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**Survivability approaches for multiple failures in WDM optical networks**

by

Pallab Datta

A dissertation submitted to the graduate faculty  
in partial fulfillment of the requirements for the degree of  
**DOCTOR OF PHILOSOPHY**

Major: Computer Engineering

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## ABSTRACT

The explosive growth of Web-related services over the Internet is bringing millions of new users online, thus fueling an enormous demand for bandwidth. Wavelength Division Multiplexed (WDM) networks, employing wavelength routing have emerged as the dominant technology to satisfy this growing demand for bandwidth. As the amount of traffic carried has increased, any single failure can be catastrophic. Survivability becomes indispensable in such networks. Therefore, it is imperative to design networks that can quickly and efficiently recover from failures. Most research to date in survivable optical network design and operation focuses on single link failures, however, the occurrence of multiple-link failures are not uncommon in a network topology. Multi-link failure scenarios can arise out of two common situations. First, an arbitrary link may fail in the network, and before that link can be repaired, another link fails, thus creating a multi-link failure sequence. Secondly, it might happen in practice that two distinct physical links may be routed via the same common duct or physical channel. A failure at that shared physical location creates a logical multiple-link failure. Such instances where separate fiber optic links share a common failure structure is often referred to as SRLG (Shared-Risk Link Groups).

In this dissertation, we study survivability paradigms for surviving multiple link failures. We study the network design and upgrade problem in WDM backbone networks and formulate it using a simulated annealing based technique. This framework provides a cost effective way of upgrading the network by identifying how much resources to budget at each stage of network evolution. This results in significant cost reductions for the network service provider.

We study protection reconfiguration using two different survivability paradigms, namely sub-graph routing and shared mesh protection. Initially sub-graphs are defined taking into

account link, SRLG, or node failures, and could, in the event of an unrelated or subsequent multi-link failure, incorporate the reactive form of sub-graph fault tolerance. Reactive sub-graph fault tolerance employs a recursive approach for tolerating numerous sequential overlapping failures. It can tolerate simultaneous multiple link failures by simply serializing the handling of each individual fault.

Connection re-routing and network reconfiguration is one of the primary challenges in sub-graph routing methodology. We propose a constrained subgraph routing methodology, which restricts the connections to be routed using the same trunk and channel in the subgraphs, thus minimizing reconfiguration. The subgraph based routing methodology is further explored to tolerate multiple link failures, in the form of shared-risk link groups and node failures.

The generalized diverse routing problem, for finding two diverse routes between a source and destination have been shown to be NP-Complete. Recent studies have also proven the NP-completeness of the SRLG diverse routing. We propose a polynomial time graph transformation algorithm for solving the diverse routing problem for certain specific SRLG's, which includes link-sets incident on a common node. The proposed graph transformation methodology for diverse routing, is also studied for shared-risk node group (SRNG) failures.

## CHAPTER 1. Introduction

In this chapter we provide a brief overview of optical networks and their different generations. We also discuss the research challenges in these networks, including the survivable network design problem and the challenges it poses. Finally, we discuss the contribution of this dissertation, and its organization.

### 1.1 Optical Networks: Background

The Internet is growing faster than ever, with traffic across the core of the network quadrupling ever year [2]. This tremendous growth in traffic demands is fueled by many factors. The explosive growth of Web-related services over the Internet has resulted in millions of users coming online, thus causing an explosive growth in the demand for bandwidth. Different applications ranging from multimedia transmissions, video-conferencing, online applications like Napster, and wide deployment of wide-scale Peer-to-peer (P2P) networks have resulted in a major shift in paradigm in terms of the bandwidth requirements. This changing trends have caused fundamental shift in traffic patterns. To fuel this ever-increasing demands of bandwidth, new technologies emerged from different research labs in the form of optical networks, and different companies were soon to embrace onto it.

Optical fiber communication systems offer a huge bandwidth as compared to copper cables. They are also less susceptible to electromagnetic interferences. The first transatlantic optical communication system, TAT-8, was installed in 1988, operating at 140 Mbps. Since then, in almost 16 years, advances in optical communication technology have facilitated transmission speeds exceeding 1 Tbps [59]. The advances in optical devices, and transmission systems, combined have enabled this to happen. Currently, two spectral regions, centered at 1300 nm

and 1550 nm, of an optical fiber are used for transmission. Using single mode optical fibers, the effective transmission windows available at these spectral regions correspond to 14 THz and 15 THz of potential frequency space for transmission.

Increasing the transmission rates could not be adopted as the only means of increasing the network capacity. Transmission rates beyond a few tens of gigabits per second could not be sustained for longer distances for reasons of impairments due to amplifiers, dispersion, non-linear effects of fiber, and cross-talk. Hence, wavelength division multiplexing (WDM) was introduced that divides the available fiber bandwidth into multiple smaller bandwidth units called wavelengths.

The WDM-based networking concept was derived from a vision of accessing a larger fraction of the approximately 50-THz theoretical information bandwidth of a single-mode fiber. A natural approach to utilize the fiber bandwidth efficiently is to partition the usable bandwidth into non-overlapping wavelength bands. Each wavelength, operating at several gigabits per second, is used at the electronic speed of the end-users. The end-stations thus can communicate using wavelength-level network interfaces. Wavelength division multiplexing turns out to be the most promising candidate for improving the fiber bandwidth utilization in future optical networks.

In literature, optical networks are categorized by dividing their evolution into two phases: first generation optical networks in which optical fiber was used as a mode of communication while all the processing happens at the electronic level, and second generation optical networks in which some of the decisions take place in the optical domain. These are described below.

### **1.1.1 First Generation Optical Networks**

First generation optical networks employ fiber only as a transmission medium. These networks essentially replace copper cables with optical fibers. The key feature of first generation optical networks is that all processing is carried out in the electronic domain. The electronics at a node must handle all data intended for that node as well as all data passing through the node and destined to other nodes in the network. This essentially puts a limitation on

the transmission speed of such networks due to the electronic processing bottleneck. First generation optical networks have been widely deployed in public as well as private enterprise networks. The public network standard for transmission and multiplexing incorporated in North America is Synchronous Optical Networks (SONET) and Synchronous Digital Hierarchy (SDH) in Europe. The private enterprise network standards include Fiber interconnects, such as Enterprise Serial Connection (ESCON), Fiber Channel, High-Performance Parallel Interface (HIPPI), and metropolitan area networks, such as Fiber Distributed Data Interface (FDDI) [70] and Gigabit Ethernet [23].

SONET networks probably are the most popular among first generation networks. They incorporate a wide variety of functions. For example, they provide point-to-point connections between different node pairs in the network. Also, they provide add/drop functionalities, such that only a part of the streams are dropped at a node, and the rest can pass through. Also, SONET networks consist of cross-connects, which can switch multiple traffic streams. Moreover, one of the most attractive feature of SONET networks is their fault tolerant capability, wherein they handle node and link failures without disrupting the services.

### **1.1.2 Second Generation Optical Networks**

The first generation optical networks are now getting in place. An increasing realization that optical networks are capable of providing more functions than just point-to-point transmission led to the emergence of second generation optical networks. Second generation optical networks use WDM technology to split the huge bandwidth provided by a fiber into multiple wavelength channels, that can be used to support multiple transmissions simultaneously. Also, some of the switching and routing functions that are performed by the electronics in first generation optical network can be carried out in the optical domain in second generation optical networks. Second generation optical networks offer different types of services to the higher network layers. The most commonly used service is the lightpath service. A lightpath is a dedicated connection on a wavelength between two nodes in the network, such that no electronic conversion takes place on the path between these two nodes. Moreover, second

generation optical networks offers transparency, i.e., they are insensitive to the nature of the coding or modulation techniques used over the lightpaths.

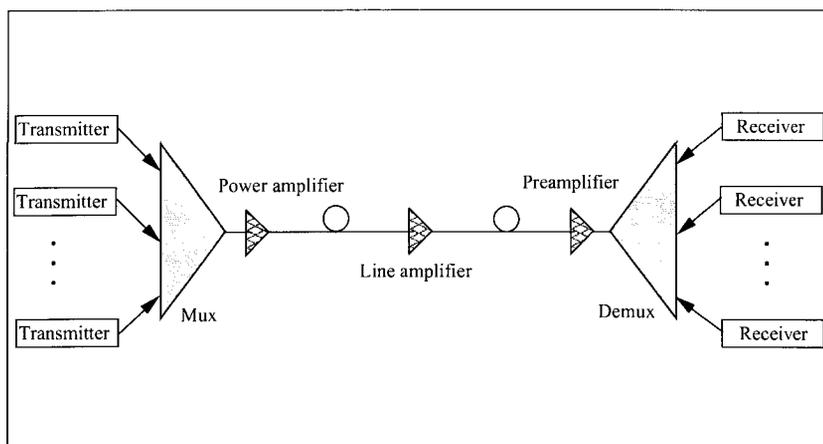


Figure 1.1 A typical WDM link.

Since, second generation optical networks employ WDM technology, they are also known as WDM networks. A typical WDM link is shown in Figure 1.1. It consists of a set of transmitters, optical amplifiers and receivers. The transmitters are lasers, each supporting one wavelength. The outgoing signals from different transmitters are multiplexed together using a multiplexer. The power amplifier immediately after the multiplexer amplifies the combined signal. The signal after travelling some distance on fiber may need amplification again due to attenuation; this task is carried out by an amplifier. Finally, at the destination, the combined signal is amplified again and demultiplexed. Due to demultiplexing, the signal is split into different wavelengths which are converted to the electronic domain using photodetectors, where each photodetector is tuned to a specific wavelength.

