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Survivability in ATM networks

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SURVIVABILITY IN ATM NETWORKS

By
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A project
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Guangyan Ma

Abstract

Survivability in ATM Networks

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In ATM network design, self-healing is the ability of the network to continue to provide service in the event of failures, and this comprises both *planning* and *operational* aspects. The planning aspect involves optimal/near-optimal network design problems while the operational aspect deals with the implementation of protection schemes using restoration mechanisms, for allocating spare capacity to the network to be used in case of a failure event[1]. This project investigates the survivability (i.e. restoration ratio) - here defined by means of the *aggregate restoration ratio* - in existing ATM networks based on various spare capacity distribution schemes, with the goal to (1) compare the network survivability for link and path restorations, and (2) determine the effects of various traffic and design related patterns on the restoration ratio.

[1] A failure event means a single link or node failure scenario at a time. It should be noticed that a node failure is equivalent to simultaneous failures of all links connected to the node, and link failure scenarios are not necessary regarded as special instances of node failure scenarios.

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List of Abbreviations

ATM	Asynchronous Transfer Mode
LB-ISDN	Large Broadband-Integrated Services Digital Networks
SONET	Synchronous Optical network
SDH	Synchronous Digital Hierarchy
IP	Internet Protocol
DWDM	Dense Wavelength Division Multiplexing
GMPLS	Generalized Multi-Protocol Label Switching
ADM	Add Drop Multiplexers
DCS	Digital Cross-Connects
PDH	Plesio-Synchronous Digital Hierarchy
CFA Problem	Capacity allocation and Flow Assignment Problem in Self-Healing ATM networks
CFA-OND Problems	Optimal/Near-Optimal Network Design Problems
CFA-NS Problem	Network Survivability Problem (or equivalently Network Reliability Evaluation)
VP	Virtual Path
BVP	Backup Virtual Path
VC	Virtual Circuit
SCR	Spare Capacity Requirement
SCD	Spare Capacity Distribution
VPee	Virtual Paths End-to-End
CVP	Concatenated Virtual Paths
VN	Virtual Network
PN	Physical Network
LN	Logical Network
VCI	Virtual Circuit Identifier (Virtual Channel Identifier)
VNI	Virtual Network Identifier
VPI	Virtual Path Identifier

QoS	Quality of Service
GoS	Grade of Service
ND	Non-Uniform Traffic Demands
UD	Uniform Traffic Demands
APP	All Possible Paths between node pairs
LDP	Link Disjoint Paths between node pairs
SI	State Independent
SD	State Dependent
LR	Link Restoration
PR	Path Restoration
LF	Link Failure Scenario
NF	Node Failure Scenario
LP	Linear Programming
MCR	Minimum Cost Route

Chapter 1 Introduction

1.1 Motivation

In the current overlay transport networks, IP/ATM/SONET/DWDM, each layer manages its own control plane, each control plane acting independently of what happens in the other. In the course of the recent years, the Generalized Multi-Protocol Label Switching (GMPLS) has emerged as the new unified control plane for all the above transport layers. As such, the already installed ATM core self-management features must be reused as a particular implementation of GMPLS, either directly or with some adaptation.

Among such transferable research works are studies related to the problem of Capacity allocation and Flow Assignment in self-healing ATM networks (*CFA problem*). This problem has been intensively investigated using two main design approaches: the path-based design approach (also referred-to as the Virtual Paths End-to-End (VPee) approach) and the link-based design approach. In the VPee approach, the focus in all proposed solutions has been to determine the optimal spare capacity and backup virtual paths (BVPs) allocation for all traffic flows. The CFA problem can be separated as two major interconnected sub-problems: (1) the optimal/near optimal network design problems (*CFA-OND problems*), and (2) the network survivability problem (*CFA-NS problem*) –also referred to as the *network reliability evaluation.*

This project contributes to the CFA-NS problem. By carrying on the work initiated in [1], we continue the investigation of the survivability in existing ATM networks. Here, the survivability (restoration ratio) is determined by means of the *aggregate restoration ratio* rather than being defined by the average restoration ratio as done in [1]. In addition to comparing the network survivability for link and path restorations, we also quantify the effect of various traffics and design related patterns on the network survivability using the path restoration scheme and predefined spare capacity distribution methods.

1.2 Background

The reliability of networks is a key challenge to the research community [2]. To cope with this issue, network architects and planners have resorted to the construction of self-healing networks, i.e., a network in which a restoration procedure is setup to quickly and automatically respond to network failures (single link or node failure), by reconfiguring connections using spare capacity which has been installed in advance for such contingencies [1], [3], [4].

Technologies and techniques that have been employed to provide reliable communications include: physical diversity, facility duplication and switching on a hot stand-by basis using add drop multiplexers (ADMs), digital cross-connects (DCSs) in the plesio-synchronous digital hierarchy (PDH), synchronous networks (SONET) and synchronous digital hierarchy (SDH) cross-connects, transmission systems deployed in self-healing rings or mesh networks, ATM switching systems, alternate and dynamic routing at the traffic layer, and more recently, GMPLS. These technologies and techniques can be employed to provide a self-healing capability in networks dimensioned according to either the path-based design approach [1] or the link-based design approach [5], [6]. In the path-based design approach, a complete mesh of virtual paths (VPs) is established among origin and destination nodes and a single path supports all traffic between endpoints, thus, the network is vulnerable to link or node failure, and thus, mandates the need for a spare network and restoration procedures to be invoked when a failure event occurs. In the link-based design approach, VPs are also defined end-to-end, but the bandwidth is managed on a virtual link basis [6]. The provision of the self-healing capability in the physical network also depends on the restoration schemes and the type of reconfiguration methods used in the network.

There are two types of restoration schemes: (1) reactive restoration schemes, where the search for spare capacity starts after a failure occurs, by broadcasting restoration messages, and (2) preplanned restoration schemes, where all restoration routes are pre-computed by for instance the network management centre, for given failure scenarios. In case of failure, a node responsible for restoring affected traffic knows exactly where to find the required spare capacity. Two types of reconfiguration schemes exist: (1) failure-oriented reconfiguration, where only the affected working VPs are rerouted upon failure of a link or node in the physical network, and (2) global reconfiguration, where the whole layout of working VPs (affected and non-affected) may be re-arranged to avoid a failed link or node. In addition, a restoration mechanism is categorized either as a link-based restoration (i.e., only the two nodes connected to the failed link are involved in the restoration process) or as a path-based restoration (i.e., the two endpoints of each failed working VP are involved in the restoration process). The problem of capacity allocation and flow assignment in self-healing mesh-type networks (our so-called CFA-OND problem) was studied in [7], [8], [9] for link-based restoration, and in [10], [11], for global reconfiguration and path-based restoration. Using the multi-commodity flow model, papers [8], [9], [12], formulated the problem as a linear programming problem. The algorithms described there give optimal solutions for the spare capacity allocation. However, the corresponding optimal flow assignments are only available in [9] and [12], not in [8]. Node failure scenarios and hop-limit constraints are also considered in [5], [9]. A practical and near-optimal algorithm was developed in [7] for spare capacity allocation, which uses k-shortest link disjoint paths for traffic rerouting. The above problem was studied in [11] as a non-simultaneous multi-commodity flow model. An efficient sub-optimal solution procedure was presented which is suitable for large-scale networks, but as in [8], no flow assignment was provided. In [10], the authors formulated the same problem as a mixed integer linear programming. Their upper and lower bounding techniques can only be applied to small and moderate-scale networks.

Unlike previous work reported, the path-based design approach presented in [1][6] focused mainly on failure-oriented restoration and state-dependent backup VP scheme [13], [14]. Our so-called CFA-NS problem was also studied in [1], using the average restoration ratio to define the network survivability. Because our work is a continuation of the study of the CFA-NS problem initiated in [1], we will use the same path restoration-based formulation of the CFA-NS problem presented in [1]. Based on the optimal solution to be obtained from this LP formulation, we will investigate the network survivability (defined here as the aggregate restoration ratio) for link and path restorations, under various traffic and design related patterns, using the following spare capacity design (SCD) schemes, which in turn, determine different ways of distributing the spare capacity in the network:

- SCD_1: Each arc has the same spare capacity.
- SCD_2: Each arc has the same spare capacity cost.
- SCD_3: The spare capacity on each arc is proportional to the working capacity on that arc.
- SCD_4: The spare capacity on each arc is inversely proportional to the working capacity on that arc.

The mathematical meanings of these SCD methods are given in Chapter 3. We also use spare optimization, single link or node failure scenario, state-dependent (SD) path restoration, and we assume 100% restoration for the predefined failure scenario.

1.3 Organization

The project is organized as follows.

Chapter 1 introduces the network survivability problem studied in this project.

Chapter 2 provides an overview of network design concepts, including the VPee design approach to ATM networks, which defines the scope of this project. The so-called optimal/near optimal design problems (CFA-OND problems) are introduced, as along with related design considerations inherited from [1]. This chapter constitutes the foundation of the work carried in this project.

Chapter 3 is the heart of this project. We describe our contribution to the CFA-NS problem. In addition to the work initiated in [1], we investigate the network survivability (i.e. restoration ratio) - here defined by means of the *aggregate restoration ratio* - for link and path restorations, under various traffic patterns and design considerations, based upon the chosen spare capacity distribution (SCD) scheme. More precisely, (1) we compare the network survivability for link and path restorations, and we determine: (2) the effect of the choice of candidate paths (All Possible Paths versus Link Disjoint Paths) on the restoration ratio, (3) the effect of restoration schemes (link restoration versus path restoration) on the restoration ratio, (4) the effect of the network connectivity (sparse versus dense networks) on the restoration ratio, (5) the effect of failure scenarios (single link versus single node failure) on the restoration ratio, and (6) the effect of SCD schemes on the restoration ratio.

Chapter 4 concludes this project and provides further research avenues.

Chapter 2 Overview of Network Design Concepts and Approaches

2.1 Introduction

A network consists of two or more computers (nodes) that are linked in order to share resources (printers, files, etc), exchange files, or allow electronic communications. The nodes on a network may be linked through cables, telephone lines, radio waves, satellites, infrared light beams, etc.

