shared workspaces - involve data delivery from multiple sources to multiple destinations, all members of the same “communication group”. For some applications, the multicast group cannot be determined a priori because the group membership changes during the course of the multipoint session. If designing an optimal tree is a complex problem, maintaining this tree optimality after changes in the membership group may be even more so. The optimal solution obtained is only ephemeral, due to the dynamic nature of multipoint applications. Consequently the challenge is to find a good compromise between the efficiency of the obtained tree and the dynamic of the group.

In this dissertation some consideration about how the Congestion Probability Routing (CPR) algorithm can be extended to routing dynamic multipoint connections are explained. Algorithms with constrained end-to-end cell loss probability are introduced. Different tree solutions are proposed varying the precedence of the considered routes and depending on the QoS requirements guaranteed in each route. Ring solutions are based on the precedence of the route selected to be replaced when a new node is added to the ring.

7.1 FUTURE RESEARCH

7.1.1 Enhanced VP cost functions

The Congestion Probability (CP) as VP cost function reflects the characteristics of current network load, but others metrics can certainly model some characteristics of the network more accurately. An ideal routing policy would take into account other traffic descriptors (call arrival rate and average holding time of calls) to have a better prediction of future bandwidth requirements and a more complex model of the network. Hence, the arrival rates and the call holding time information should also be considered in the VP cost function. A narrow-band call could occupy network resources, however small, for relatively longer periods of time (if the holding time is high) resulting in a possible increase in the number of blocked calls.

In all the routing algorithms discussed in this dissertation, only the Congestion Probability (CP) over the link is used as metric cost, but the information of arrival rates and mean call holding times are ignored in VP cost function. In future research, these parameters are also considered.

Therefore, two mixed metrics of the VP cost function will be proposed: Future Bandwidth requirements and Past Behaviour. In Future Bandwidth VP cost function, other traffic descriptors - call arrival rate (CAR), average holding time (AHT) and demanded bandwidth (DB) - are taken into account to make a better prediction of future bandwidth requirements and a more complex model of the network. In Past Behaviour VP cost function, the CBP will be considered to reflect the past behaviour of the routing algorithms.

7.1.2 Dynamic Routing Control Parameter

The call arrival rate and the holding time could be used to active or deactivate the RCP. Moreover, the obtained NCBP and CBP could also be used to determinate dynamically the Routing Control Parameter used in Congestion Probability Routing,

As has been explained in this dissertation, to prevent the network from excessive overflow, a protection mechanism has been considered. The amount of resources reserved (in this case Congestion Probability) for direct traffic will be set periodically based on the blocking of some VCC. The CBP will determine dynamically the value of the RCP used in Congestion Probability Routing algorithms.

Similar dynamic threshold (Dynamic Trunk Reservation) which is taken from [ASH91] and has been discussed in [DAV95] and [MED97c] is used in [SUK96]

7.1.3 Alternative route selection scheme

The obtained NCBP and CBP could also be used as a parameter of the alternative route selection scheme. In RallCPR (RavaiCPR) schemes, all (available) alternative routes have the same probability. A possible variation of the RavaiCPR scheme is to assign the probability of alternative routes depending on the CBP. The crucial step in this method is the dynamic adjusting of the path selection probabilities. If a VCC is accepted through an alternative route, then the CBP decreases and the probability of selecting that particular alternative route may be increased, while the probability of selecting that particular alternative route has decreased if the VCC is rejected. It is noted that a change in the probability of a selected path causes the probabilities of available alternative routes to change so that the sum of the probabilities over all available alternative routes connecting origin and destination nodes is equal to one.

7.1.4 Dymanic Multipoint CPR performance evaluation

Although the objective of this dissertation is explain how the Congestion Probability Routing (CPR) algorithm can be extended to routing dynamic multipoint connections, to

evaluate the performance of Dynamic Multipoint CPR algorithm is also an area of future research. In appendix simple simulations are shown.

7.1.5 Routing Protocol

To propose signalling protocols to provide support for multipoint routing algorithms will be useful area for research in the near future. In this dissertation, we are explain that, for efficient usage of resources and simplicity of connection management, it is desirable that the same multicast tree is shared by all the senders. In such cases, there is a one to one correspondence between the multicast group identifier and the connection identifier that specifies the multipoint to multipoint connection. The sender identification problem occurs when multiple senders send data to a multipoint connection using the same connection identifier. If the ATM cells from different senders are interleaved on any link, the receiver will not be able to uniquely identify the sender of the ATM cell, unless the sender information is included as part of the header. The problem is addressed and several solutions have been explained in [VEN97th].

8. Appendix

8.1 MULTIPOINT PERFORMANCE EVALUATION

In this appendix single simulations of multipoint connections are presented. In this case, we have to model the point to multipoint connections. A Multipoint Connection Demand Class (MCDC) is composed by a set of CDCs and it is characterised by the interarrival time and the expected duration of the multipoint connection (holding time). The point to point connections (CDC) has previously been defined in this dissertation.

We consider that all destination nodes of a multipoint connection demand join and leave the multicast tree and the same time and that they have identical QoS requirements.

The following table show the definition of two CDC and one MCDC.