WDM network architectures can be classified broadly into two categories: broadcast and select networks, and wavelength routing networks. In a broadcast and select WDM network, the nodes can normally transmit at different wavelengths. The signals are broadcast by a passive device, which is either an optical star coupler or a bus. In case of a coupler, the signals are combined from all nodes by the coupler and the combined signal is transmitted on each of its output ports using a fraction of the power of each signal. When using a bus topology,

each node employs a set of couplers to transmit and receive from the bus. The number of the couplers and their usage is different in both topologies. In a star coupler topology, there is a single  $n \times n$  star coupler for a total of  $n$  nodes in the network, which can also be implemented using  $n/2 \log_2 n$   $2 \times 2$  couplers. A corresponding bus topology requires  $2n$   $2 \times 2$  couplers. In a broadcast and select WDM network, routing is provided to all nodes by default, and hence, no routing function is provided by the network. This is one of the features that differentiates broadcast and select networks from the wavelength routed networks, in which, as the name implies, the network provides the routing functionality. A broadcast and select WDM network, using a star coupler, is shown in Figure 1.2.

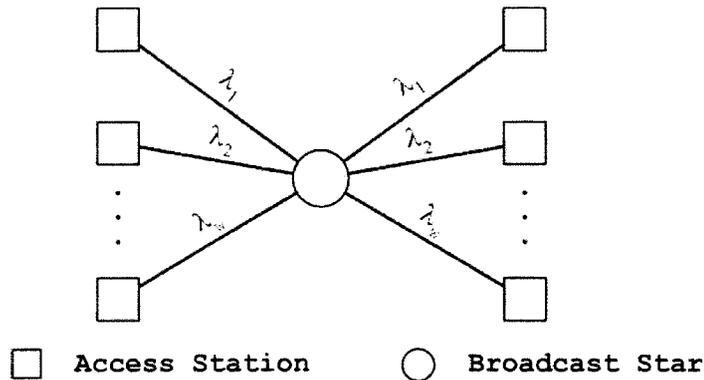


Figure 1.2 A broadcast and select network with a star coupler.

Broadcast and select WDM networks are suitable for local-area or metropolitan-area networks. However, these networks are limited by the number of nodes they can support because wavelengths cannot be reused in the network (at a time, a specific wavelength can be used by only one node in the network,) and also because the transmitted power from a node must be split among all the receivers in the network.

In case of wavelength routing networks, the nodes in the network are capable of routing different wavelengths at an input port to different output ports. This feature enables many nodes in the network to transmit simultaneously at the same wavelength using spatial diversity. For example, a simple wavelength routed network is shown in Figure 1.3. Nodes A and C have established a lightpath on wavelength  $\lambda_1$ , while nodes B and F have established a lightpath

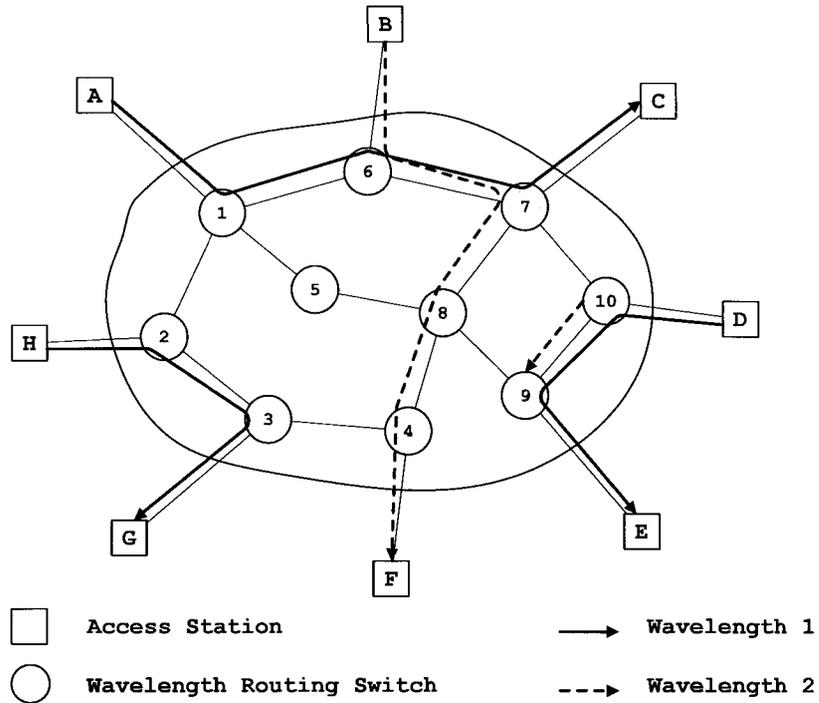


Figure 1.3 A wavelength routed WDM network.

on wavelength  $\lambda_2$ . The lightpath between nodes B and F cannot be established on wavelength  $\lambda_1$  since this wavelength has been occupied on the link 6 – 7 earlier. Also note that the lightpath between node A and node C is using the same wavelength on all the links between the source and the destination nodes. This restriction to maintain the same wavelength on all the physical links traversed by a lightpath is called wavelength-continuity constraint. However, with the use of optical wavelength converters at some nodes this constraint can be relaxed. We will illustrate this point with the help of an example. Figure 1.4 demonstrates the use of wavelength converters. Suppose we have a situation where  $\lambda_2$  is free on a link between nodes 2 and 3, and  $\lambda_1$  is free on the link between nodes 1 and 2. If node 2 is not equipped with a wavelength converter, the connection or call would get blocked. However a wavelength converter at node 2, helps to switch the connection from wavelength  $\lambda_1$  to  $\lambda_2$  and hence helps in improving network performance. However, the trade-off between the cost of wavelengths and wavelength converters need to be taken into consideration.

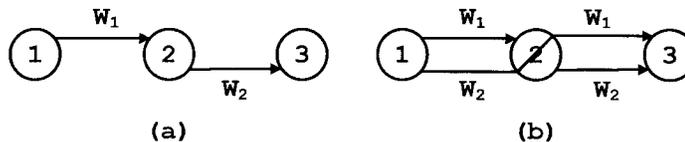


Figure 1.4 A wavelength routing network with a wavelength converter at node 2.

Most wide area networks employ wavelength routing networks. In a wide area network, nodes are interconnected by point-to-point links and hence, unlike broadcast and select networks, the signals are transmitted over only a subset of the links.

### 1.1.3 Optical Networking: Services Perspective

In first generation optical networks the physical layer is merely an optical fiber providing a single wavelength. In second generation optical networks, the physical layer is much more intelligent and is capable of providing many services. The role of the second generation optical networks are defined by the services that can potentially be offered to users [58, 69]. The network can be viewed as different layers interoperating with each other, as shown in Figure 1.5. Different carriers, depending on their requirements can choose different ways to realize the network.

New carriers on the block might use the large installed base of SONET/SDH gear, and the extensive grooming and monitoring capabilities of the digital cross-connects. An Internet service provider might choose to deploy IP over the fiber without the intervening SONET layer. Some carriers, who would like to ensure certain amount of Quality of Service (QoS) guarantees, would prefer to use ATM as their transport technology. The underlying layer is the emerging WDM layer or the optical layer. This layer provides end-to-end routing of lightpaths. Each lightpath may traverse several physical links, and may use one or more wavelengths depending on the availability of the optical wavelength converters in the network. Lightpaths are basically circuit switched pipes carrying traffic at very high rates (2.5Gbps to 40 Gbps). The optical layer provides lightpath service to the higher layers which can be viewed as client layers that makes use of the services provided by the optical layer. We would be mostly looking at the

optical layer from the protection services perspective that need to be provided by the optical layer to the higher layers.

The IP, ATM and SONET layers all incorporate their own protection and restoration mechanisms. These layers are designed to interoperate with other layers and can also directly operate with the fiber. It is interesting to investigate why the optical layer is a better alternative to provide protection and restoration services.

Network service providers can offer varying classes of service based on the choice of protection which can vary from full protection to no protection [28, 58]. Hence, based on the service classes, the traffic in the network can be divided into three classes, full protection, no protection and best-effort. Full-protection traffic is usually the high-priority traffic which requires complete protection at the optical layer. There may be a second category of carriers, which support high priority traffic but requires no protection at the optical layer, as they might be protected by some higher layers such as SONET. The best-effort class attempts to provide protection for the connections based on the resources available. This may include the IP traffic which may have their own protection mechanisms that are slower, and in which cases the optical layer protection maybe beneficial.

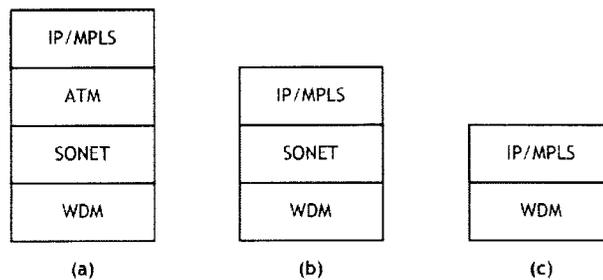


Figure 1.5 Possible Layering Architectures

The optical layer provides the following functionalities:

- It provides transparency, which means that the lightpaths can carry data at different data rates, different formats, follow different protocols etc. This functionality indeed helps an optical layer to support many different layers operating on top of it concurrently. This

basically means that some lightpaths can be carrying SONET data while others are carrying ATM or IP data.

- It provides wavelength re-useability. As different lightpaths may be traversing different physical links, the non-overlapping lightpaths at the physical level can use the same wavelength simultaneously.
- It provides reliability at the optical level. The network can be configured in a way that in the case of failures some automated process re-routes the connections on the failed link(s) or node(s) onto alternative paths.

## 1.2 Research Challenges in Survivable WDM Optical Networks

In this section we discuss major challenges regarding the design and operation of survivable WDM networks. Under the heading of WDM network, we will cover only wavelength routed networks and not broadcast and select networks.