Without security considerations, a network design is an iterative process which can be thought as comprising the following steps: (1) *Network planning process* – which deals with how the network and its services will operate, as well as the economic information concerning the cost, and technical details on the network's capabilities, (2) *Topological design* - which involves determining where to place the nodes and how to connect them, (3) *Network synthesis* - which deals with determining the size of nodes in the network based on predefined performance criteria, then using this information to determine the routing process to be adopted, (4) *Network realization* - which involves determining how to meet capacity requirements while ensuring an acceptable level of QoS requirement, and (5) *Network operations and maintenance* - which deal with how the network will run on a day-to-day basis.

Among these steps, the network synthesis one is a biggest chunk of work, which involves: (1) *the routing and dimensioning* processes, and (2) the *network survivability* process. The routing process deals with determining a suitable method for selecting the paths in the network along which the network traffic will be send. The dimensioning process involves determining the network topology, routing plan, traffic demands matrix, and GoS requirement, then using this information to develop a model that accurately simulates the behavior of the network equipment and routing protocols used. These inter-dependant processes can be realized either separately or in an *integrated* fashion.

Based upon the above optimal routing and dimensioning processes, the network survivability (also termed as *network reliability*) is a process that enables the network to maintain a maximum connectivity and QoS under failure events (i.e., a single link or node failure at a time). Since this process involves setting some design requirements on the network topology, protocol, bandwidth allocation, etc, it becomes evident that it should be linked to the routing and dimensioning sub-processes. This project adopts the aforementioned integrated option. Based on this, an overview of existing ATM network designs with self-healing capability is already provided in Chapter 1.

Our focus in this Chapter is on introducing the context of our work, by providing relevant network design concepts, including those inherited from [1], which are necessary for the understanding of the problem investigated in this project.

2.2 Circuit-Switched Versus Packet-Switched Networks

In the past, most communication systems were built using direct and dedicated links, which are established when two users request a line in order to communicate with each other. However, due to the advent of new applications with diverse and increasing bandwidth requirements, this traditional system was no longer appropriate in many contexts [15]. As a result, two switching techniques were developed in response to these more complex networks: circuit switching and packet switching.

Circuit-switched connections are direct physical connections between two physical devices. A circuit switch is a device with *n* inputs and *m* outputs that create temporary links between two devices. When a connection is requested, a fixed capacity to the pathway is allocated between the two devices. Allocated bandwidth is, therefore, dedicated to the link until the connection between the two devices is terminated. A downfall to this approach is that the bandwidth cannot be shared among other links even if there is no data being sent through the pathway. On the other hand, non-voice data tends to be sent in spurts with idle gaps, thus, circuit-switched networks are less suited for data communication since network resources would be wasted. Another disadvantage of a circuit-switched network is its inflexibility since there is only one path established between two devices, and all transmission takes place through that path whether or not it is the most efficient available.

Packet-switched networks were developed to handle burst data transmission, which is something circuit-switched networks had difficulty to deal with. This type of network divides traffic into standardized packets, which are sent through the network via routers and switches, which in turns sort and direct all traffic in the network. Packet-switched networks use two major types of routing approaches: the datagram approach and the virtual circuit (VC) approach. In the datagram approach, the desired traffic to be sent through the network is segmented in multiple packets and transmitted through the network. One of the advantages to this approach is that each packet in a data transmission is treated independently to one another. As a result, each packet with the same source and destination may take several different routes. In the VC Approach, a link is established only when the data is ready to be sent. The path (or channel) between the sender and the receiver is predetermined. All data transmission between the two devices follows the same path. VCs can thus be thought as logical channels between two end systems that are identified by labels termed as Virtual Circuit Identifier (VCI). Each packet transmitted by the sender carries a VCI. The VCI field of the header is then used to forward the packet en route to its receiver.

2.3 ATM Networks

To take advantage of both circuit and packet switching technologies, the asynchronous transfer mode (ATM) protocol was developed and has since evolved and integrated into a new transport management standard called IP/ATM/SONET/DWDM [16], designed for next-generation networks.

2.3.1 Definition of an ATM Network at the Call Level

The ATM protocol can be defined as a technology of packets transmission using VCs. Each packet possess a fix length of 53 octets, among which the first 5 are used as header and the rest of 48 octets are reserved for the transmission of information [17]. At the beginning of a connection, a VC is established from origin to destination nodes, and all packets of that connection use the same VC.

This definition of an ATM network (referred to as *cell level* definition) is not appropriate for network synthesis purpose. To circumvent this difficulty, an ATM network is rather treated as a multi-rate circuit switched network. This way, rather than considering the packet transmission delay as the performance constraint, one could instead use the end-to-end blocking probability of connections. This is possible because one could use the "equivalent bandwidth allocation" feature [18] to establish a correspondence between the packet level and the connection level while guaranteeing the performance of the network at the cell level.

With that definition of an ATM network at the connection level, optimization methods that were employed for circuit-switched Large Broadband-Integrated Services Digital Networks (LB-ISDN) can be reused in the ATM context [19]. These methods depend, of course, on the chosen traffic model.

2.3.2 Traffic Model

The integration of several classes of traffic, which can simultaneously share the same resources in the network, mandates the need to design an efficient traffic model that will be used to calculate the blocking probabilities of the different classes of services. Under certain assumptions that guarantee some equilibrium between mutual interactions that occurred between the considered different classes of traffics, a traffic model such as the one proposed in [20], referred to as "complete load sharing system", can be considered. Using this traffic model, one can calculate the blocking probability of a commodity (origin-destination node pair) in both the homogeneous case (i.e. case of a single class of traffic) and heterogeneous case (i.e. case of multiple classes of traffics).

2.3.3 Routing Strategies in ATM Networks

In ATM networks, the routing strategy of a cell is as important as the physical nature of the cell itself. The VC switching (also referred to as cell switching) mechanism is used to handle the sequential delivery of traffic, and can lead to low delay and jitter, but its penalty is in higher overhead. A VC is established before the data transfer process. VCs are used to allow cells belonging to the same message to follow the same route to their destination. The motivation behind this concept is to allow related cells to arrive at their locations in the same order they left the sender. Therefore, the receiver of the data is relieved from the task of sorting the cells. But if the cells arrive out of order, unpredictable delays will likely occur. This is quite disadvantageous to multimedia applications such as video and audio transmissions.

There are two types of connections that can occur in an ATM network. The first one is a virtual path (VP) connection, which encompasses a set of virtual channels or VCs. Each VP is uniquely identified by means of a Virtual Path Identifier (VPI). The second type of connection is the VC connection itself, which is identified by combining the VPI and the Virtual Channel Identifier (VCI). This combination can be used to identify the potential channels the cell should be directed to. In the event that a VP connection is established between two switches which are not directly connected, it is understood that these switches will be communicating through other adjacent ones.

ATM networks use two level hierarchy identifiers (VPI and VCI) in contrast to other VC-based technologies such as X.25 and Frame Relay, which use only a single label. An important feature of this two-level hierarchy is that VPs can be distinguished based on QoS requirements. This means that when designing ATM networks using the VPee approach (as it is the case in this project), one must specify whether a single VP or a group VPs per node pair should be considered as part of design requirements.

In our study, we consider the traffic model in [20] and both the single VP option (case of homogeneous traffic) and the group VPs option (more realistic case of heterogeneous traffics). In the former, the blocking probability of a commodity, and thus the bandwidth of a VP is calculated by means of the Erlang-B formula [21], whereas in the later, the blocking probability of a commodity, and thereby the bandwidth of a VP is determined by means of the Kaufman formula [20].

2.3.4 Self-Healing in ATM Networks

Self-healing can be defined as the capability of a network to quickly reconfigure itself upon a failure event (single link or node failure), without degrading significantly the expected QoS. There is no way to design a large-scale fully reliable network that never goes down. Therefore, in more realistic scenarios, the network is restored as soon as possible once these disturbances happen. Self-healing schemes are of two types [22]: *dynamic self-healing* and *preplanned self-healing.*

In the dynamic self-healing approach, each node is assumed to have a limited knowledge about the network. When a link failure occurs, the downstream node broadcasts route search messages for all VPs. A hop limit is set to restrict the large search space, then a confirmation message is sent out by a chosen node (upstream node) when an alternate VP has been found to replace the failed physical link.

In the preplanned self-healing approach, each VP is assigned one or several backup VPs (BVPs). When a failure occur, a node responsible for restoring the traffic (for instance, a network management center) sends a restoration message along the chosen BVP, and switches the failed physical path with the chosen BVP.

Dynamic self-healing schemes require less spare resources than preplanned self-healing schemes, but, generate a large number of messages when broadcasting the route searching. In this project, we follow the preplanned self-healing approach.

2.3.5 ATM Network Design Approaches

ATM networks essentially provide an integration of all services into one uniform transport layer. Unfortunately, this integration of services creates resource management and traffic control issues that become very complex and difficult to manage. The *virtual network (VN) concept* strives to alleviate this problem by introducing two types of separation: separation of management functions and virtual separation of resources [23]. The separation of management functions allows for the customization of services and user groups in order to meet their unique needs, and the virtual separation of resources can be used to guarantee a particular GoS for specific services or user groups.

For these reasons, the network is generally composed of two layers: a *physical* layer, and a *logical* layer. The physical layer (physical network) is composed of physical nodes and links. The logical layer is generally composed of one or several logical networks (or VNs) [23]. This layer is used for controlling the traffic in the physical layer, and for managing the required bandwidths. Therefore, VN nodes are essentially composed of a subset of physical network nodes (in some cases, the entire set of physical network nodes) and a set of virtual links connecting those nodes. Nodes in a VN have specific switching or routing capabilities that distinguish them from physical network nodes. For instance, nodes in a VN include switches, routers, etc, whereas typical nodes in a physical network are multiplexers, etc.

A VN is uniquely identified by a Virtual Network Identifier (VNI). A virtual network link is a predefined path (consisting of one or more physical links) between two VN nodes. These paths are also known as VPs. It should be noticed that in some cases [23], several VNs coexist in the same physical network while constituting independent entities. In some other cases, VNs may be nested within one another.

