The Journal of Systems and Software 83 (2010) 457–466

Contents lists available at ScienceDirect

The Journal of Systems and Software

journal homepage: www.elsevier.com/locate/jss

# Survivable ATM mesh networks: Techniques and performance evaluation ☆

Isaac Woungang [a,*], Guangyan Ma [a], Mieso K. Denko [b], Sudip Misra [c], Han-Chieh Chao [d], Mohammad S. Obaidat [e]

[a] *Department of Computer Science, Ryerson University, Toronto, ON, Canada*
[b] *Department of Computing and Information Science, University of Guelph, Guelph, ON, Canada*
[c] *School of Information Technology, Indian Institute of Technology, Kharagpur, West Bengal, India*
[d] *College of Electrical Engineering and Computer Science, National I-Lan University, I-Lan, Taiwan, ROC*
[e] *Department of Computer Science, Monmouth University, NJ, USA*

ARTICLE INFO

*Article history:*
Received 18 April 2009
Received in revised form 17 September 2009
Accepted 18 September 2009
Available online 12 October 2009

*Keywords:*
ATM
Capacity and flow assignment
Spare capacity
Self-healing
Path-based design approach
Survivability
Restoration ratio

ABSTRACT

The Capacity and Flow Assignment problem in self-healing ATM networks is an interesting one from a Generalized Multi-Protocol Label Switching (GMPLS) prospective since IP and ATM protocols are destined to co-exist together in this unified platform. This paper continues the investigation of the path-based design approach of the network survivability problem in existing ATM mesh networks. Our contribution consists in quantifying (1) the effects the selection of candidate paths per node pair has on the restoration ratio, (2) the effect of restoration schemes on the restoration ratio, (3) the effect of failure scenarios on the restoration ratio, and finally (4) the effect of network connectivity on the restoration ratio. Numerical results are presented under representative network topologies, various traffic demands and spare capacity distribution schemes. They provide additional guidelines for the design of survivable ATM mesh-type networks, from a network reliability viewpoint.



## 1. Introduction

With the advent of GMPLS as the new control plane for all transport networks, IP and ATM protocols are clearly destined to co-exist together in this unified environment. This will allow for instance the establishment of end-to-end paths in both packet-based and cell-based networks, thereby consolidating the creation of end-to-end Label Switched Paths (LSP) for several types of networks, including Time Division Multiplexing and Optical networks. To this effect, addressing the network reliability in existing ATM mesh networks is important from a GMPLS design prospective. The design of survivable ATM mesh networks is a specific aspect of a more general problem, referred to as the Capacity and Flow Assignment (CFA) problem in self-healing ATM networks.

The CFA problem has been investigated in many papers (Woungang et al., 2007, 2009; Xiong and Mason, 1999, 2002a; Mason et al., 1999; Medhi, 1997; Medhi and Tipper, 2000; Minoux and Serreault, 1981; Murakami and Kim, 1995; Al-Rumaih et al., 2000; Kasera and Sethi, 2007; Dziong et al., 1990, 1996; Minos, 2009), to name a few. In these studies, several approaches have been proposed to ensure the network survivability (Dziong et al., 1996; Gerstel et al., 1998), where survivability architectures are based on either dedicated resources (for instance, 1 + 1 automatic protection switching) or dynamic restorations (for example, by using available spare capacity for restoring the affected service in a failed link or node). The CFA problem can be considered as a combination of two sub-problems: (1) the Optimal/Near-optimal network design problems (*CFA-ON problems*) – here, the goal is to optimize the link capacities, traffic flows, and restoration paths in the network while achieving the lowest possible network cost or the highest possible network revenue, and (2) the network reliability evaluation (Network Survivability) problem (*CFA-NS problem*) – where the goal is to study the link capacity requirements, the routing, and assignment of working paths and backup virtual paths (BVPs), in order for designing the protection schemes to deal with the failure of a network component (link or node) while maintaining a continuous service performance.