In general the design of a WDM network is an off-line activity, where a designer is supplied with a projected static traffic matrix and is required to design and provision the corresponding WDM network that realizes the traffic matrix while meeting an objective, which maybe minimizing the cost of the network. Alternatively, the network architecture is given and the task is either to fully accommodate the given traffic matrix using the least number of network resources, or to maximally accommodate the given matrix using available resources. On the other hand, operation of a survivable WDM network is an on-line activity in which the network has already been designed and most probably supporting some traffic. The task here is to either accommodate as many new traffic requests while optimizing the network resource usage, or to accommodate all the new traffic with a minimum number of additional resources. The distinct classification of each problem into off-line and on-line, however, is sometimes blurred. Summarizing, the design and operation of the WDM networks basically addresses the following issues:

- For a given amount of resources, how much traffic can be accommodated?

- How much resources are needed to fully accommodate a given traffic matrix?
- How to route and assign wavelengths to traffic requests in a way that satisfies a certain objective function?
- How to provide protection to either all or critical traffic requests, while achieving some objective, such as optimization of network resources?

Several methods have been proposed for joint working and spare capacity planning in survivable WDM networks [8, 9, 45, 57, 73, 83]. These methods considers a static traffic demand and optimizes network cost assuming various cost models and survivability paradigms. However none of these approaches study the incremental network upgrade problem. Some ILP formulations have been studied in [54] for the incremental network upgrade problem. However the ILP techniques have limitations in its applicability in large networks with huge traffic demands. To overcome this limitation the network upgrade problem is explored further in more details in this dissertation.

We briefly discuss some issues and challenges that arise in the design and operation of the mesh-restorable WDM Networks.

### 1.2.1 Routing and Wavelength Assignment

The Routing and Wavelength Assignment (RWA) problem is defined as: *given a network topology, a set of end-to-end lightpath requests, determine how to route those requests, and which wavelengths they should be assigned using the minimum possible number of wavelengths* [69]. This is a very well studied problem [6, 4, 11, 23, 32, 66, 70] and is known to be NP-Complete<sup>1</sup> on arbitrary topologies[69]. Sometimes routing is either given or is straight forward, e.g., in a unidirectional ring. In such cases, the RWA problem reduces to solving the wavelength assignment problem only. The wavelength assignment for a network must satisfy two constraints, namely, no two lightpaths on the same physical link be assigned the same wavelength, and if wavelength conversion is not available, then wavelength continuity constraints

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<sup>1</sup>For a detailed discussion of NP-Completeness please see [51].

be satisfied on all the links that a lightpath traverses. Interestingly, even the wavelength assignment problem is NP-Complete [33].

### 1.2.2 Survivability

Survivability of a network refers to a network's capability to provide continuous service in the presence of failures [21]. In a WDM network, as a single channel may be carrying tens of gigabits of data per second, a single failure would cause a huge amount of service disruption to a large number of users. Design of survivable WDM networks has therefore attracted the attention of the research community. The basic types of failures in the network can be categorized as either link or node failures. Link failure usually occurs because of cable cuts, while nodes failures occurs because of equipment failure at network nodes. Besides, channel failures are also possible in WDM networks. A channel failure is usually caused by the failure of transmitting and/or receiving equipment operating on that channel (wavelength).

The restoration schemes differ in their assumption about the functionality of cross-connects, traffic demand, performance metric, and network control. Survivability paradigms are classified based on their re-routing methodology as path/link based, execution mechanisms as centralized/distributed, by their computation timing as precomputed/real time, and their capacity sharing as dedicated/shared. There are two commonly used protection schemes: shared path protection and dedicated path protection. In case of shared path protection, spare capacity is shared among different protection paths, while in dedicated path protection, the spare capacity is dedicated to individual protection paths. Shared path protection, although more difficult to implement, have been proven to be more capacity efficient than dedicated path protection.

**Proactive Versus Reactive Restoration.** A pro-active or reactive restoration method is either *link based* or *path based*[9]. In a special case, segment based approach can also be used. In a segment based de-touring, a backup segment is assigned for more than one link. A link may be covered by more than one segment. The restoration path, as shown in Figure 1.6, is computed for each path. In case of a link failure, the backup segment is used.

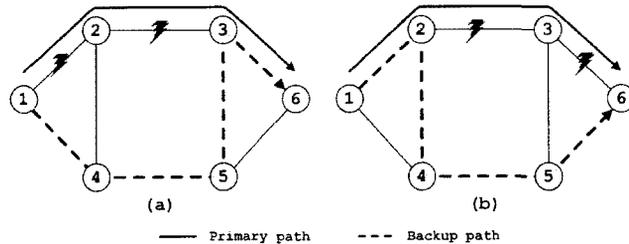


Figure 1.6 Segmented path protection

Link based restoration methods re-route disrupted traffic around the failed link, while path based re-routing replaces the whole path between the source and destination of a demand. Thus, a link based method employs *local de-touring* while the path based method employs *end-to-end de-touring*. The two de-touring mechanisms are shown in Figure 1.7. For a link based method, all routes passing through a link are transferred to a local re-routing path that replaces that link. While this method is attractive for its local nature, it limits the choices for alternatives [9]. In case of wavelength selective networks, the backup path must use the same wavelengths for existing requests as that of their corresponding primary paths as the working segments are retained.

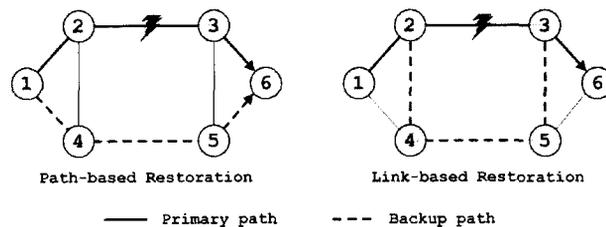


Figure 1.7 Path and link based restoration

The protection approaches are classified as  $1 + 1$ ,  $1 : 1$ , and  $1 : N$  to represent the number of the entities reserved for protection. For example, in a  $1 + 1$  protection scheme, the signal is sent simultaneously over two disjoint lightpaths. The receiver receives the signal from both lightpaths and selects the better one. In a  $1 : 1$  protection scheme each primary lightpath has a dedicated backup lightpath, however, the backup lightpath is used only in a case of failure. In  $1 : N$  protection scheme,  $N$  primary lightpaths share a common backup lightpath. The

necessary condition in this case, is that all the  $N$  lightpaths do not have any overlapping links. These schemes are quite similar to those of SONET networks [21]. In WDM systems, due to the availability of multiple wavelengths on a single fiber, protection methods can be more flexible. This, however, makes the problem more complicated.

WDM networks provide survivability by providing fault-tolerance at the optical layer. However, this has its own merits and demerits. In the following, we provide a brief account of such aspects:

- Optical layer protection and restoration may be used to provide an additional level of resilience in the network. For example, many transport networks are designed to handle a single failure at a time, but not multiple failures. Optical restoration can be used to provide resilience against multiple failures
- Some of the layers operating above the optical layer may not be fully able to provide all the protection functions needed in the network, hence optical layer survivability techniques can fill this deficiency.
- Optical layer protection can be more efficient at handling certain types of failures, such as fiber cuts. Handling such failures at a higher layer, say SONET, will overwhelm the network as a large number of SONET connections need to be restored.
- Optical layer protection cannot handle all types of faults in the network. For example, it cannot handle the failure of an IP router or a SONET ADM attached to the optical network.
- The optical layer protects traffic in units of lightpaths. Thus owing to its transparency, the optical layer cannot provide different levels of protection to different parts of the traffic being carried on a lightpath (part of the traffic may be high-priority, while others may be of low-priority).

Considerable research needs to be done to understand the interactions of recovery protocols that operate at multiple layers in the event of a fiber failure. The outage durations in the

event of a failure, could be lengthened as recovery protocols from various layers might interact with each other. The network might end up in a deadlocked state never converging to a new topology. Such protection interoperability studies are gaining prominence [56]. Many approaches have appeared in the literature in the field of survivability in optical network. For a brief list, interested readers are referred to [21, 28, 58, 62, 81]. For a detailed study of WDM networks we recommend the books in references [63, 69, 75].

### 1.3 Contributions of this Dissertation

In this dissertation we address the challenges discussed in Section 1.2. Our approach is to start with simple models and evolve into more complex but realistic models for the design and provisioning of WDM network considering both static and dynamic traffic arrival following a specific pattern. We propose heuristic approaches for the design of survivable optical networks. One of the main thrust of our work is to develop more realistic and generic models and provide solutions for designing networks which are resilient to multiple failures arising out of shared resources and component failures. We summarize the contributions of the work in this dissertation as follows.

- We provide solutions for the design and provisioning of WDM networks for a static traffic matrix. We formulate the network design and upgrade problem using a simulated annealing based heuristic approach which helps in the designing networks. This heuristic approach makes innovative approximations and leads to translation of the design problem into a well-known solution approach.
- We provide a model for optimal network dimensioning and channel provisioning scheme for static traffic. We provide a cost optimal way to perform network upgrades. As the traffic increases during the life time of the network, more resources can be cost-effectively added to accommodate the increased traffic, thereby incrementally realizing the future topology. The proposed framework encompasses network evolution across multiple generations.

- We develop a generic network restoration architecture, which helps in designing networks that are resilient to single and multi-link failures. The performance of the proposed restoration architecture is compared with other restoration architectures already existing in literature.
- Finally we propose a graph transformation technique for solving the diverse routing problem in the presence of shared resource group failures (in the form of nodes and links). The generalized version of the diverse routing problem has been proved to be NP-Complete [38]. The transformation techniques allows to identify routes in the presence of certain specific failure structures in polynomial time and also allows for better network performance in terms of capability to find out eligible routes in a topology.