In our work, we consider the VPee approach and the aforementioned two-level networks model, termed as physical network (working network) and spare network (VN). Thus, we use the term *working capacity cost* to represent the total physical link capacities when all commodities (working VPs) in the network take the shortest paths to their destinations in the non-failure state (normal state)[2], and the term *spare capacity* represents the total capacity installed on the spare network to compensate the loss of traffic in case of failure event (single link or node failure) in the working network.

ATM network design approaches must take into account QoS requirements at the cell level and the service availability at the connection level when high traffic demands and node failures occur. In [5], a quantitative comparison of different ATM network design approaches is described in terms of network transmission, VC switching, and VP-switching costs. These design approaches are referred to as Virtual Paths End-to-End (VPee), Concatenated Virtual Paths (CVP), and Virtual Network (VN) approaches.

2.3.5.1 The VPee Design Approach

In the VPee approach, a complete mesh of VPs is established among origin and destination nodes. VCs between endpoints are multiplexed (or de-multiplexed) by edge

[2] It should be noticed that the working capacity cost is *constant* for the given network topology and traffic demand matrix.

VC switches onto (and from) corresponding VPs linking the same endpoints. In addition, all VCs between endpoints are carried by the corresponding end-to-end VP. As the underlying physical network is typically not fully connected, several such VPs connecting different endpoints can share the same link of the physical network. The fact that a single path supports all traffic between endpoints makes this type of networks vulnerable to link or node failure. Therefore, this kind of approach mandates the provision of bandwidth to the spare network and restoration procedures to be invoked when a failure event occur. Here, the network resource management is done by means of VPs assuming that all VPs take the shortest paths to their destinations.

This approach has several advantages. Firstly, the call admission is greatly simplified in the sense that the information required to make the admission decision of a new VC request is readily available at the origin node of the corresponding VP. Secondly, no core or transit VC switching is necessary. The main disadvantage of the VPee approach is its inefficient use of the transmission capacity for given QoS and GoS requirements.

2.3.5.2 The CVP Design Approach

In this approach, VPs are no longer defined in an end-to-end fashion, but rather between VP cross-connect switches [5]. In addition, VC switches must be deployed at junction points to route the incoming VC requests onto the required outbound physical link and VP. Here, the bandwidth is managed by the virtual network link, resulting to a more efficient multiplexing of the physical link capacity at the cell and call levels compared to the VPee approach. However, the penalty is that call admission procedures are much more complex than in the VPee approach because all the necessary information on all the VC hops for the VC request must be supplied to the origin node.

2.3.5.3 The VN Design Approach

The VN approach combines the advantages of both the VPee and the CVP approaches in which VPs are also defined end-to-end (as in the VPee case) and the bandwidth is managed on a *virtual link* basis as in the CVP approach. Here, the advantage of the VN approach over the CVP one is that there is no need to provide VC switching for transit traffic.

In this project, we will be using the VPee design approach for the following reasons: (1) this approach greatly simplifies the network management, and (2) our work is an extension of the work initiated in [1] on the *CFA-NS problem.* As such, we will be considering the same path-based formulations of the *ATM network synthesis problems* (our so-called *CFA-OND problems*) and the path restoration-based formulation of the *ATM network survivability* problem (*CFA-NS problem*) introduced in [1]. Since our optimization approach to the CFA-NS problem involves using a set of optimal spare capacity costs on each arc (our so-called *spare.dat*) as input file (obtained from solutions to the CFA-OND problems), we will first concentrate on the CFA-OND problems and discuss how their solutions approach was presented in [1][3].

[3] In the sense that they constitute an integrated solution to self-healing ATM network designs.

2.3.6 Optimal/Near-Optimal Design Problems Using the VPee Approach

As already discussed in Chapter 1, the investigation of the CFA-OND problems based on the VPee approach is not new and several solutions have been proposed in the literature. In all these solutions, the focus has been to determine the optimal spare capacity allocation assignment and backup virtual paths allocation for all traffic flows. Unlike previous work reported, the VPee-based approach of the CFA-OND problems studied in [1] focused mainly on failure-oriented restoration and state-dependent BVP scheme. The purpose of the following sections is to describe the main design artifacts inherited from these studies, and which are relevant to the work carried in this project.

2.3.6.1 Design Considerations

To address the CFA-OND problems, the authors in [1] adopted a preplanned restoration scheme under a single link or node failure scenario, with restoration performed at the VP level only[4]. The design objective was to provide a reliable and cost-effective network. Assuming that spare capacity is the main cost, the CFA-OND problems were formulated in the form of various IP/LP formulations depending on whether the link restoration or path restoration was considered as restoration option. A Minimum Cost Route (MCR) algorithm was also developed for the optimal/near-optimal design of large self-healing ATM networks. Finally, the authors compared various restoration strategies for self-healing networks, quantitatively in terms of the spare capacity requirements (SCR). The design considerations that were followed are described next.

[4] It should be noticed that restoration could be performed at the VC level or at the VN level as well.

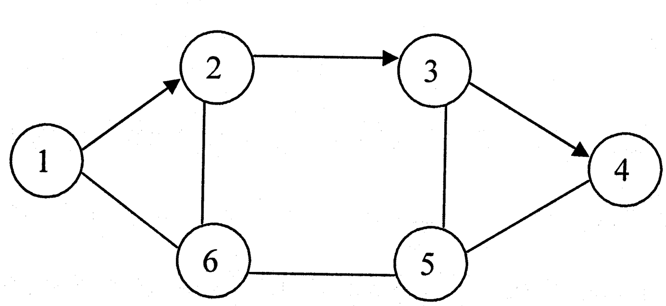
2.3.6.1.1 Network Model and Bandwidth Allocation Method

In the VPee approach, the network is modeled as a two-level network: the physical network and the spare network. Technically, the physical network can be described as a graph *G (N, L)* consisting of |*N*| nodes and |*L*| links. Each entity (link or node) in the network consists of two possible states: a failure state (s), and a normal or working state (s_0). The state of the network can thus be represented as a vector of networks states.

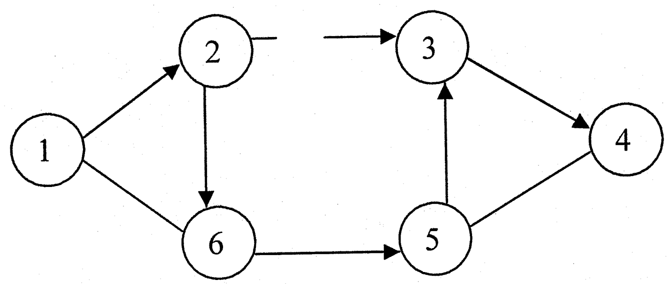
The static bandwidth allocation of VPs is used, and the total bandwidth between an origin-destination (o-d) pair is assumed to be equal to the sum of individual VP bandwidths between that node-pair. Moreover, the traffic flow in the network is modeled as a multi-commodity flow.

2.3.6.1.2 Restoration Schemes

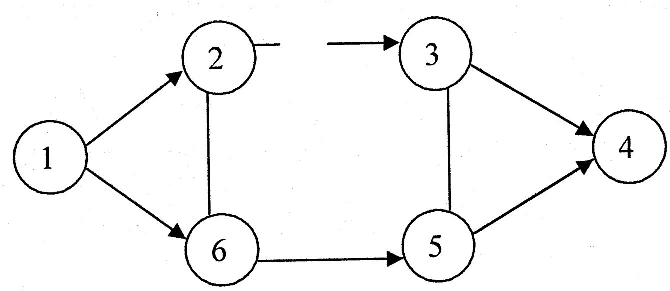
As already mentioned, preplanned restoration schemes are used in [1], [5], and the restoration can be performed either at the link level (link restoration) or path level (path restoration). The difference between link restoration and path restoration is clearly illustrated in Fig. 1 using a simple network example.



a. Network with working path 1-2-3-4



b. Link restoration when (2,3) fails yields the restoration path 1-2-6-5-3-4



c. Path restoration when (2,3) fails yields the restoration path 1-6-5-4

Figure 1: Sample network illustrating link restoration versus path restoration.

For path restoration, one must distinguish between *global reconfiguration* (i.e. affected and unaffected VPs are rearranged) and *failure-oriented reconfiguration* (i.e. only the affected working VPs are rerouted) upon a failure event (link or node failure). The later is further divided into *state-dependent* (*SD*) restoration and *state-independent* (*SI*) restoration schemes. In the SI restoration scheme (known as BVP scheme), each working VP has only one corresponding BVP, which takes link/node disjoint path. When the working VP fails, the affected traffic will be switched to its BVP. In the SD restoration scheme, each working VP may have more than one BVP. In that case, the choice of a particular BVP when the working VP fails will depend on the network failure state.

In this project, the network is designed based on the assumption that 100% restoration[5] (of restorable affected traffic) for a single link or node failure scenario will be met. We also use the path restoration[6] under the SD scheme.

2.3.6.1.3 Spare Capacity Allocation

Spare capacity allocation is a method of creating sufficient redundant capacity that is to be pre-allocated in the network. Spare capacity can be categorized into two types: dedicated or shared. Dedicated spare capacity is considered to be a very inefficient restoration scheme because it requires 100% redundancy. It has only been successfully implemented in ring-type networks. In mesh networks, this type of implementation is not desirable because it is very costly. In this project, we focus on mesh type ATM networks with shared spare capacity.

If c_{work} is the total working capacity cost[7] assuming that all working VPs are given which take the shortest routes to their destinations in the non-failure state s_0, then, the SCR of a self-healing network is defined as

$$SCR = \frac{C_{spare}}{C_{work}} = \frac{C_{tot} - C_{work}}{C_{work}} \tag{2.1}$$

[5] When *less than 100% restoration* is assumed, the network dimensioning problem is more difficult.

[6] We have chosen to use the path restoration because it has been proved [1] that this scheme leads to shorter restoration time than the link restoration scheme

[7] It should be noticed that c_{work} is unique for the given network topology and traffic demand

where c_{spare} is the total spare capacity cost (also referred to as *spare cost*) and c_{tot} is the total network cost.