<pre> CDC { id: 1 origen: 1 desti: 3 font: 1 Inter arrival: ExponNeg 0.1 0 Holding time: ExponNeg 10 0 Temps inici: 0 Temps fi: 1e5 Time out: 10 QoS: 1.0e-5 Numero de rutes: 1 { ruta: 12,prior: 0,actiu: 1,qos: 1 } } </pre>	<pre> CDC { id: 31 origen: 1 desti: 2 font: 1 Inter arrival: ExponNeg 0.1 0 Holding time: ExponNeg 10 0 Temps inici: 0 Temps fi: 1e5 Time out: 10 QoS: 1.0e-5 Numero de rutes: 5 { ruta: 12,prior: 0,actiu: 1,qos: 1 } { ruta: 132,prior: 1,actiu: 1,qos: 1 } { ruta: 142,prior: 1,actiu: 1,qos: 1 } { ruta: 152,prior: 1,actiu: 1,qos: 1 } { ruta: 162,prior: 1,actiu: 1,qos: 1 } } </pre>	<pre> MCDC { id: 1 origen: 1 font: 1 Inter arrival: ExponNeg 0.3 0 Holding time: ExponNeg 10 0 Temps inici: 0 Temps fi: 1e5 Time out: 10 QoS: 1.0e-5 Metode connexio: Naive Metode acceptacio: Atomic Numero de CDC: 3 Fifo { CDC: 1,inici: General ,fi: General } { CDC: 31,inici: General ,fi: General } } </pre>
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Tabla 40 : CDC and MCDC definition

The set of considered Connection Demand Class (CDC) and Multipoint Connection Demand Class (MCDC) are shown in the following tables. The set of possible available routes and the interarrival time are also provided.

CDC(id) by id = 1, ..., 30 are used to load the Virtual Network Links. In this case, only direct route from source to destination node is considered. CDC(id) by id = 31, ..., 42 are used in the MCDC. In this case alternative routes through the other nodes of the network are considered.

Connection Demand Class :CDC	Source	Destination	Routes	Interarrival time
CDC (id) ; id = 1, ..., 30	$s \forall s = 1, \dots, 6$	$\forall d = 1, \dots, 6 ; d \neq s$	Route (s,d) *	0.1
CDC (id) ; id = 31, ..., 42	$\forall s = 1, \dots, 4$	$\forall d = 1, \dots, 4 ; d \neq s$	Route (s,d) $d \neq s$ Route (s,i,d) $d \neq s$ and $i \neq s$ **	0.1

Tabla 41 : Definition characteristics of CDCs

(*)Only direct route is considered.

(**) Direct routes and alternative routes are considered.

Multipoint Connection Demand Class : MCDC	Source	CDCs	Destinations *	Interarrival time
MCDC (1)	1	{31, 32, 33}	{2, 3, 4}	λ_1
MCDC (2)	2	{34, 35, 36}	{1, 3, 4}	λ_2
MCDC (3)	3	{37, 38, 39}	{1, 2, 4}	λ_3
MCDC (4)	4	{40, 41, 42}	{1, 2, 3}	λ_4

Tabla 42 : Definition characteristics of CDCs

(*) The set of destinations nodes is determined by the set of CDCs.

In this section the performance of the different algorithms is studied through simulations on a 6-node fully connected VP network under variable traffic conditions. Only homogeneous traffic is considered. Two classes of traffic patterns are studied to compare the performance of these multipoint routing algorithms :

- **ONLY MCDC :** There are only MCDC. Point-to-Multipoint traffic contributes all the network traffic. Point-to-point traffic -CDC (id) $\forall id = 1, \dots, 30$ -, is not considered.
- **UNIFORM POINT TO POINT TRAFFIC :** All the Virtual Network Links has the same background load. Uniform point-to-point traffic, -CDC (id) $\forall id = 1, \dots, 30$ -, is considered.

Experiment A-1: Only MCDC

In these experiments all the traffic considered is generated by MCDC(1), ..., MCDC(4). The interarrival time of MCDCs is = 0.1. The following table shows the Call Blocking Probability (CBP = rejected MCDC / demanded MCDC) of different MCDC. A MCDC is accepted if all implicated CDC are accepted.

CBP (MCDC)	naive	onlydirect	after	between	before
RCP=1	0,40175948	0,64637555	0,3875816	0,40953488	0,45862639
RCP=1e-6	0,45252835	0,64433239	0,41378164	0,41514925	0,41304457

Tabla 43 : Numerical results of experiment A-1

Experiment A-2: Uniform point to point traffic

In this experiment the traffic considered is generated by Uniform point to point CDC(1), ..., CDC(30) and MCDC(1), ..., MCDC(4). The interarrival time of MCDC is = 0.1. The following table shows the Call Blocking Probability (CBP = rejected CDC / demanded CDC) of different CDC and the Call Blocking Probability of MCDC. A MCDC is accepted if all implicated CDC are accepted. It also shows the Network Call Blocking Probability (NCBP). In this case, a MCDC is count as 3 CDC.

RCP=1	naive	onlydirect	after	between	before
CBP (1-30)	0,65922108	0,67924936	0,71056477	0,69495538	0,71309052
CBP (MCDC)	0,93525915	0,85797569	0,61797154	0,61955053	0,63745366
NCBP	0,72150924	0,71691329	0,68273306	0,68447021	0,70218336

Tabla 44 : Numerical results of experiment A-1

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