#### 1.4 Dissertation Organization

The rest of the dissertation is organized as follows. In Chapter 2, we provide an overview of the related work in the literature on survivability in WDM networks. In Chapter 6 ([62]), we consider design of a WDM network using a simulated annealing approach. In Chapter 3 ([49, 50]), we address the dual-link failure restorability problem, using the sub-graph routing framework. We study the performance of sub-graph routing and compare it with shared mesh protection approaches. In Chapter 4 ([50, 61]), we address the restorability against multiple link failures under shared-risk link groups and shared-risk node groups. We also propose a constrained routing technique namely, constrained sub-graph routing [61], which helps to improve in performance on sub-graph routing. In Chapter 5 ([60]) we propose a graph transformation heuristic for solving the problem of diverse routing in presence of shared-risk resource group failures. In Chapter 7, we conclude this dissertation and outline future research directions in the field of survivable network design in WDM networks in presence of multiple failures.

## CHAPTER 2. Design and Operation of Survivable Networks

Research on survivability and network design can be categorized according to: (1) traffic types, e.g., static traffic and dynamic traffic, (2) network topologies, e.g., unidirectional rings, bidirectional rings, and random mesh-like topologies, (3) solution approaches to the network design problem can be of varied types, e.g., exact solutions and heuristic techniques (4) objective functions, e.g., minimization of network resources, network resource utilization, blocking probability etc.

Survivability in WDM optical networks has been broadly studied over the past several years in different contexts. To the best of our knowledge the earliest papers that talk about survivability in optical networks appeared in [9, 52, 54, 73]. There are currently several survey papers addressing different issues in the design and operation of WDM networks, e.g., [42].

To review the literature in the field of network design and survivability in WDM networks, we first review works that deal with static traffic, and sub-categorize it further based on topology, i.e., ring and mesh topologies. We then review some studies made in the area of dynamic routing approaches. Finally, we present, in separate sections, works related to survivability against dual-link failures and restorability approaches for shared resource group failures.

### 2.1 Network Design Studies: Static Traffic

Design problems in mesh-restorable WDM network research have been extensively studied in [9, 57, 69, 80, 83]. The study in [83] proposes an optimal design scheme for survivable WDM transport network in which fast restoration can be achieved by using predetermined restoration paths.

In [8] ILP and heuristics were used to solve optimization problems for routing, planning of working capacity, rerouting and planning of spare capacity in WDM networks. The planning is done in two steps: first, routing and working capacity assignment are optimized and second, the spare capacity is assigned. The outcome is the dimensioned network with an optimized number of working and spare fibers. The cost model consists of three parameters: cost related to the cable ( $\alpha$  cost), to the fiber ( $\beta$  cost), and to the channel ( $\gamma$  cost). The  $\alpha$  cost stands for the required investment in a link before any capacity on this link can be used. The  $\beta$  cost typically includes the multiplexer, demultiplexer, optical amplifiers, and dispersion compensation management components. It can be subdivided into three components. a) fixed amount ( $\beta_{oi}$ ): represents the fiber terminating equipment (eg. (de)multiplexer ) b) amount of scaling with the fiber length ( $\beta_{li}$ ): represents for example, the fiber c) amount of scaling with the amplifiers ( $\beta_{ai}$ ): represents for example, the amplifier cost. The total cost  $\beta = \beta_{oi} + \beta_{li} * li + \beta_{ai} * \#a$ . where  $li$  is the length of fiber in link  $i$ , and  $\#a$  to the number of amplifiers along the fiber.  $\gamma$  includes all per channel cost e.g., management and regeneration, wavelength conversion, and wavelength cards. The total link cost is  $(\alpha_i + \beta_i * \# fibers_i + \gamma_j * channels_i)$ . The network cost is then the sum of all link and node costs.

Joint optimization of primary and restoration routes to minimize network capacity was studied in [9]. The work in [80] studies the influence of modularity and economy-of-scale effects on the survivable network design.

In [73], Ramamurthy and Mukherjee considered the design of a survivable WDM mesh network. The two main approaches studied in their work are path based protection/restoration and link based protection/restoration. The authors presented some Integer Linear Programming (ILP) formulations to study the capacity requirements for the above protection schemes for a static traffic demand. They also analyzed the protection switching times for different protection schemes, propose distributed restoration protocols and analyze the restoration times and restoration efficiency characteristics of the different restoration protocols.

### 2.1.1 Routing and Wavelength Assignment (RWA) Problem

The routing and wavelength assignment problem has been well studied in wavelength division multiplexed (WDM) optical networks. Both the routing and wavelength assignment subproblems have been proved to be NP-complete [31, 32]. This section previews some of the work done related to this topic.

Reference [32] focuses on the routing and Wavelength-Assignment (RWA) problem in wavelength-routed optical WDM networks. Most of the attention in WDM networks is devoted to networks operating under the wavelength-continuity constraint, in which lightpaths are set up for connection requests between node pairs, and a single lightpath occupy the same wavelength on all of the links that it spans. This paper examines the RWA problem and reviews various routing approaches and wavelength-assignment approaches proposed in the literature. The authors also briefly review the characteristics of wavelength-converted networks. Finally, they propose a new wavelength-assignment scheme, called Distributed Relative Capacity Loss (DRCL), which works well in distributed-controlled networks.

In [10], the authors explore design principles for next-generation WDM optical wide-area networks. This paper formulates the virtual topology design problem as an optimization problem with objective functions: 1) for a given traffic matrix, minimize the network-wide average packet delay, or 2) maximize the scale factor by which the traffic matrix can be scaled up (to provide the maximum capacity upgrade for future traffic demands). The authors resort to heuristic approaches which employ an iterative approach that combines simulated annealing (to search for a good virtual topology) and flow deviation (to optimally route the traffic-and possibly bifurcate its components-on the virtual topology).

Reference [14] proposes a practical approach for solving the routing and wavelength assignment (RWA) problem. A large RWA problem is partitioned into several smaller subproblems, each of which may be solved independently and efficiently using well-known approximation techniques. A multicommodity flow formulation combined with randomized rounding is employed to calculate the routes for lightpaths. Wavelength assignments for lightpaths are performed based on graph-coloring techniques.

The study in [31] investigates the problem of fault management in a wavelength-division multiplexing (WDM)-based optical mesh network in which failures occur due to fiber cuts. This work addresses the routing and wavelength-assignment problem in a network with path protection under duct-layer constraints. Off-line algorithms for static traffic is developed to combat single-duct failures. Both integer linear programs and heuristic algorithms are presented and their performance are compared through numerical examples.

Reference [79] considers the problem of determining an optimal facilities route topology for an optical mesh-restorable network. In general there will be a set of existing right-of-way for cable ducts etc. and a limited number of new acquisition prospects for topology evolution. The enhancement of network connectivity is important in a mesh-based transport network, but new rights-of-way can be very expensive. The work in [79] describes a three-stage heuristic, which produces solutions that are within 8% of optimal results obtained through an ILP.

### 2.1.2 Network Design Solutions: Ring Versus Mesh Approaches

Different mesh based network design solutions have been proposed in literature. Some of the important mesh based network design models are covered in the previous section. In this section, we address some of the network design approaches for ring based networks.

In [46] a comparison of ring and mesh architectures for restorable transport networking is presented from the point of view of service path availability. The comparison is based on detailed simulations of the networks response to random sequences of failures and repairs. The study in this paper shows significantly higher average service path availability in the mesh architecture.

Conventional optical networks are based on SONET rings, but since rings are known to use bandwidth inefficiently, there has been much research into shared mesh protection, which promises significant bandwidth savings [28]. Unfortunately, most shared mesh protection schemes cannot guarantee that failed traffic will be restored within the 50-ms timeframe that SONET standards specify. A notable exception is the p-cycle scheme of Grover and Stamatelakis.

**p-cycles** offer a promising new approach to optical network survivability. Being based on closed cyclic paths of protection capacity, p-cycles offer ring-like speed and pre-configured simplicity but are essentially as efficient as span-restorable mesh networks thereby offering three to six times greater demand-carrying capability than rings for a given transmission capacity. Unlike rings, p-cycles protect straddling failures as well as on-cycle failures and allow working paths to take shortest routes. In contrast, optical rings and fiber-level cycle double covers are at best 100% redundant (and often much higher) in terms of spare and unused working capacity.

p-cycles also offers the much-touted 50 ms restoration guarantee. In [78] the authors address two open and inter-related issues about the design of p-cycle based networks. One of these is to reduce the complexity of solving optimal p-cycle design problems. The second issue is to study how the efficiency of a p-cycle network increases under joint optimization of the working path routes with p-cycle placement. The results indicate impressive improvements in the efficiency from joint design. In [5] the existing p-cycle network design is extended to include the capability of direct restriction of protection path lengths, rather than indirect restriction through circumference limits. The main findings are that p-cycles do exhibit threshold hop-limiting effects (at about two or three hops above those in corresponding mesh networks) and that cycle limiting is a simple and effective surrogate for direct limitation on path lengths in p-cycle design problems.

Cycle-oriented pre-configuration of spare capacity is a well studied approach for the design and operation of mesh-restorable networks. The authors in [77] demonstrate that through a strategy of pre-failure cross-connection between the spare links of a mesh network, it is possible to achieve 100% restoration with little additional spare capacity than in a mesh network.

In [76] the authors consider the routing and wavelength assignment (RWA) problem on WDM ring networks without wavelength conversion. The above work proposes an ILP formulation of the problem and proposes an algorithm to solve it. Although the formulation has exponentially many variables, the authors solve the linear programming relaxation of it by using the column generation technique.

In [24] the authors determine the number of wavelengths required to support all possible virtual topologies on a bidirectional ring physical topology. The authors first determine the wavelength requirements for networks using shortest path routing. The wavelength requirements are further reduced by presenting novel adaptive lightpath RWA strategies. The authors also show that this reduced wavelength requirement is optimal.

In WDM SONET rings, the equipment costs are predominantly high, so efficient traffic grooming can greatly reduce the network cost. In [39], the authors present a comprehensive ILP. The authors also propose a heuristic algorithm for traffic grooming. This paper focuses on nonuniform traffic and both unidirectional and bidirectional rings.