For a given SCR, there are many possible ways of distributing the spare capacity in the network. This project, considers the following possibilities [1]:

- SCD_1: Each arc has the same spare capacity.
- SCD_2: Each arc has the same spare capacity cost.
- SCD_3: The spare capacity on each arc is proportional to the working capacity on that arc.
- SCD_4: The spare capacity on each arc is inversely proportional to the working capacity on that arc.

In any of these options, the SCR is used as the performance metric in [1] to validate the solutions to the CFA-OND and CFA-NS problems. More precisely, for the CFA-OND problems, the SCR is used for comparing the restoration strategies for self-healing networks, while for the CFA-NS problem, the SCR is used to determine the level (if this exist) at which the assumption of 100% restoration can be met.

In this project, we use the same performance metric (i.e. SCR) to quantify the network survivability (here defined by means of the *aggregate restoration ratio*) for various network scenarios, under the above SCD design schemes.

2.3.6.1.4 Optimization Scenarios and Traffic Demands

Two kinds of network optimization can be considered when solving the CFA-OND problems: (1) *joint optimization* – in which the working and spare capacities are optimized simultaneously, and (2) *spare optimization* – in which only the spare capacity is optimized assuming that the working VPs take the shortest paths to their destinations.

Furthermore, two types of candidate routes for each node pair in the network can be considered: (1) All Possible Paths (APP) between a node pair, and (2) mutually Link Disjoint Paths (LDP) between a node pair. For a given node pair, it should be noticed that the choice of candidate restoration routes depends on the way the BVP have been selected. Four options can be implemented for the BVP selection:

- Option 1: The second shortest disjoint path for the BVP.
- Option 2: One of the shortest disjoint paths for the BVP.
- Option 3: Joint selection of working VPs and BVPs among shortest disjoint paths.
- Option 4: Joint selection of working VPs and BVPs among all possible paths.

Finally, two types of traffic demands are considered: uniform traffic demands (UD) and non-uniform traffic demands (ND). In the UD case, the bandwidth requirement between each node pair equals B (bits per second) in the non-failure state. In the ND case, the traffic between each node pair is uniformly distributed between 0.1B and 1.9B with mean value of B, where B is the bandwidth per VP used in the UD case. In this case, the traffic is generated using 10 different sets of data.

In this project, we used both APP and LDP options, along with the above Option 4 of BVP selection method[8]. We also use both UD and ND traffic demands, under a single link failure (LF) or node failure (NF) scenario. Finally, we use the spare optimization scheme and the assumption of 100% restoration (of restorable affected traffic) in case of failure event.

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[8] It has been demonstrated in [6] that this option is the best of proposed BVP selection strategies.

2.3.6.2 Resolution Techniques

Given the network topology, the traffic (bandwidth) demand matrix, the SD restoration scheme, and the spare optimization design approach, the CFA-OND problems in self-healing ATM networks [1] consists in determining how to layout the BVPs in order to minimize the spare capacity cost.

Two types of resolution techniques were employed in [1] to solve these problems: (1) local optimization methods for small and medium size networks (here, the Simplex method and the use of MINOS [24], a FORTRAN77-based Callable Library package), and (2) a heuristic (so-called MCR algorithm) for large-scale networks.

Chapter 3 Survivability in Existing ATM Networks

3.1 Introduction

Network survivability can be defined as the ability of a network to continue to function even in case of a failure event, thus can be perceived as a composite of both network failure duration and failure impact on the network. A *survivable network design* refers to the incorporation of survivability strategies into the network design stage in order to mitigate the impact of a set of specific failure scenarios. By doing so, survivability is typically achieved through either placing diversity and spare capacity in the network topology (or virtual topology) or adding redundancy to network components (for instance, by means of the 1+1 automatic protection switching scheme).

This project favours the option of placing the spare capacity in the virtual topology (our so-called spare network) to handle a single link or node failure in the physical network. To this end, three possible strategic options [25] can be used to address survivability in VPee-based ATM networks. Option 1 consists in redesigning the entire network for every possible failure scenario. Option 2 consists in designing the affected VPs for any failure scenario, and Option 3 deals with built-in diversity in the initial design of the network. In [1], Option 2 was used and various multi-commodity flow-based optimization models for the CFA-OND and CFA-NS problems were developed.

This chapter continues the study of the CFA-NS problem introduced in [1]. We investigate the survivability in existing ATM networks. The goal is to study the network survivability (restoration ratio) - here defined by means of the *aggregate restoration ratio*

- for path and link restorations, under various traffic and design related patterns, using the aforementioned SCD schemes. More precisely, (1) we compare the network survivability for link and path restorations, and we quantitatively determine: (2) the effect of the choice of candidate paths for node pairs (i.e. All Possible Paths versus Link Disjoint Paths) on the restoration ratio, (3) the effect of restoration schemes (link restoration versus path restoration) on the restoration ratio, (4) the effect of the network connectivity (sparse versus dense networks) on the restoration ratio, (5) the effect of failure scenarios (single link versus single node failure) on the restoration ratio, and (6) the effect of SCD schemes on the restoration ratio.

3.2 Notations

Symbol	Explanation
A	Set of directed arcs of the network. Each link l consists of two arcs which have the same end nodes as l but with opposite directions.
S	Set of network states.
s_0	Normal network operation state (non-failure state), $s_0 \in S$
Π	Set of origin-destination node pairs (so-called commodities)
$O(\pi)$	Origin node of the commodity $\pi \in \Pi$
$D(\pi)$	Destination of the commodity $\pi \in \Pi$
R_{π}^{s}	Set of candidate routes for commodity $\pi \in \Pi$ when the network is in state $s \in S$
$x_{r\pi}^{s0}$	Normalized traffic flow of commodity π on route r, $r \in R_{\pi}^{s0}$, $\pi \in \Pi$ when the network is in non-failure state (normal state).
$y_{r\pi}^{s}$	Restoration flow on route r for the affected commodity π when the network is in failure state $s \in S$
δ_{rw}	The delta function, which equals 1 when the network component w is on route r and 0 otherwise.
$F(s)$	Set of failed components (links or nodes) when the network is in state $s \in S - s_0$
$\gamma_{\pi}^{s_0}$	Traffic demand expressing the minimum bandwidth requirement for commodity $\pi \in \Pi$ when the network is in non-failure state.
c_{a}^{spare}	Spare capacity on arc $a \in A$

c_a^{work}	Working capacity on arc a
c_{work}	Working capacity cost
c_{spare}	Spare cost (depends on the restoration strategies used in the network).
$t_r(s)$	Maximal amount of restored traffic for a given network failure state $s \in S$
$t_a(s)$	Restorable affected traffic in state $s \in S - s_0$
$\theta(s)$	Restoration ratio in state $s \in S - s_0$
η	Average restoration ratio
η^*	Aggregation restoration ratio
SCD_i	i[th] spare capacity distribution method

3.3 Network Survivability Problem Formulation

Considering that in an existing ATM network, the arc capacity and working VPs are well known in advance, and the spare capacity on any arc is simply the remaining unused capacity on that arc, the authors in [1] formulated the network survivability problem as the following LP problem:

Maximize

$$\sum_{s \in S - s_0} \sum_{\pi \in \Pi} \sum_{r \in R_\pi^s} y_{r\pi}^s \tag{3.1}$$

Subject to

$$\sum_{\pi \in \Pi} \sum_{r \in R_\pi^s} \delta_{ra} \gamma_\pi^{s_0} y_{r\pi}^s \le c_a^{spare}, \; a \in A, s \in S - s_0 \tag{3.2}$$

$$\sum_{r \in R_\pi^s} y_{r\pi}^s - \sum_{r \in R_\pi^{s0}} \Omega(\pi, r, s) x_{r\pi}^{s_0} \le 0, \quad \pi \in \Pi, s \in S - s_0 \tag{3.3}$$

where

$$\Omega(\pi, r, s) = 1 \quad \text{if } F(s) \cap \{r\} \neq \varnothing \text{ and } \{\, O(\pi), D(\pi)\} \cap F(s) = \varnothing$$

$$\Omega(\pi, r, s) = 0 \quad \text{otherwise.}$$

Here, the objective function (Equation 3.1) is to maximize the total restoration flows for all affected commodities $\pi \in \Pi$ and for all failure states. Constraints (3.2) ensure that the capacity used by the restoration flows passing each arc will not exceed the available spare capacity on that arc. Constraints (3.3) guarantee that the volume of restoration flow will not exceed the affected traffic flows for every commodity.

3.4 Network Survivability Measures

Under the assumption that the network can be in only one failure state at a time, the solution to the above formulation (3.1) - (3.3) can be used to determine $\theta(s)$, the restoration ratio in a given network failure state $s \in S - s_0$:

$$\theta(s) = t_r(s) / t_a(s) \tag{3.4}$$

where $t_r(s)$ is the maximal amount of restored traffic and $t_a(s)$ is the restorable affected traffic in state s.

In [1], the network survivability is defined by means of the average restoration ratio (denoted η) over all possible failure cases:

$$\eta = \frac{\sum_{s \in S - s_0} \theta(s)}{| S - s_0 |} \tag{3.5}$$

In this project, we use an alternative definition of the network survivability, termed as the aggregate restoration ratio η^* over all possible failure cases:

$$\eta^* = \frac{\sum_{s \in S - s_0} t_r(s)}{\sum_{s \in S - s_0} t_a(s)} \tag{3.6}$$

From Equations (3.5) and (3.6), it follows that

$$\eta \geq \eta^* \tag{3.7}$$

For a given spare cost C_{spare} (or equivalently SCR), we use the following formulas for implementing the spare capacity distribution methods:

- SCD_1: Each arc has the same spare capacity:

$$c_a^{spare} = C_{spare} \Big/ \sum_{a \in A} d_a \tag{3.8}$$

- SCD_2: Each arc has the same spare capacity cost:

$$c_a^{spare} = C_{spare} \Big/ (|A| \, d_a) \tag{3.9}$$

- SCD_3: The spare capacity on each arc is proportional to the working capacity on that arc:

$$c_a^{spare} = c_a^{work} \, . \, SCR \tag{3.10}$$

- SCD_4: The spare capacity on each arc is inversely proportional to working capacity on that arc:

$$c_a^{spare} = \frac{C_{spare}}{c_a^{work} . \left(\sum_{a \in A} d_a \Big/ c_a^{work} \right)} \tag{3.11}$$

3.5 Simulation Workflow, Parameters and Traffic Requirements

The computations were performed on a 1.8 GHz Pentium IV processor with the Linux Operating system. We use the resolution techniques described in Chapter 2

(Section 2.3.6.2) to generate the solution to the CFA-NS problem and determine the network survivability using Equation (3.6). The workflow of resolution techniques for the CFA-NS problem is depicted in Fig. 2, Fig. 3 and Fig. 4.