☆ An abridged version of this paper [1] appeared in the Proceedings of IEEE 23rd International Conference on Advanced Information Networking and Applications (AINA 2009), Bradford, UK, May 26–29, 2009.

* Corresponding author.
*E-mail addresses:* iwoungan@scs.ryerson.ca (I. Woungang), guangyan_ma@hotmail.com (G. Ma), denko@cis.uoguelph.ca (M.K. Denko), sudip_misra@yahoo.com (S. Misra), hcc@niu.edu.tw (H.-C. Chao), obaidat@monmouth.edu (M.S. Obaidat).

0164-1212/$ - see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.jss.2009.09.034

In this paper, we continue the investigation of the CFA-NS problem initiated in Xiong and Mason (1999). In that study, the authors considered the end-to-end virtual path (VPee) design approach and the failure-oriented reconfiguration scheme, and derived a linear programming (LP) formulation of the CFA-NS problem. Based on our obtained solutions to this LP problem, our goal is to quantify the network survivability [here defined by means of the *aggregate restoration ratio* – rather than via the average restoration ratio (Xiong and Mason, 1999)] for link and path restorations, under various traffic and design patterns, and spare capacity distribution (SCD) schemes. These schemes represent in fact the different ways that the spare capacity can be distributed in the network, which are as follows:

(1) The spare capacity are evenly distributed among network links (SCD_1).
(2) Each arc has the same spare capacity cost (SCD_2).
(3) The spare capacity on each arc is proportional to the working capacity on that arc.
(4) The spare capacity on each arc is inversely proportional to the working capacity on that arc.

More precisely, this paper quantifies: (1) the effect of the choice of candidate paths (per node pair) on the restoration ratio, (2) the effect of restoration schemes on the restoration ratio, (3) the effect of failure scenarios on the restoration ratio, and (4) the effect of network connectivity on the restoration ratio. These results complement those presented in Xiong and Mason (1999), thereby, provide a solid foundation for the design of restorable ATM mesh-type networks.

This paper deals with ATM mesh restorable networks. From a pragmatic application prospective, the role of bandwidth management in quality and network reliability assurance in such networks is crucial because of the availability of a wide variety of potentially handled service-classes, which renders the resource management more difficult. Typically, an ATM restorable mesh network application's successfulness can be measured by determining the impact the Virtual Path Bandwidth (VPB) control has on the ATM mesh network performance. This is justified by the fact that the VPB allocation (i.e. the distribution of the total bandwidth installed in the network to the VPs) can highly assure network reliability (Medhi, 1997). Thus, optimizing the VPB control is essential. This can be achieved through using a network optimization model such as the one presented in this paper, inherited from Xiong and Mason (1999), where the following requirements should be accounted: model network topology, offered traffic, installed bandwidth in transmission links, demand for reliability and optimization criterion, design of routing table comprising all VPs, specifications of the constraints in bandwidth capacity of the transmission links, and reliability.

It is advocated that the network be designed using cross-connect systems to facilitate both the reallocation of the VP bandwidth, and the efficiency of VPB control in resource management. Finally, the throughput of the model network is often considered as a common measure of the network survivability. It should be calculated based on the fluctuation of the offered traffic and the variation of the desired degree of reliability at the network design phase or afterwards. Many experimental ATM restorable mesh networks have been established worldwide based on commercially available ATM products and switch architectures. For instance, ATM networks for enterprise networks (Dziong et al., 1996; Gerstel et al., 1998), ATM networks for broadband multimedia (Armbruster and Wimmer, 1992), ATM networks for multimedia personal communications (Raychaudhuri, 1996), and other applications (Dziong et al., 1996; Handel et al., 1994), to name a few.

The rest of the paper is organized as follows. Section 2 discusses the related background work on the CFA-NS problem. In Section 3, the ATM network design model is presented. Section 4 discusses the design requirements of the CFA problems inherited from Xiong and Mason (1999). Section 5 introduces the CFA-NS problem and its LP formulation. Section 6 presents our numerical results for the CFA-NS problem on representative network topologies. Finally, Section 7 concludes our work.