The authors in [34] address the problem of traffic grooming in WDM rings with all-to-all uniform unitary traffic. The authors in this paper minimize the total number of SONET add-drop multiplexers (ADMs) required. They show that this problem corresponds to a partition of the edges of the complete graph into subgraphs, where each subgraph has at most  $C$  edges (where  $C$  is the grooming ratio) and where the total number of vertices has to be minimized. They optimally solve the problem for practical values and infinite congruence classes of values for a given  $C$ .

In [3] the authors developed traffic grooming algorithms for unidirectional SONET WDM ring networks. They show that the general traffic grooming problem is NP-complete. In the more general case of all-to-all uniform traffic they obtain a lower bound on the number of ADMs required, and provide a heuristic algorithm that performs closely to that bound. Finally, the authors consider the use of a hub node, where traffic can be switched between different wavelengths, and obtained an optimal algorithm which minimizes the number of ADMs by efficiently multiplexing and switching the traffic at the hub.

## 2.2 Dynamic Routing in WDM Optical Networks

The authors in [7] study the effect of dynamic routing algorithms in the context of routing with partial information. One of the main results indicate that dynamic routing algorithms perform better than static routing algorithms. However, the network capacity allocated for

backup resources is found to be high. In order to alleviate this problem, the authors study the effectiveness of protecting a connection using a simple segmented path protection scheme. They compared the performance of the partial information routing algorithm with and without segmented path protection through simulation studies. Similar studies related to request specific routing are also conducted in [72]. Dynamic routing schemes improve the performance of WDM grooming networks compared to static routing as they can adapt to changes in the network state.

In a network with dynamic traffic pattern, lightpaths are torn down after the connection holding time. In [30] the authors propose an online network-control mechanism to manage the connections in such a network using path-protection schemes. A comparative study between dedicated path protection and shared path protection is also presented in this work. In [43] the authors present two dynamic routing algorithms based on path and neighborhood link congestion in all-optical networks. The authors in this work consider fixed-path least-congestion (FPLC) routing in which the shortest path may not be preferred. They extended the algorithm to develop a new routing method: dynamic routing using neighborhood information. It is shown by using both analysis and simulation methods that FPLC routing with the first-fit wavelength-assignment method performs much better than the alternate routing method.

Related work in algorithms for dynamic routing of restorable bandwidth guaranteed paths have been done in [53]. The joint on-line routing problem is particularly important in optical networks and in MPLS (Multi Protocol Label Switching) based networks. Given a restoration objective, such as protection against single link failures, backup path bandwidth usage can be reduced by judicious sharing of backup paths amongst certain active paths while still maintaining restorability. The best sharing performance is achieved if the routing of every path in progress in the network is known to the routing algorithm at the time of a new path set-up.

The work in [52] develops an algorithm for integrated dynamic routing of bandwidth guaranteed paths in IP over WDM networks. By integrated routing, we mean routing taking into account the combined topology and resource usage information at the IP and optical layers.

Typically, routing in IP over WDM networks has been separated into routing at the IP layer taking only IP layer information into account, and wavelength routing at the optical layer taking only optical network information into account. The motivation for integrated routing is the potential for better network usage. The performance objective studied is the accommodation of as many requests as possible without requiring any a priori knowledge regarding future arrivals.

### 2.3 Network Operation and Restorability Studies

Most research to date in survivable optical network design and operation focuses on single link failures [70], however, the occurrence of double-link failures is not uncommon in a network topology [18, 26].

Reference [47] considers extensions of the most common mesh-restorable network capacity design formulation that enhance the dual-failure restorability. A significant finding is that design for complete dual-failure restorability requires triple the spare capacity. A second design model, allows a user to specify a total capacity budget limit and obtain the highest average dual-failure restorability possible for that investment limit. This formulation can also be used to traceout the capacity-versus-availability trade-off curve for a mesh network. A third design strategy supports multiple restorability service classes at a minimum total cost.

In [19], the authors suggest methods for achieving high dual-failure restorability in p-cycle networks that are optimally designed only to withstand all single failures, or have minimized amounts of additional capacity for dual failure considerations. In one set of circumstances the authors consider static p-cycles and proposed strategies to enhance the dual-failure restorability based on concepts of failure spreading and limiting the maximum number of protection relationships of any p-cycle. They also considered the case of reconfigurable p-cycles, in which the spare capacity can be reconfigured dynamically, creating a new set of p-cycles that are optimized to withstand possible second failures.

In [74], the authors consider a failure model in which any two links in the network may fail in an arbitrary order. Three loopback methods of recovering from double-link failures are

presented. The first two methods require the identification of the failed links, while the third one does not. However, pre-computing the backup paths for the third method is more difficult than for the first two. A heuristic algorithm that pre-computes backup paths for links is also presented.

The authors in [81] consider a path-based protection methods for two-link failures in mesh optical networks. Two link-disjoint backup paths are pre-computed for each source and destination node pair. The above work identifies scenarios where the backup paths can share their wavelengths without violating 100% restoration guarantee (backup multiplexing). Integer linear programming (ILP) techniques are used to optimize the total capacity requirement for both dedicated and shared-path protection schemes. The results presented in the paper, indicate that backup multiplexing significantly improves the efficiency of total capacity utilization. For double link failure recovery methods, path-based methods are more efficient in capacity utilization than link-based methods. Dedicated-path scheme performs better than shared-link scheme in total capacity utilization on average.

The failure of a single optical link or node in a wavelength division multiplexing (WDM) network may cause simultaneous failure of several optical channels. In some cases, this simultaneity may make it impossible for the higher level (SONET or IP) to restore service. This occurs when the higher level is not aware of the internal details of network design at the WDM level. This phenomenon is often referred to as failure propagation. The study in [56] analyzes three types of failure propagation, called bottleneck, connectivity, and multiple groups. The authors present a solution based on the definition of appropriate requirements at network design and a WDM channel placement algorithm, protection interoperability for WDM (PIW). The proposed method does not require the higher level to be aware of WDM internals, but still avoids the three types of failure propagation mentioned above.

The work in [58] provides a perspective on optical layer protection and restoration based on the services offered by carriers using the optical layer. This is different from other viewpoints that provides a taxonomy of protection techniques in a more abstract fashion for the purposes of standardization. In contrast, taking a services-based view provides a way to distinguish

between protection schemes based on implementation costs and the associated services enabled by the protection scheme.

In [64], a framework for end-to-end service-guaranteed shared protection in dynamic wavelength division multiplexing (WDM) mesh networks, called Short Leap Shared Protection (SLSP), is introduced. The idea of SLSP is to divide each working path into several overlapped protection domains, each of which contains a working and protection path-pair. In addition to a guaranteed restoration service, SLSP is designed to satisfy the future requirements of wavelength-routed optical mesh networks in scalability, class of service, and capacity efficiency.

## 2.4 Restorability Studies Against Multiple Failures

### 2.4.1 Motivation

Multi-link failure scenarios can arise out of two common situations. First, an arbitrary link may fail in the network, and before that link can be repaired, another link fails, thus creating a multi-link failure sequence. Secondly, it might happen in practice that two distinct physical links may be routed via the same common conduit or duct. Instances where separate fiber optic links share a common failure structure are often referred to as SRLG (Shared-Risk Link Group) [16, 36, 65]. In traditional networks the importance of considering SRLG's (Shared Risk Link Groups) is increasing, thus motivating us to study the robustness of a fault tolerant scheme under the scenario of multi-link failures [16, 36]. SRLG's that involve links incident on a common node, are considered to be more common in practise and are often referred to as *coincident SRLG's* [36]. Another class of SRLG's which involves multiple links not incident on the same node are referred to as *non-coincident SRLG's*. A failure at the duct invokes a logical multiple-link failure scenario.

Two examples of shared-risk link groups are shown in Figure 2.1, which illustrates two diverse fiber links which maybe placed in the same conduit at the physical layer and are subject to a single point of failure.

The diverse routing problem have been shown to be NP-Complete in [38], a result that

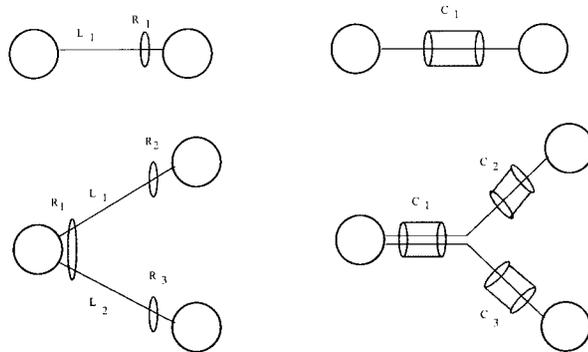


Figure 2.1 Shared-Risk Link Groups and their corresponding physical routes

has been conjectured by several researchers in [27, 40, 67]. Recent studies have proven the NP-completeness of the SRLG diverse routing [24, 26, 38] a special case of the diverse routing problem. The two sub-problems, the least coupled SRLG path problem and the minimum cost SRLG diverse routing problem has been also shown to be NP-Complete [38]. The routing problem under both wavelength capacity and path length constraints has been also shown to be NP-complete [51].

In [26, 31, 67], different heuristic approaches have been studied for diverse routing in presence of SRLG's. In [22] the authors assess the benefits of using statistical techniques to ascertain the shareability of protection channels when computing shared mesh restored lightpaths. With this approach the authors show that with less information, independent of the amount of traffic demand, it is possible to determine the shareability of protection channels with remarkable accuracy.

Different other heuristics such as Active Path First (APF), which finds an active path first, followed by an SRLG-disjoint backup path, is a simplistic viable technique but it sometimes leads to trap scenarios [20]. One of the common problems that arises in restoration path computation is the existence of a *trap topology*. With a trap topology, if a service path is independently routed over a trap topology, then there may not exist a diverse restoration path, even though two diverse paths exist in the network. Different alternative solutions for avoiding trap scenarios in shared risk link disjoint routing have been proposed in [20, 26].