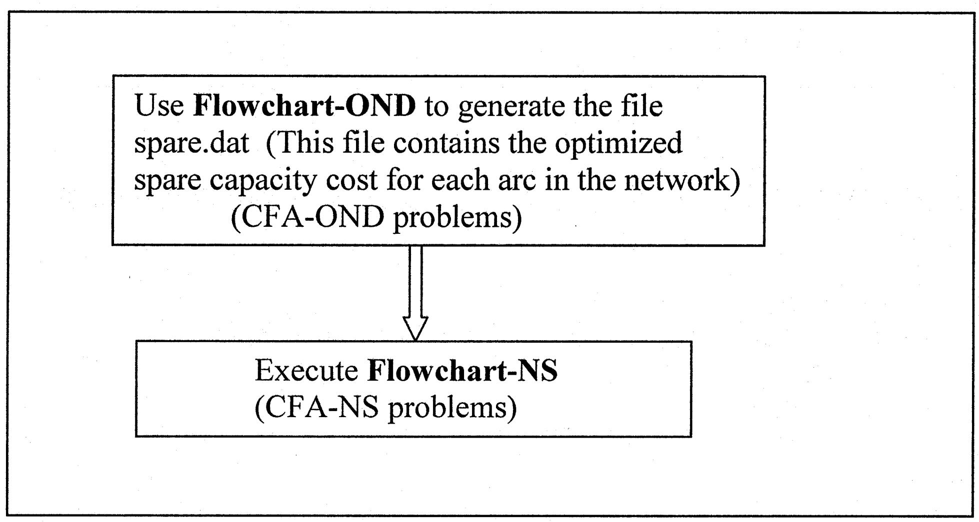

Figure 2: Workflow of resolution techniques for the CFA-NS problem.

Flowchart-OND

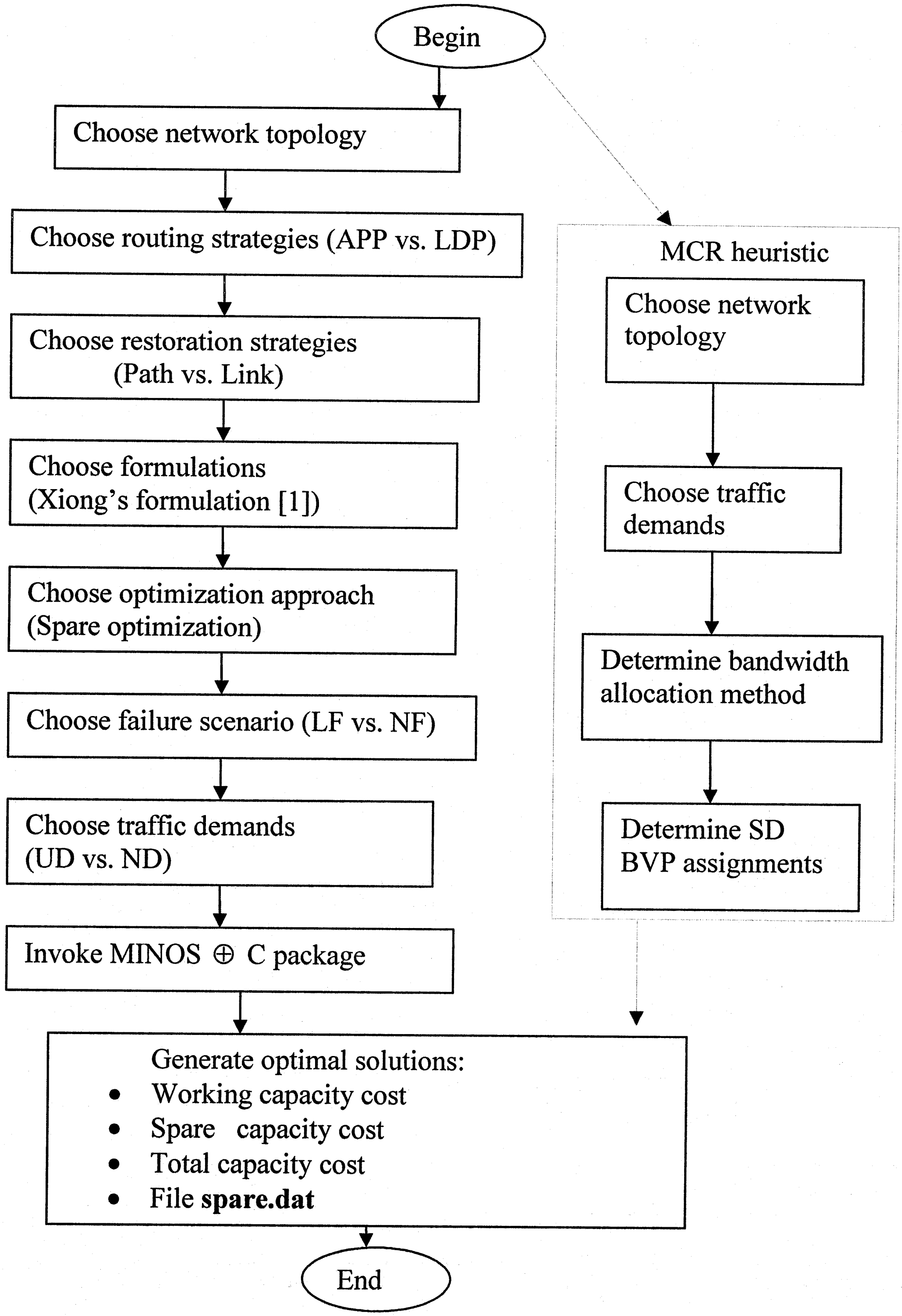

Figure 3: Flowchart-OND for the CFA-OND problems

Flowchart-NS

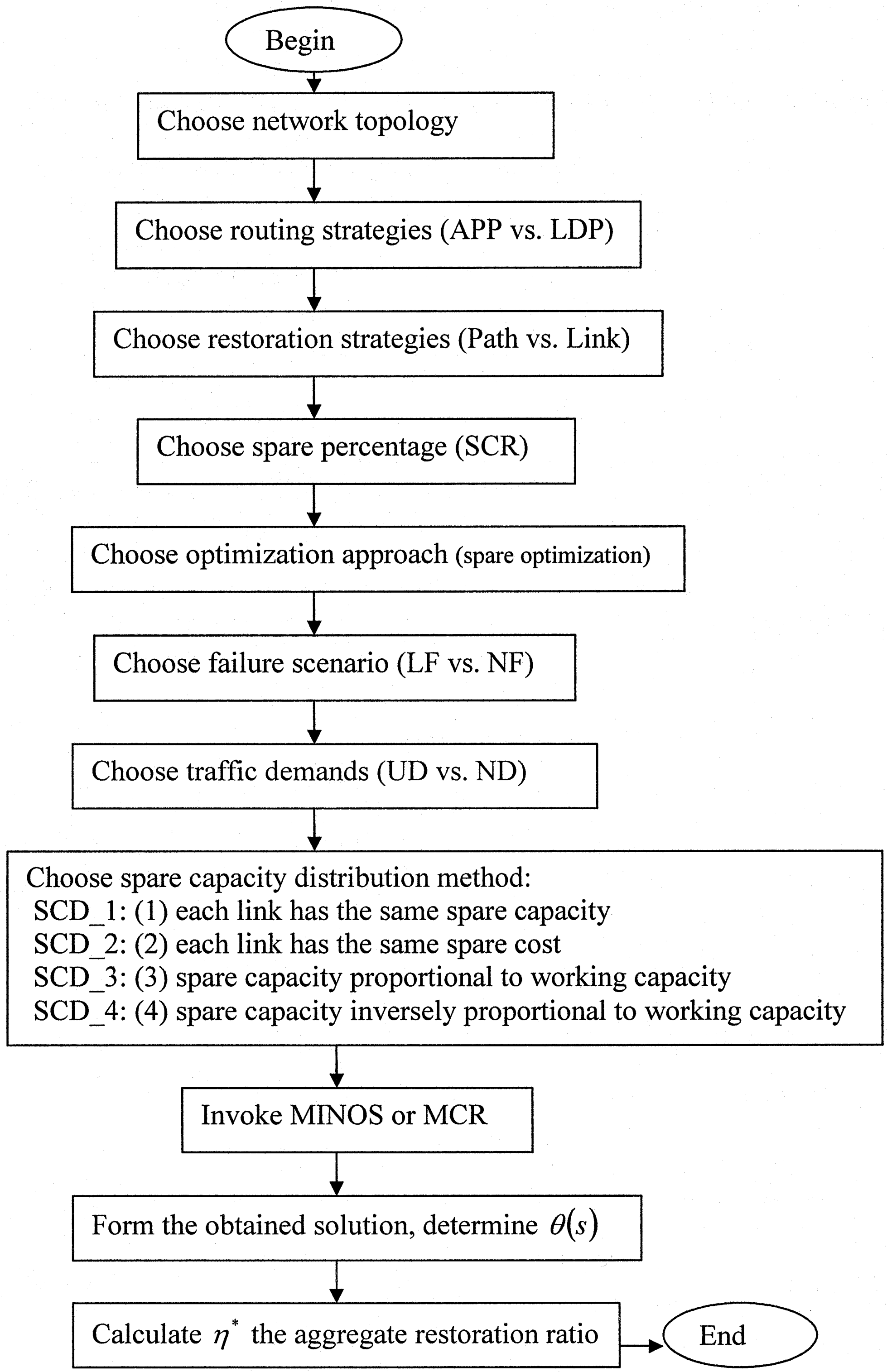

Figure 4: Flowchart-NS for the CFA-NS problems

In this project, the parameters for traffic requirements are inherited from the design considerations highlighted in Section 2.3.6.1. These are summarized in Table 1.