## 2. Background

A multitude of methods and models have been used for solving the CFA-NS problem in multi-services networks, including ATM mesh networks, depending on the control and switching strategies involved. A common objective has been to provide a fast restoration upon network failure (single link or node failure) while guaranteeing a minimal spare capacity cost. To this effect, restoration schemes have been employed to protect the working traffic in case of network failure, by reserving spare bandwidth (capacity) in BVPs (Xiong and Mason, 1999; Medhi, 1997; Medhi and Tipper, 2000). To this effect, one should distinguish (a) reactive restoration schemes – where spare capacities are searched only when a network failure occurs, and (b) pre-planned restoration schemes – where spare capacities are identified prior to a network failure event and assigned to pre-computed restoration routes when a failure event occurs. In addition, two kinds of restoration mechanisms have been employed: (a) link restoration – where the two nodes connected to the failed link are responsible for the restoration process, and (b) path restoration – where the two endpoints of each failed working VP are involved in the restoration process.

The multi-commodity flow models have been used to formulate the CFA problems in different networks such as ATM (Woungang et al., 2009; Xiong and Mason, 1999, 2002a,b; Medhi, 1997; Medhi and Tipper, 2000; Minoux and Serreault, 1981; Murakami and Kim, 1995; Al-Rumaih et al., 2000), and SONET/SDH, WDM, MPLS (Xian, 2003). In these models, to compute the search space for the design variables, pre-planned path sets for all traffic demand pairs have been used, with the objective to minimize the total spare capacity required for the restoration from specific failure scenarios (single link/node failure). In addition, link-disjoint BVPs in failure-independent path restoration have been employed. In Gavish et al. (1989), the CFA problem has been formulated as a mixed integer linear programming problem using upper and lower bounding techniques. Unlike previous work, the CFA-NS problem has been investigated in Xiong and Mason (1999) using path restoration and state-dependent BVPs, and the authors have derived an LP formulation of the CFA-NS problem. In this paper, we continue that investigation, using the aggregate restoration ratio [instead of the average restoration ratio (Xiong and Mason, 1999)] as the performance metric to quantify the network survivability, under various traffic demands, design patterns, and the aforementioned SCD schemes.

## 3. Network design model

ATM is a packet-switched technology, which has been designed to reduce the networking costs of maintaining separate specialized networks, by enabling the combination of packet-switched and circuit-switched networks into a single platform. From a network synthesis point of view (Girard and Gardouh, 1993), this objective has been realized by treating ATM as a multi-rate circuit switched network, henceforth, by establishing that the quality of service (QoS) at cell level can be guaranteed through the use of the equivalent capacity (Dziong et al., 1996; Guerin and Ahmadi, 1990) while at the same time maintaining an acceptable grade of service at the connection level. Based on this feature, several mathematical models for dimensioning the circuit-switched networks have been employed in ATM mesh networks (Girard and Gardouh, 1993; Kim et al., 1995), of course, using the appropriate traffic models.

In this work, the end-to-end virtual paths (VPee) design approach of the ATM synthesis (Xiong and Mason, 1999) is considered – here, a complete mesh of VPs is established among origin–destination node pairs and the bandwidth is managed by means of these VPs. Using the distance between two nodes as a metric, the shortest path routing is used as the BVPs routing method, assuming that all working VPs take shortest routes to their destinations.

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 their QoS requirements. This means that when designing ATM networks under the VPee approach (as it is the case in this paper), one needs to clarify whether a single VP or a group VPs per node pair should be considered as part of the design requirements. In our study, we consider the traffic model in Kaufman (1981) 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 (Qiao and Qiao, 2009), 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 (Kaufman, 1981).