The authors in [36] tries to derive guidelines or insights as to how many such SRLG's can be sustained before the capacity penalty becomes severe. They try to diagnose which SRLG's are the most limiting to overall network efficiency. In addressing these questions they provide a design formulation and procedure for planning any span-restorable network for a known set of SRLGs. One finding of interest is that if all dual failure combinations incident to a common node are allowed for in the design, then nearly all other dual span failure combinations (any two spans in the network) will also be restorable.

The authors in [35] proposed a relatively simple extension to current methods for span-based restoration or protection. The extension allows methods to be designed to deal with node failures, as well as span failures, while retaining most of the locality of operations of span-oriented methods. They outline the operational concept and the corresponding capacity design models. Results show that the method is almost as capacity-efficient as the best end-to-end schemes, but still operates in the network region close to the failure.

The issues of avoiding traps (to be defined later) in path determination and maximizing bandwidth sharing, are more challenging in providing shared SRLG protection than in providing shared path protection without considering SRLG's. In [20], the authors proposed a novel survivability approach called protection using multiple segments (PROMISE) to provide efficient SRLG protection, which can achieve a higher bandwidth efficiency and lower blocking probability at quick speed compared to previous schemes.

In [65] the authors evaluate location-based methods for the auto-discovery of Shared Risk Link Groups (SRLG's), guided by the topology and design of AT&T's next generation transport network. Under realistic scenarios, they find these methods extremely effective in identifying SRLG's and associated link diversity relationships.

In [44], the authors incorporates some realistic constraints into the static provisioning problem, and formulate it under different network resource availability conditions. They considered three classes of shared risk link group (SRLG)-diverse path protection schemes: dedicated, shared, and unprotected. Each connection request is associated with a lightpath length constraint and a revenue value. When the network resources are not sufficient to accommodate

all the connection requests, the static provisioning problem is formulated as a revenue maximization problem. When the network has sufficient resources, the problem becomes a capacity minimization problem with the objective of minimizing the number of used wavelength-links. The authors also propose a tabu search heuristic to solve these problems.

This summarizes some of the important work related to design and operation of survivable WDM networks. As can be seen most of the approaches studied in literature concentrate on single link failure models. A few work have been done related to dual-link failure approaches, and multiple failures due to shared-risk link groups. Node failures, mostly remain unaddressed in the context of WDM optical networks. In the following chapters, we will address some of the research challenges in network design problems and restorability approaches for shared component failures in WDM optical networks.

### CHAPTER 3. Subgraph-Based Routing

In this section we discuss sub-graph based routing strategy for mesh-restorable WDM networks. The sub-graph based routing strategy for tolerating single link failures in a network was first introduced in [48]. In this chapter we attempt to study subgraph-based routing for providing resilience against all possible failure scenarios  $\mathcal{F}$  which includes single link failures, single node failures or a group of node or link failures.

Sub-graph routing attempts to provide a passive form of redundancy in optical networks in the event of a given failure. It is passive in that, before a connection is established, it is subjected to the constraints that it can be routed in the network in both a fault-free state as well as in the presence of failures in the network. The end user experiences nominal interruption in services due to network state restoration which is characterized in [55]. The key characteristics of the subgraph-based routing strategy are as follows:

- The redundancy in routing is provided using the resources available in the network
- Fault recovery network states are maintained throughout the operation of the network
- Sub-graph fault tolerance provides a 100% guarantee for recovery from all possible pre-defined failure states
- Sub-graph routing is a proactive path-based fault tolerance strategy
- The network state must be altered to accommodate the new topology of the network caused by a failure state

The first characteristic highlights one of the most important aspects of the strategy; it doesn't require the allocation of system transmission resources to ensure recoverability after

the detection and location of a link failure. Simply put, there is no explicit link capacity lost due to the routing of backup connections because no active backup connections exist in this strategy. The second characteristic is important because, upon the occurrence of a fault, the network restores itself to a state that eliminates the defective component from consideration, and the network operates as if the failed components never existed. Third, 100% restoration is guaranteed in the event of a designated failure scenario occurring. Fourth, sub-graph routing is proactive because when a failure occurs, the network knows how to recover from it. Finally, it must be stressed that there are no active backup paths present in sub-graph fault tolerance. This results in reduced capacity needs for connections, but requires connections to be possibly re-routed in the event of a component failure, even if they don't traverse the failed component. This property results in the possible interruption of an altruistic connection as discussed in [17]. However, constrained routing [61], Inter-Arrival Planning [17], and Dynamic Sub-Graph Routing Protection [15] all address the issue of connection reconfiguration, and reduce or eliminate the need for it to occur.

### 3.1 Network and Fault Model

A network is represented by a graph  $G = (V, E)$  where  $V$  is the set of nodes  $V = \{v_1, v_2, \dots, v_N\}$  and  $|V| = N$  and  $E$  is the set of edges or link,  $E = \{e_1, e_2, \dots, e_L\}$  and  $|E| = L$ . A failure may be of a single link  $e_l \in E$  or a single node  $v_n \in V$  or a group of multiple links or multiple nodes or a combination of links and nodes. Such groups are said to be SRLG as explained earlier. A group failure is represented by  $s_m$ . A set of all such groups is represented by set  $S$ ,  $S = \{s_1, s_2, \dots, s_M\}$ , where  $|S| = M$ . Thus a set of all possible faults consists of  $\mathcal{F} = E \cup V \cup S$  and

$$\mathcal{F} = \{f_1, f_2, \dots, f_K\} \quad (3.1)$$

A node failure can be represented equivalently by a set of links incident on it. Thus failure of a node  $v_n$  can be represented by a SRLG  $s_j$  where

$$s_j = \{e_l \mid e_l \text{ is incident on node } v_n\} \quad (3.2)$$

Therefore, we do not have to explicitly consider the failure of nodes. Similarly a single link failure can also be treated as an SRLG failure, but to keep terminologies simple, we will keep single link and multi-link failure sets represented separately by E & S.

### 3.2 Algorithm Description

Sub-graph routing is a proactive fault tolerant technique that ensures 100% restoration for all failure scenarios, included in set  $\mathcal{F}$ , for which the network is designed.

A sub-graph,  $G_k = (V_k, E_k)$ , derived from a network  $G = (V, E)$ , is created for each of the failure scenarios  $f_k \in F$  by removing all the edges contained within the failure set. Mathematically,  $G_k = (V_k, E_k)$  where  $V_k = V$  and  $E_k = E - f_k$ . For a connection entering a sub-graph fault tolerant network, it must be successfully routed in all the sub-graphs  $G'_k$ s. If it cannot be routed for any  $G_k$ , then the request is blocked, as it would not be protected against all failure scenarios.

**INPUT:** Graph  $G = (V, E)$ , Failure set  $F = \{f_1, f_2, \dots, f_K\}$  and a set of requests  $R$ .  
**OUTPUT:** To route a request  $R_i$ .  
**ALGORITHM:**  
*Step 1:* Create sub-graphs  $G_k = (V_k, E_k)$  where  $V_k = V$  and  $E_k = E - f_k \forall f_k \in F$   
*Step 2:* Attempt routing the connection on each sub-graph  $G_k$ .  
*Step 3:* If the connection is accepted in all  $G'_k$ s, then the connection is accepted in the base network  
*Else* The connection is dropped from the network.

Figure 3.1 Sub-Graph Routing for all possible failure sets

The original graph,  $G = (V, E)$ , is referred to as the base network. The base network's constituent sub-graphs,  $G_k = (V_k, E_k)$ , are conceptual graphs as they only maintain a state of the base network.

### 3.2.1 Complexity Analysis for Sub-graph Routing

In order to route a connection  $R_i$  in the base network, the connection needs to be routed in all the  $K$  sub-graphs, where  $K$  is the cardinality of the failure-set. The time complexity of routing a request  $R_i$  in a network is governed by the complexity of the routing algorithm. In our case, Dijkstra's shortest path algorithm can be used for routing the connections in each of the sub-graphs. The complexity of the Dijkstra's shortest path algorithm is given by  $O(N \log N)$  [67], where  $N$  is the total number of nodes in the network. Thus, the overall complexity of routing these requests using Dijkstra's is  $O(K \cdot N \log N)$ . It is important to note that sub-graph routing is not limited to using only shortest path routing, but rather can accommodate any other desired routing strategy.

### 3.3 Sub-graph Routing: An Example

A graph with 5 nodes and 7 edges, as shown in Figure 3.2, there will be 7 subgraphs for tolerating all single link failures. For the purposes of this example, each edge in the base network (and its constituent subgraphs) has a capacity of one and that the distance between any pair of adjacent vertices is one.