Candidate paths per node pair	All Possible Path (APP) or Link Disjoint Path (LDP).
Maximum number of candidate restoration routes per node pair	10
Maximum hop limit of paths	6 for networks N(11,23) and N(11,17) and 10 for networks N(20,30) and N(20,42)
Call blocking probabilities requirements for all connection requests (i.e., GoS)	1% in the normal state and 20% in each failure state.
Cell loss probability requirement (or QoS)	0.1%
Traffic demands	Both uniform traffic demands (UD) and non-uniform traffic demands (ND).

Table 1: Parameters for traffic requirements

Finally, the specific parameters employed in generating the link capacity requirements are given in Table 2.

Network Topologies	N (11, 17), N(11,23), N(20,30) and N(20,42) (See Appendix).
Candidate paths per node pair	All Possible Path (APP) or Link Disjoint Path (LDP).
Link cost model	Proportional to length and capacity.
Restoration scheme	State-dependent (SD) path restoration.
Formulation:	Xiong et al. [1]

Optimization option	Spare optimization (given the working VPs layout)
Link orientation	Bidirectional links
Failure scenarios	Single link failure (LF) or node failure (NF) scenario

Table 2: Parameters used for generating the link capacity requirements

3.6 Considered Network Topologies

The considered topologies are shown in Fig. 8 to 11 (see Appendix), where the virtual network nodes are those represented by both VC and VP switches. For instance, the virtual network (VN) associated to the network N(11,23) (respectively N(11, 17)) has 5 nodes and the VNs corresponding to N(20,30) and N(20,42) are identical to their respective physical networks. Here, N(11,23) and N(20,30) are real networks, whereas N(11, 17) and N(20,42) are artificial ones.

3.7 Simulation Results

This section presents the results of our study on survivability (restoration ratio) – here defined by means of the *aggregate restoration ratio* – in existing ATM networks, both for link and path restorations, under various traffic patterns and design related considerations (Table 1 and Table 2 and Section 2.3.6.1), and spare capacity distribution schemes (SCD_1, SCD_2, SCD_3, and SCD_4). More precisely, from our solution to the CFA-NS problem (Formulation (3.1) to (3.3)), we determine the aggregate restoration ratio from Equation (3.6). Next, (1) we compare the network survivability for link and path restorations, and we determine: (2) the effect of the choice of candidate paths on the restoration ratio, (3) the effect of restoration schemes on the restoration ratio, (4) the effect of network connectivity on the restoration ratio, (5) the effect of failure scenarios on the restoration ratio, and (6) the effect of SCD methods on the restoration ratio. These results complement those presented in [1], and contribute to enhancing the design choices and/or decisions when designing self-healing and survivable ATM networks. In the sequel, we assume that all working VPs take their shortest paths to the destination, meaning that the working capacity cost is constant for the given network topology and traffic demand matrix.

3.7.1 Aggregate Restoration Ratio Versus Average Restoration Ratio

We assume that the path set of APP (All Possible Paths) is used. Fig. 5 illustrates the impact of the SCR on the aggregate restoration ratio versus the average restoration ratio, using uniform traffic demands, path restoration, and the SCD_1 scheme, under a single link failure (LF) scenario. It is observed that the aggregate restoration ratio η^* as well as the average restoration ratio η grow quickly when the SCR increases from 0% to certain threshold (50% in the case of η) and (60% in the case of η^*), and the growth starts to slow down progressively when the SCR further increases. The difference in growing values of η and η^* after those thresholds is very small (less than 2%). It is also observed that using the path restoration and SCD_1, the value SCR=61.14% (case of η) and SCR=71.11 % (case of η^*) suffices to ensure that 100% restoration under a single link failure scenario. It should be noticed that our result for the restoration ratio in terms of η concurs with the one presented in [1].

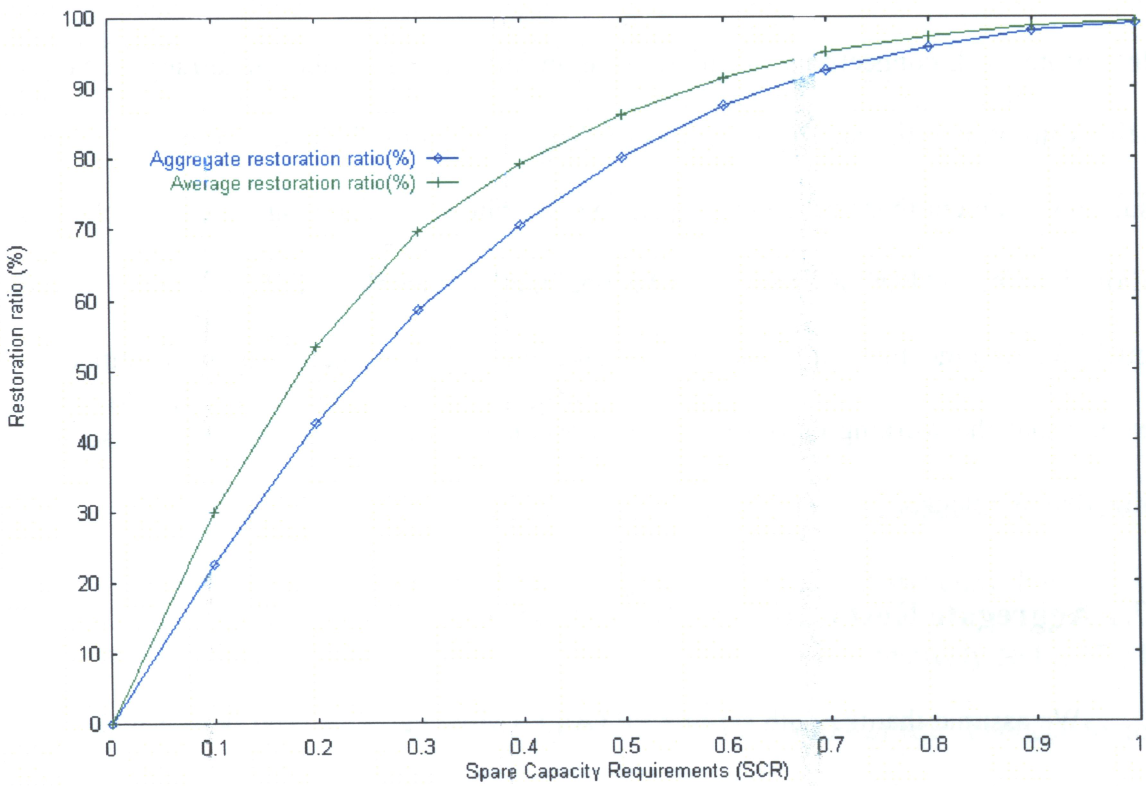

Figure 5: Aggregate restoration ratio versus average restoration ratio, under uniform traffic demands, and APP option, using N(20,30) and SCD_1

3.7.2 Effect of Spare Capacity Distribution Schemes on the Restoration Ratio

We also assume that the path set of APP is used. Fig. 6 depicts the effect of the selection of SCD schemes on the restoration ratio using η^*, under path restoration, and a single link failure scenario. It is observed in both Fig. 6 (case of uniform traffic demands) and Table 3 (case of non-uniform traffic demands) that the aggregate restoration ratio η^* is smaller when using SCD_4 compared to all other SCD schemes. From Fig. 6, it is clear that independently of the selected SCD scheme, the aggregate restoration ratio grows quickly when the SCR increases from 0% up to a certain threshold (60% for SCD_1, SCD_2, SCD_3, and 70% for SCD_4), then the growth continuously slows down when the SCR continues to increase after those thresholds. It is also noticed that when using SCD_1 (respectively SCD_2), SCR=71.11% (respectively 91.04%) is sufficient for ensuring 100% restoration under a single link failure scenario. No such conclusion could be reached on the studied network when using respectively SCD_3 and SCD_4. These observations suggest that using SCD_1 and SCD_2 would guarantee that the 100% restoration assumption is met for the studied network under a single failure scenario, without the need to make full usage of available spare capacity resources. Moreover, in this capacity, SCD_1 is a much better scheme than SCD_2.

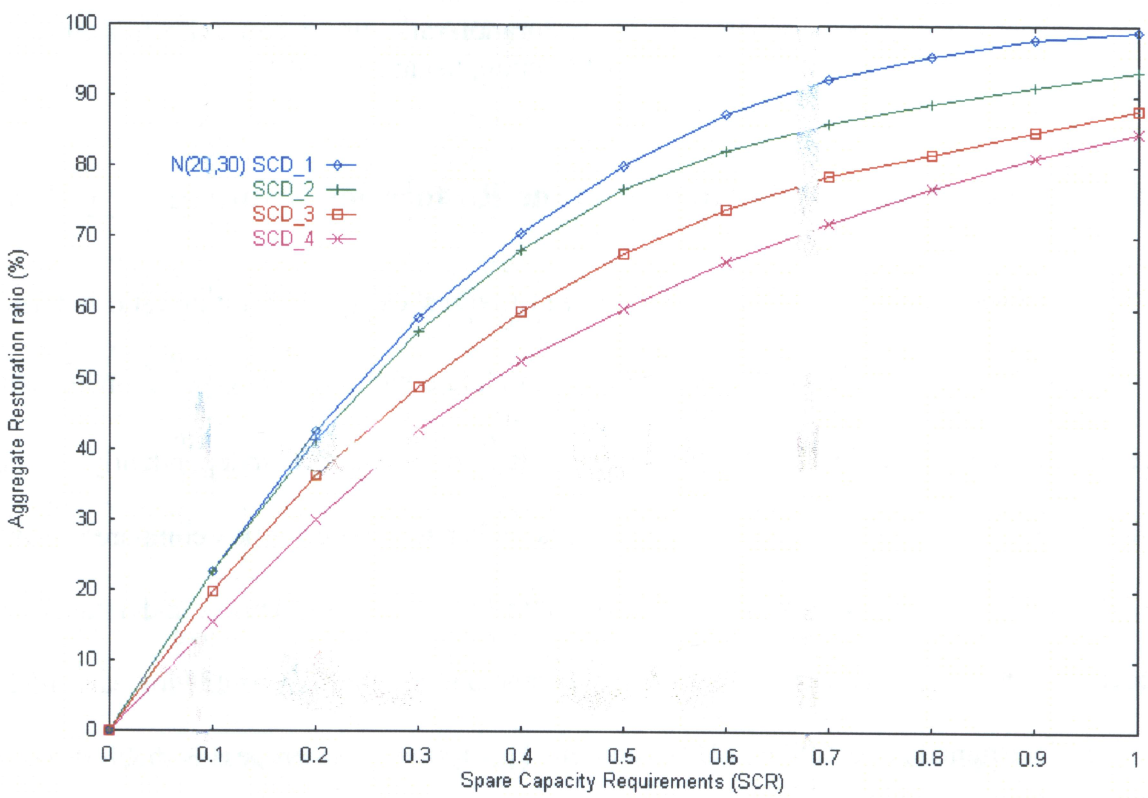

Figure 6: Effect of SCD schemes on the restoration ratio, under uniform traffic demands and APP option, using N(20,30).