We also employ the two-layer network model proposed in Xiong and Mason (1999). This model is composed of a physical layer (or working network) and one logical layer (logical network or spare network) – it should be noticed that several logical networks can co-exists together in a logical layer. The logical layer has been introduced to promote a "virtual" separation of resources and management functions. Each node in the spare network has specific routing or switching capabilities and each node in the working network is connected to at least one node in the spare network. Here, 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), and the term spare capacity to represent the total capacity installed on the spare network to compensate the loss of traffic in case of failure event (single link/node failure) in the working network.

This paper considers a self-healing mesh-type ATM networks using the VP concept (Medhi, 1997) and a pre-planned restoration scheme. In this case, there exists a complete mesh of VPs is established among all node pairs and VCs between two endpoints are multiplexed (respectively, de-multiplexed) by edge VC switches onto (respectively, from) the corresponding VPs linking the same endpoints. VP cross-connects are installed at junction points of the physical network to route incoming VPs to the appropriate outbound physical link supporting these VPs. The information needed to make the admission decision of a novel VC request is available at the origin of the corresponding VP. This information is used by the CAC algorithm to determine whether sufficient bandwidth is available on a proposed route (it is assumed that all working VPs take their shortest route to the destination in the non-failure state) through the network to satisfy the service requirements of a VC or a VP.

In UNI (User Network Interface) mode, given a network failure scenario (i.e. a single link or a single node failure), the restoration of affected traffic takes place at the VP level only and on a path basis as shown in Fig. 1.

In Fig. 1, when the link B–C fails, the network reroutes the failed signal units over the end-to-end replacement path A–D (represented by the dot lines), hence, avoids the "backhauls" shown in Fig. 1. Typically, path restoration requires finding a set of replacement paths between numerous source and destination pairs. To this effect, to obtain the minimum spare capacity cost for a given restoration requirement, a global reconfiguration scenario is often adopted (due to the restoration time constraint), where both affected and unaffected working VPs are rearranged to overcome the failed link or node. The appropriate restoration strategy ultimately depends on many factors among which are the spare capacity requirement, the restoration speed, the amount of memory storage needed at each node, the processing capability at each node, to name a few.

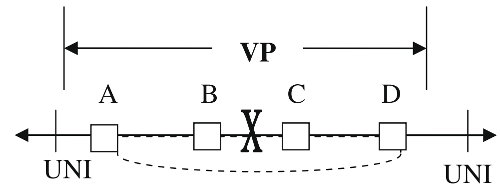


**Fig. 1.** Path restoration.

## 4. Design requirements

The CFA-OND problems have been formulated in Xiong and Mason (1999) as various IP/LP formulations depending on the type of restoration type and restoration mechanism employed. A heuristic termed as *Minimum Cost Route* (*MCR*) algorithm was developed for solving the CFA-OND problems in large-scale ATM networks. Using the MCR coupled with the Simplex method, the authors compared various restoration strategies for self-healing ATM networks, quantitatively in terms of spare capacity requirements. Some of the design considerations that have been employed to these effects are also relevant to the context of this work. We describe them in the sequel.

### 4.1. Bandwidth allocation method

Technically, the working network is described as a graph $Net(|N|, |L|)$ 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 is thus represented as a vector of networks states. Static bandwidth allocation of VPs is used, and the total bandwidth between each origin–destination node 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.

### 4.2. Spare capacity allocation method

Spare capacity allocation can be defined as a method of creating sufficient redundant capacity that can be used in the network in the event of a link or node failure. Spare capacity can be categorized as two types: dedicated or shared. Dedicated spare capacity is considered to be an inefficient restoration scheme because it requires 100% redundancy. It has been successfully implemented only in ring-type networks. In mesh networks, this type of implementation is not desirable because it is very costly. In this paper, we focus on mesh ATM networks with shared spare capacity. Assuming that all working VPs are given and assuming that they take the shortest routes to their destinations in the normal state $s_0$, the spare capacity requirement (SCR) of a self-healing network is defined (Xiong and Mason, 1999) as