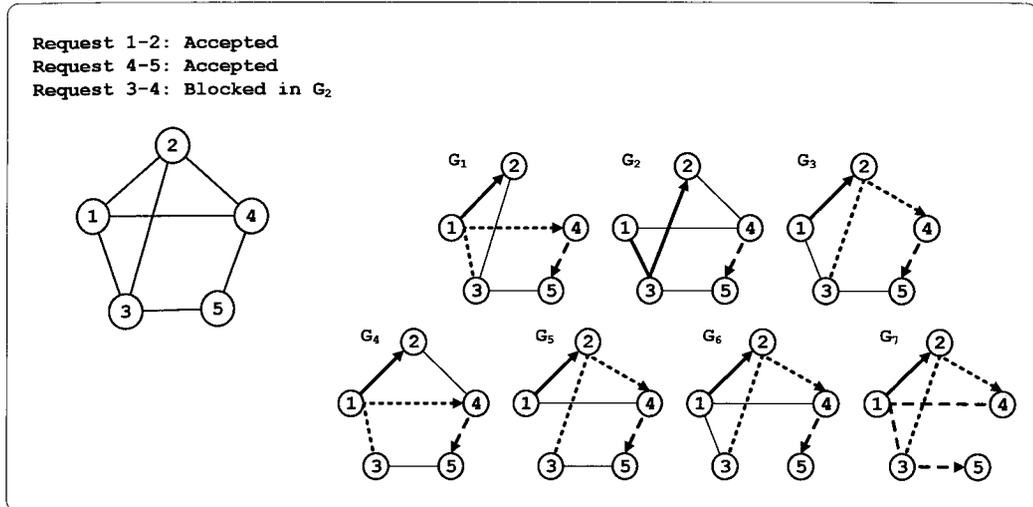


Figure 3.2 Example of sub-graph routing

**Sub-graph Example and Routing Example** Consider the network as shown in Figure 3.2. It has six nodes and seven bi-directional links. Let there be a request issued by vertex  $1 \rightarrow 2$ . This connection attempts to find a path from vertex 1 to 2 on all of the sub-graphs of the base network as shown in Figure 3.2. The connection request from 1 to 2 is accepted as a path is available in all the sub-graphs. Another request from vertex 4 to 5 is routed in the same way as the path from vertex 4 to 5 is available in all subgraphs (although it may be a different path in different subgraphs). When a third request from vertex 3 to 4 arrives, it cannot find paths in subgraph  $G_2$ . Thus the connection request between node 3 to node 4 fails to be routed due to non-availability of resources, and is consequently not accepted in the base network.

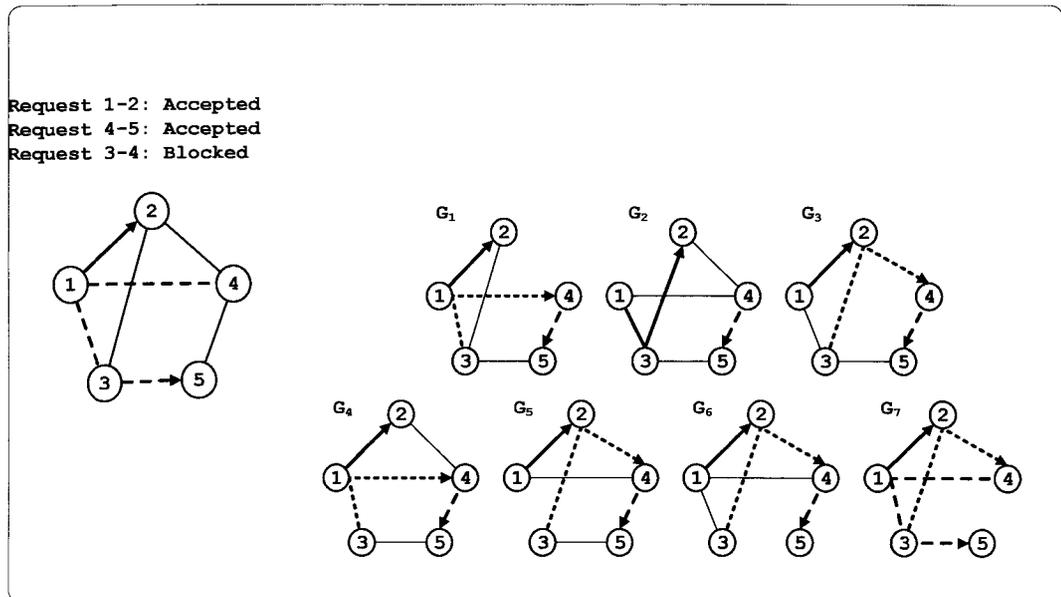


Figure 3.3 Sub-graph based fault-tolerance

**Fault Tolerance With Subgraph-Based Routing** In the event of a fault, the sub-graph-based routed network can fully recover by accepting the subgraph network state corresponding to the located edge failure. For example, assume that there is an arbitrary failure of edge 4 to 5. Suppose the failure is in both directions and for some reason the edge is left non-

operational. To recover, the network reroutes all current connections to reflect the network state depicted by subgraph  $G_7$ . The fault occurrence and recovery cycle is such that connections from the base network are rerouted to the paths in the selected subgraph (corresponding to the failed link). For the example, the request from 4 to 5 need not be rerouted as the path taken in the bases network as well in subgraph  $G_7$  are the same. However the path for the request node 4 to 5 has to be now rerouted through the links (4, 1), (1, 3), and (3, 5) as shown in  $G_7$  of Figure 3.3.

### 3.4 Constrained Sub-graph Routing

A limitation of sub-graph based fault tolerance is the possibility of connections being re-assigned during transition from the base network to the target sub-graph [48] when a fault occurs even if they do not traverse the failed component. The above proposed scheme depends on the network's ability to change to the state of a sub-graph during fault recovery. This potentially requires many connections in the network to be reassigned to different paths as defined by a sub-graph.

To overcome this limitation the concept of *constrained sub-graph routing* is introduced. The constrained sub-graph routing minimizes the probability of reassignment during transition from the base network to the final sub-graph when a fault occurs. Constrained sub-graph routing can be of two types. They are:

- **Constraint 1:** A connection is constrained to be routed on the same path as in the base network in all the sub-graphs which contain all the links traversed by the path.
- **Constraint 2:** If constraint 1 is fulfilled, then the connection can be further constrained to be routed along the same trunk in the sub-graph as in the base network.

The probability that a connection will have to be re-assigned can be reduced by constraining the route that a connection takes on each sub-graph. Simply stated, whatever the path a connection takes in the base network exists in a sub-graph, the connection must be routed along that path. In the example of a single-link fault tolerant network, a connection will have

the same route in  $(E-l)$  sub-graphs, where  $l$  denotes the number of links along the path of an arbitrary connection. It has been studied in [61] that constraining the path (constraint 1) that a connection takes in all possible sub-graphs has the effect of reducing the blocking probability of requests entering the network as well as the probability that connections will have to be path reassigned in the event of a failure.

Constraint 2 requires that a sub-graph connection not only take the same path, but also the same trunk along that path as in the base network. In this manner, any connection not directly affected by the failed link will not be interrupted in  $(E-l)$  sub-graphs. This is an attempt to avoid node reconfiguration by minimizing the probability of reassignment. Trunk constrained routing, in its simplest form, significantly degrades network performance in terms of increasing blocking probability, but realizes a very low probability of reassignment for sub-graph routing architectures. Mechanisms have been also developed in [55], which accomplish the task of switching connections that causes the minimal amount of service disruption and delay in the network.

#### 3.4.1 Complexity analysis of constrained sub-graph routing

Constrained sub-graph routing requires that each sub-graph containing all of the links of a request's selected path in the base network use the same path. In other words, if a request's path contains  $l$  links, that request, if accepted, will be routed on the same path in the base network as well as  $(K-l)$  sub-graphs. Constrained sub-graph routing improves network performance by decreasing blocking probability and the probability of reassignment. The probability of reassignment is the probability that an active connection in the network will have to be reassigned in the event of a fault. Constrained sub-graph routing also lowers the complexity of routing in sub-graph routed networks. Instead of a complexity of  $O(K \cdot W \cdot N \log N)$ , assuming the use of Dijkstra's, an overall time complexity of  $O((K + 1 - (K - l)) \cdot W \cdot N \log N) \approx O(l \cdot W \cdot N \log N)$ , where  $W$  is the number of wavelengths in each link and  $l$  is the length of the path, is achieved because a path needs to be selected only for the base network and the  $l$  sub-graphs that doesn't contain all of the links of the path selected by the

base network.

### **3.5 Dual failure Restorability Using Single Failure Tolerant Design Approach**

In this section we study the restorability achieved for dual-failures in a network, when it is provisioned to tolerate only single link failures. Since most applications require very high availability, it is important to design networks which can tolerate single link failures in a network. We further study the amount of restorability that can be achieved against a subsequent second link failure. We study two different paradigms of protection, namely sub-graph routing and shared mesh protection. We evaluate the degree of restorability achieved for both the schemes, and also attempt to minimize the network cost by minimizing the higher layer electronic equipment cost, and simultaneously minimize the total number of wavelengths used. We also evaluate the degree of protection against a dual-link failure, that is automatically achieved by each of these protection schemes.

The main contributions of this work are summarized as follows:

- It provides a framework for studying overlapping sequential failures under two different protection paradigms. The ability to tolerate a high percentage of multiple overlapping sequential or unrelated simultaneous link failures, using the merits of sub-graph fault tolerance and shared mesh protection in a reactive manner is the subject of this work. The framework provides a recursive solution for accommodating dual link failures, which can be extended for higher order link failures.
- It provides a comparative study of two different protection methodologies for dual link failure scenario.
- In this work sub-graph protection is employed to tolerate all single link failures and we analyze its ability to restore connections from a second link failure in the network.

### 3.5.1 Motivation

In [47], the capacity required to ensure complete restorability against all dual-failure situations is studied. One of the significant findings is that design for complete dual-failure restorability requires almost triple amount of spare capacity. An Integer Linear Programming (ILP) formulation for supporting multiple restorability service classes at an overall minimum cost is also presented.

In this work, networks are provisioned to tolerate all single link failure scenarios using both shared mesh protection and sub-graph routing. In the event of the first link failure, the restoration of connections is studied and the ability to tolerate an additional link fault is assessed. In the case of shared mesh protection, additional backup paths are dynamically calculated for all affected connections, be they backup or primary. This approach is similar to protection-reconfiguration approach to accommodate higher order link failures. With respect to sub-graph routing, the approach is a recursive one in that the set of sub-graphs fails the link that has failed in the original network. Attempted rerouting of the connections affected by the failed link is performed in order to obtain second link failure protection. The idea is recursive because it can be extended to an indefinite number of successive link failures, so long as the network remains adequately connected.