Ratio η^*(%)				
SCR		0.2	0.5	0.7
	min	41.60%	79.03%	91.56%
	avg	42.35%	79.90%	92.24%
SCD_1	max	42.97%	80.47%	92.52%
	min	40.29%	75.93%	85.88%
	avg	41.04%	76.66%	86.34%
SCD_2	max	41.61%	77.43%	86.78%
	min	34.33%	64.67%	77.24%
	avg	35.89%	67.29%	78.43%
SCD_3	max	37.11%	69.08%	79.73%
	min	27.86%	56.79%	68.42%
	avg	28.67%	58.69%	70.71%
SCD_4	max	29.69%	60.30%	73.16%

Table 3: Effect of SCD schemes on the restoration ratio, under non-uniform traffic demands (ND) and APP option, using N(20,30).

3.7.3 Effect of Routing Strategies on the Restoration Ratio

Table 4 (case of UD) and Table 5 (case of ND) show the restoration ratio in terms of η^* when using APP versus LDP options as candidate paths per node pairs, under path restoration and a single link failure scenario. It is observed that independently of the chosen SCD scheme, the APP option produces higher restoration ratios compared to the LDP option, for the tested network examples and traffic patterns. This is understandable because during the optimization process, the candidate restoration routes for each node pair is determined once APP or LDP is chosen. The optimization process is much flexible when using APP compared to LDP since APP would lead to more flexible choices of alternative paths for each node pair than LDP does. Furthermore, it is observed that the highest restoration ratio is achieved when using the SCD_1 scheme (i.e., each arc is assigned the same spare capacity). This might be justified by the fact that SCD_1 (among all other SCD schemes) is the one capable of ensuring 100% restoration with the best minimal SCR requirement (as previously observed in Fig. 6).

Ratio η^*	APP (%)			APP-LDP (%)		
SCR	0.2	0.5	0.7	0.2	0.5	0.7
SCD_1	41.95%	77.79%	90.33%	0.67%	2.35%	2.19%
SCD_2	40.15%	71.59%	82.74%	1.12%	5.14%	3.54%
SCD_3	34.18%	63.02%	74.59%	2.07%	4.48%	4.19%
SCD_4	26.99%	55.45%	66.34%	2.89%	4.51%	5.83%

Table 4: Effect of routing strategies (LDP versus APP) on the restoration ratio, for network N(20,30), under uniform traffic demands.

Ratio η^*		APP (%)			APP - LDP (%)		
SCR		0.2	0.5	0.7	0.2	0.5	0.7
	min	41.60%	79.03%	91.56%	0.60%	2.31%	2.16%
	avg	42.35%	79.90%	92.24%	0.79%	2.60%	2.46%
SCD_1	max	42.97%	80.47%	92.52%	0.90%	2.57%	2.33%
	min	40.29%	75.93%	85.88%	1.15%	5.25%	3.31%
	avg	41.04%	76.66%	86.34%	1.43%	5.25%	3.58%
SCD_2	max	41.61%	77.43%	86.78%	1.56%	5.36%	3.62%
	min	34.33%	64.67%	77.24%	2.20%	4.40%	5.21%
	avg	35.89%	67.29%	78.43%	2.58%	4.88%	4.55%
SCD_3	max	35.89%	67.29%	78.43%	2.58%	4.88%	4.55%
	min	27.86%	56.79%	68.42%	2.61%	5.20%	15.11%
	avg	28.67%	58.69%	70.71%	2.67%	5.07%	8.36%
SCD_4	max	29.69%	60.30%	73.16%	3.20%	5.44%	7.14%

Table 5: Effect of routing strategies (LDP versus APP) on the restoration ratio, for network N(20,30), under non-uniform traffic demands.

3.7.4. Effect of Restoration Schemes on the Restoration Ratio

As before, we assume that the path set of APP is used in obtaining the results of the comparison of link restoration (LR) and path restoration (PR), under uniform traffic demands. Table 6 shows that the restoration ratio using η^* is larger when using the path restoration compared to the link restoration. This might be due to the fact that in the link restoration scheme, there is less flexibility in selecting the restoration routes during the optimization process (compared to when the path restoration scheme is employed), and the origin-destination information of affected traffic flows are not considered. Thus, the link restoration scheme cannot "better" share the spare capacity on arcs of the network than the path restoration scheme would do, which might result to more traffic loss in case of link restoration.

Ratio η^*	PR (%)			PR-LR (%)		
SCR	0.2	0.5	0.7	0.2	0.5	0.7
SCD_1	42.58%	80.14%	92.52%	10.63%	14.72%	13.04%
SCD_2	41.27%	76.72%	86.30%	9.01%	11.70%	7.10%
SCD_3	36.25%	67.80%	78.78%	10.83%	12.85%	9.62%
SCD_4	29.87%	59.80%	72.17%	8.92%	12.93%	13.06%

Table 6: Effect of restoration schemes on the restoration ratio under uniform traffic demands, using APP and N(20,30).

3.7.5 Effect of Failure Scenarios on the Restoration Ratio

We assume that the path set of APP is used. Here, we consider the network N(11,23) under path restoration and uniform traffic demands. Table 7 shows that independently of the chosen SCD scheme, a single link failure scenario (LF) produces higher restoration ratios compared to a single node failure scenario (NF). This observation is understandable because in the NF case, it is required that simultaneous failure of all links connected to the node be realized, and this can result to a more sophisticated restoration algorithm, which in turn does not necessary guarantee that 100% restoration of restorable affected traffic will be achieved by the network. In addition, the optimization process is more complicated in the NF scenario than in the LF case.

Ratio η^*	LF (%)			LF- NF (%)		
SCR	0.2	0.5	0.7	0.2	0.5	0.7
SCD_1	46.15%	80.17%	87.63%	8.14%	11.20%	9.36%
SCD_2	49.10%	83.88%	92.14%	9.04%	11.93%	10.98%
SCD_3	41.61%	72.99%	83.33%	6.07%	9.32%	9.58%
SCD_4	37.21%	69.94%	80.06%	7.63%	11.31%	11.25%

Table 7: Effect of failure scenarios on the restoration ratio, under uniform traffic demands, using N(11,23).

3.7.6 Impact of the Network Connectivity on the Restoration Ratio

We assume that the path set of APP is used. We also consider the sparse network N(20,30) and the dense network N(20,42) (see Appendix), under a single link failure scenario, the path restoration, the SCD_1 scheme and uniform traffic demands. Fig. 7 shows that the aggregate restoration ratio η^*grows rapidly from 0% to 60% (case of sparse network) and from 0% to 50% (case of dense network) and the growth slows down rapidly in the dense network compared to the sparse network when the SCR further increases. It is also observed that when the spare capacity is optimally distributed, using the path restoration, the value SCR=71.11% (case of sparse network) and SCR=50.13% (case of dense network) is sufficient to ensure 100% restoration under a single link failure scenario. Similar results are observed when using the other SCD schemes, under the same network topologies, and uniform, and non-uniform traffic demands. These observations indicates that in case of failure event, dense networks are more prone to achieve fast recovery of affected restorable traffic compared to sparse networks. This might be due to the fact that in dense networks, there are more choices for candidate restoration routes than in sparse networks.

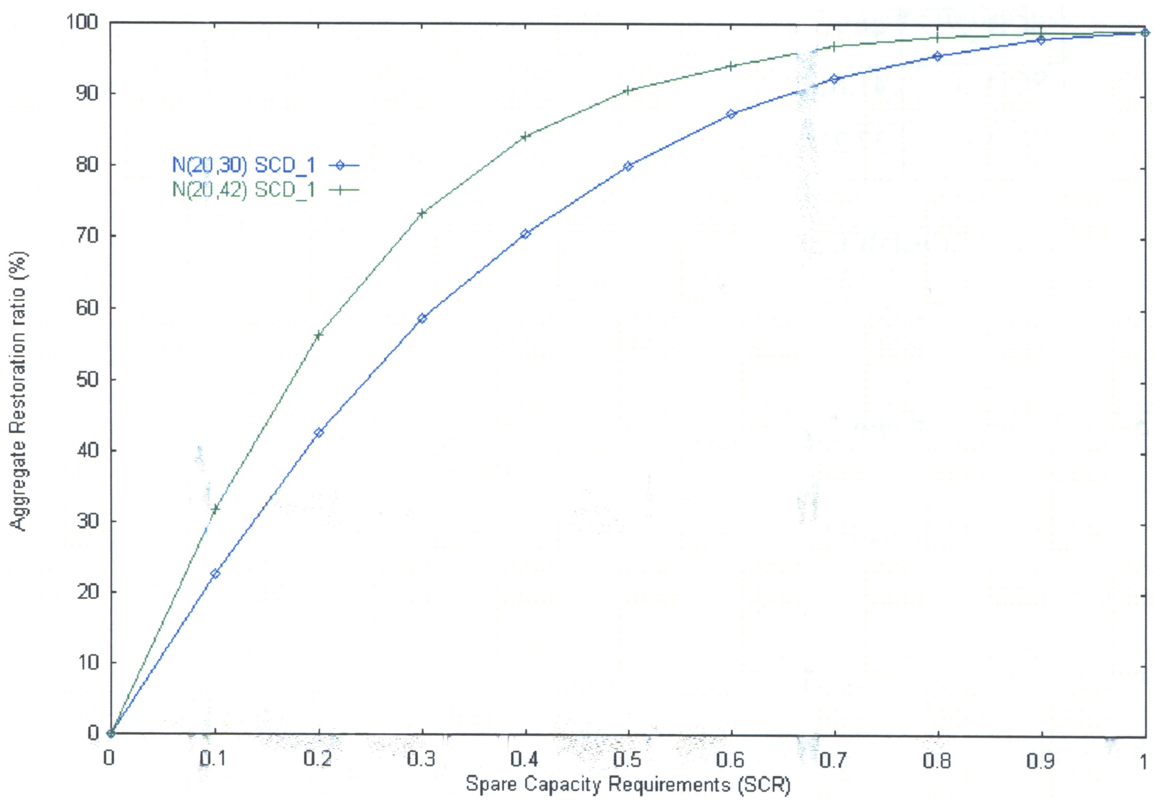

Figure 7: Impact of the network connectivity on the restoration ratio, under uniform traffic demands and APP option, using SCD_1.

Chapter 4 Conclusion

In this project, we have studied the survivability (restoration ratio) in existing ATM networks. We have found that:

1) For a given spare capacity requirement and spare capacity distribution method, the restoration ratio (here defined by means of the *aggregate restoration ratio*) is larger when using path restoration compared to link restoration, i.e., using path restoration for the network survivability is advantageous compared to using link restoration.

2) Focusing only on path restoration only, among the studied spare capacity distribution methods, SCD_1 (i.e., each arc has the same spare capacity) is the most suitable one for addressing the survivability problem since it provides the smallest of the spare capacity requirements that would be minimally needed to guarantee that the 100% restoration assumption is achieved for the studied networks under a single failure scenario.

3) Focusing only on path restoration only, using the path set of All Possible Paths per node pair appears to be attractive because it produces higher restoration ratios compared to using the path set of Link Disjoint Paths, for the tested networks and traffic patterns.

4) Focusing only on path restoration only, a single link failure scenario results in higher restoration ratio compared to using a single node failure scenario, i.e., in

case of failure event, it would be desirable for a network to encounter link failure scenarios more often than node failure scenarios. This confirms our expectation that the restoration process is much faster when using the link failure scenario compared to using the node failure scenario.

5) Focusing only on path restoration only, in case of failure event, dense networks are more prone to achieve fast recovery of affected restorable traffic compared to sparse networks.

These results contribute in enhancing the design choices and/or decisions when designing self-healing and survivable ATM networks.

The network survivability problem addressed in this project deals with the assumption of 100% restoration for a given failure scenario. It is an interesting study to address the case of less than 100% restoration assumption. Furthermore, the work in this project do not address other design issues such as capacity modularization, nonlinearity of VP bandwidth and link capacity, restoration speed, VPI redundancy, node storage capacity, to name a few. These are left as future works.

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Appendix: Network Topologies

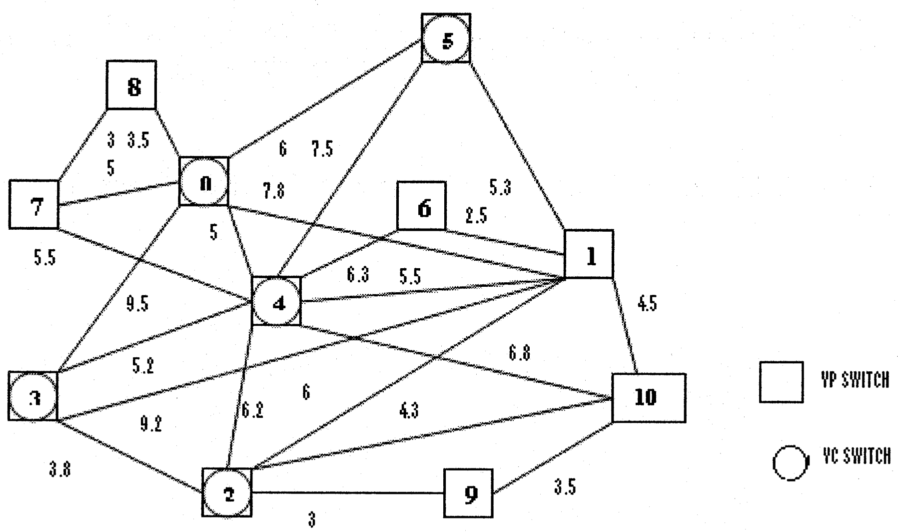

Figure 8: N(11,23) (dense network with 11 nodes and 23 links)

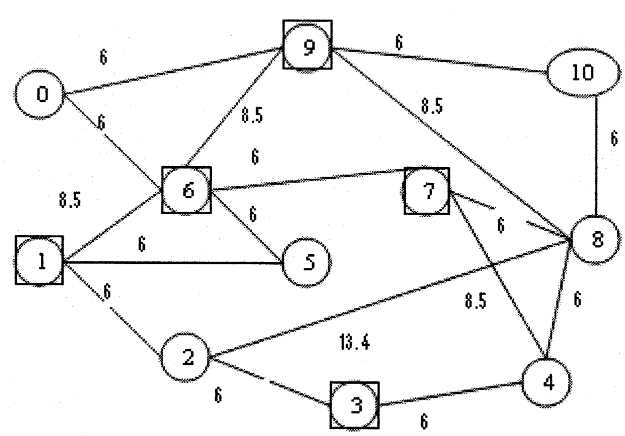

Figure 9: N(11,17) (sparse network with 11 nodes and 17 links)

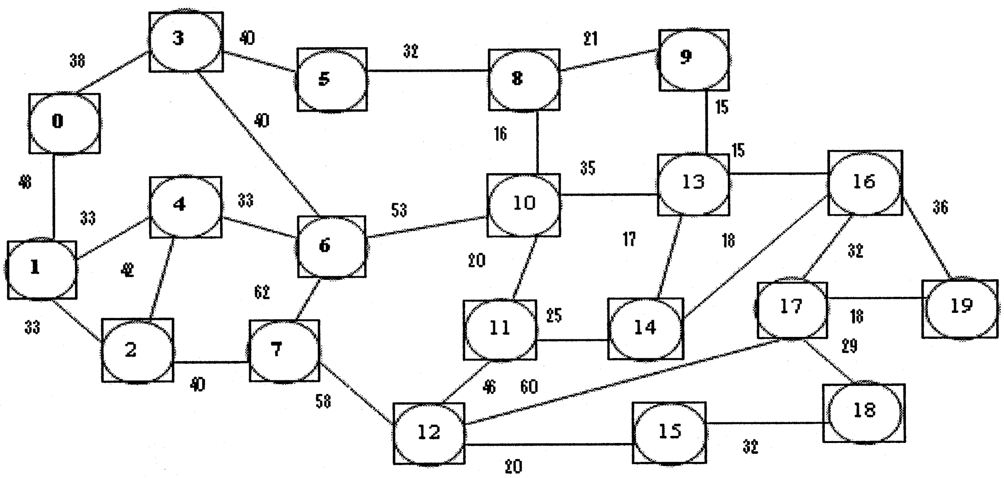

Figure 10: N(20,30) (sparse network with 20 nodes and 30 links)

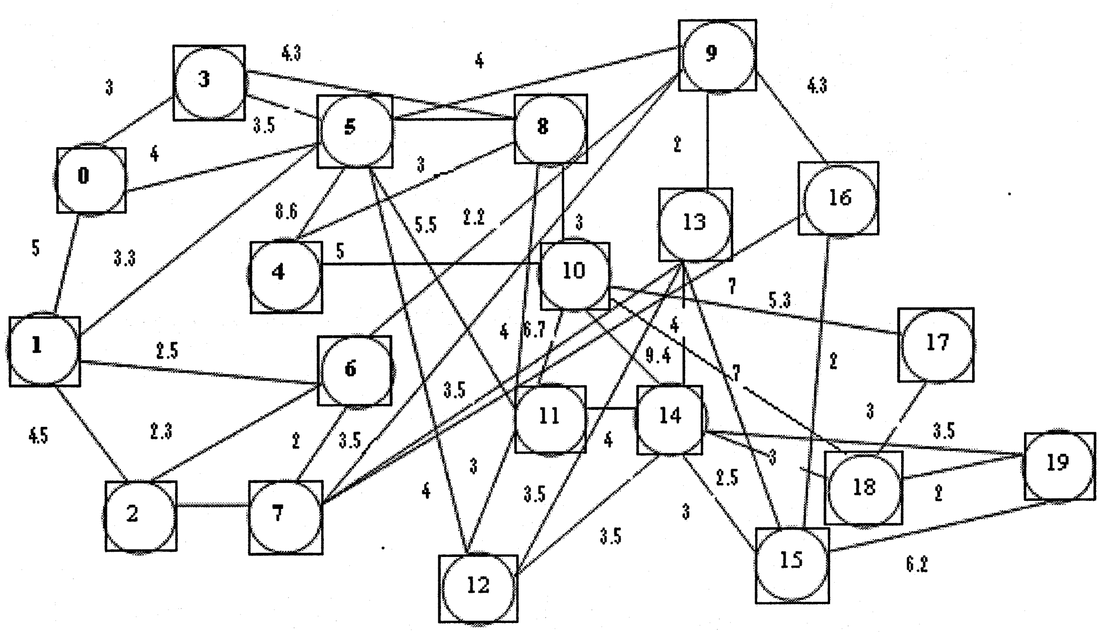

Figure 11: N(20, 42) (dense network with 20 nodes and 42 links).