Proactive sub-graph routing has the advantage of providing protection for 100% of the failure scenarios for which sub-graphs are designed. Unfortunately, in the case of link fault tolerant sub-graphs, there are  $L(L-1)$  possible dual-link failure states in a network with  $L$  links. Hence, far too many sub-graphs network instances needs to be generated, to provide protection against all possible dual-failure scenarios, not to mention multi-link failures exceeding two links.

Additionally, there is no mechanism provided to accommodate overlapping sequential failures, only simultaneous related ones. Fortunately, the flexibility of the sub-graph strategy also allows it to be used in the reactive tolerance of link failures. The ability to tolerate a high percentage of multiple overlapping sequential or unrelated simultaneous link failures, using the merits of sub-graph fault tolerance in a reactive manner is the subject of this work.

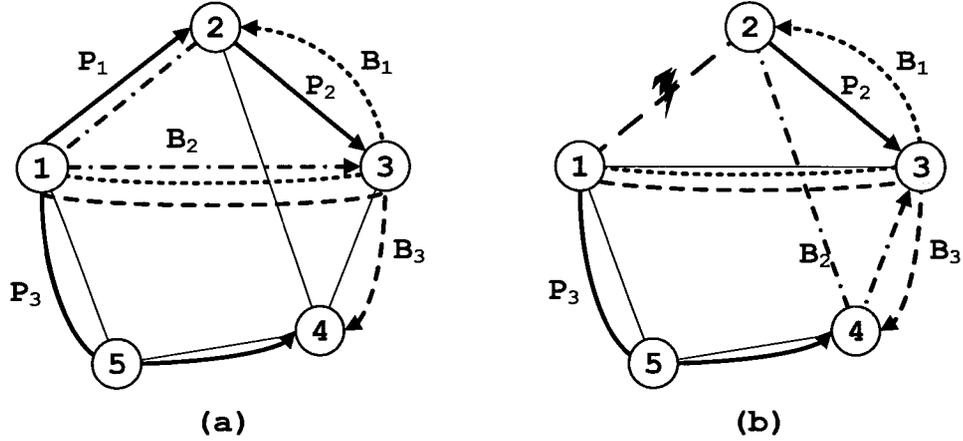


Figure 3.4 (a) Routing of requests using shared mesh protection. (b) Rerouting of requests on failure of link  $1 \rightarrow 2$ .

### 3.6 Coverage for Dual-Link Failure Scenarios Using Shared-Mesh Protection

Let the primary path of a request  $R_i$  be denoted by  $P_i$  and the two link-disjoint end-to-end backup paths for tolerating two independent link failures  $e$  and  $f$  be  $B_i(e)$  and  $B_i(f)$ . Figure 3.4(a) indicates the primary and backup routes and wavelength assignment using backup multiplexing or shared mesh protection for three requests ( $R_1 - R_3$ ). The routes and the wavelengths assigned for each request are also shown in Table 3.1. The primary and backup connections for request  $R_1$  are given by  $1 \rightarrow 2$ , and  $1 \rightarrow 3 \rightarrow 2$ , respectively, and is assigned wavelength  $\lambda_1$ . Similarly request  $R_2$  is assigned primary and backup routes  $2 \rightarrow 3$ , and  $2 \rightarrow 1 \rightarrow 3$ , respectively. Since the primary routes of the requests  $R_1$  and  $R_2$  don't share common links their backup paths can share wavelength  $\lambda_1$ .

Connection request  $R_3$  is routed using primary and backup routes  $1 \rightarrow 5 \rightarrow 4$ , and  $1 \rightarrow 3 \rightarrow 4$  on wavelength  $\lambda_1$ . The backup route for  $R_3$  can be assigned the wavelength  $\lambda_1$  and it can share this wavelength with the two other backup paths, since the corresponding primary paths are link disjoint.

Let there be a failure at link  $e$  ( $1 \rightarrow 2$ ) as shown in Figure 3.4(b). The effected primary route is  $P_1' : 1 \rightarrow 2$ . The effected backup connections which were multiplexed on the effected

Table 3.1 Primary and backup paths before failure.

Requests	Primary Lightpath	Backup Lightpath
$R_1$ (1→2)	(1→2) - $\lambda_1$	(1→3→2) - $\lambda_1$
$R_2$ (2→3)	(2→3) - $\lambda_1$	(2→1→3) - $\lambda_1$
$R_3$ (1→4)	(1→5→4) - $\lambda_1$	(1→3→4) - $\lambda_1$

link  $e$  correspond to requests  $R_2$  and  $R_3$ , whose primary and backup path combinations are shown in Table 3.1.

After the failure of link  $e$ ,  $B_1(e) : 1 \rightarrow 3 \rightarrow 2$  restores  $P_1$  and  $P_2$ , respectively, as shown in Figure 3.4 and Table 3.2. A new alternate backup connection corresponding to  $P_1$  should be found on the graph so that the connection can tolerate a second failure in the network. This backup connection is referred to as  $B_1(f)$ , since it guarantees restoration for the second failure  $f$  in the network. Assuming each request is of unit capacity and each link is a bidirectional link having a capacity of one unit in each direction, in the above example  $B_1(f)$  doesn't exist. Thus, this request cannot be restored in the event of a second failure overlapping in time and incident on one of the links of  $B_1(e)$ .

Table 3.2 Primary and backup paths after failure of link 1-2.

Requests	Primary Lightpath	Backup Lightpath
$R_1$ (1→2)	(1→3→2) - $\lambda_1$	<i>No routes possible</i>
$R_2$ (2→3)	(2→3) - $\lambda_1$	(2→4→3) - $\lambda_1$
$R_3$ (1→4)	(1→5→4) - $\lambda_1$	<i>No routes possible</i>

$P_2$  corresponding to the backup connection  $B_2(e)$  that was multiplexed on the failed link  $1 \rightarrow 2$ , needs to find  $B_2(f)$ . Since  $P_2$  remains unaffected by the link failure, it can potentially reroute its backup such that  $B_2(f)$  can also be multiplexed. However, this is constrained by the available capacity on a link and more importantly, the availability of an alternate backup path in the first place because the failure of a critical link may cause complete disconnection of the graph. It is important to note that primary and backup connections that are unaffected by any link failures remain uninterrupted in their service and are not re-routed.

The second alternate backup path for the connection  $R_2$  is given by  $B_2(f) : 2 \rightarrow 4 \rightarrow 3$ . Moreover, the routing of request  $R_1$  along  $B_1(e)$  would force  $R_3$  to search for a new alternate backup path to tolerate a second link failure, due to the capacity constraint on link  $1 \rightarrow 3$ . However, request  $R_3$  fails to find  $B_3(f)$  and hence cannot be recovered in the event of a second overlapping link failure along its primary path.

### 3.7 Coverage for Second Sequential Link Failure Scenario

In this section, the capability of the sub-graph routing scheme, presented in [48], to tolerate sequential overlapping link failures in the network is studied. The set of  $L$  sub-graphs represent all possible single-link failures in the network. The original graph is referred to as the base network. The base network's constituent sub-graphs are not referred to as networks because they correspond to a base network state reached through failure of any one link.

In the sub-graph routing strategy, a connection request is accepted in the base network only if it can be routed in all the sub-graphs. Hence, the accepted connections are guaranteed restorability against all single link failure scenarios. If any link,  $e_i$ , fails in the network, the network transitions to the state of the sub-graph,  $G_i$ , and some of the connections directly unaffected by the failure in the base network are potentially re-routed corresponding to the routing of the requests in sub-graph  $G_i$ . Let us consider that the link  $1 \rightarrow 3$  fails. The network tries to restore all the present connections by migrating to the sub-graph  $G_4$  as shown in Figure 3.5.

In order to ensure that these requests also have complete coverage against a second link fault in the network, we delete the corresponding failed link  $e_i$  from the other  $L-1$  sub-graphs, and route the compromised connections in  $G_4$  on the remaining sub-graphs. The connections that get accepted in all the remaining sub-graphs satisfy complete 100% coverage against all overlapping dual-failure scenarios. However, the connections which are unsuccessful in being re-routed in the remaining sub-graphs are guaranteed restorability only against the initial single link failure. Thus we can efficiently route connections that are protected against all single link failures, and hopefully a high percentage of all possible sequential overlapping dual

link failures, using a heuristic best-effort strategy.

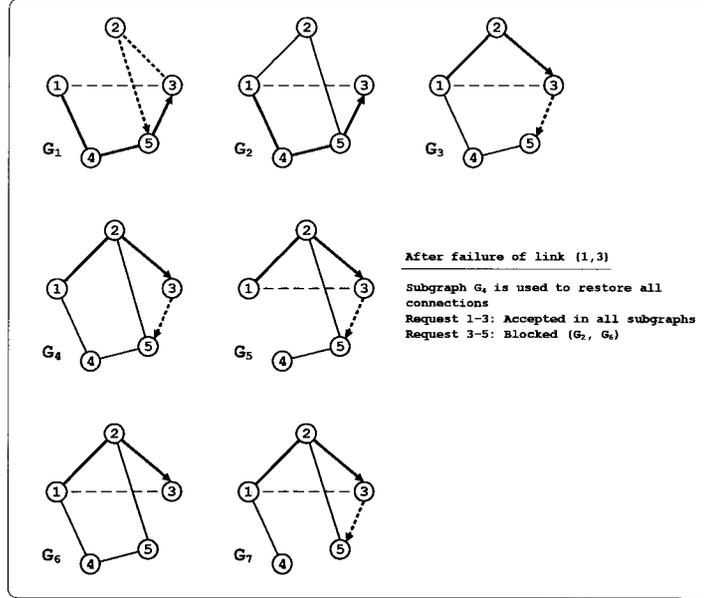


Figure 3.5 Rerouting of requests upon failure of link  $1 \rightarrow 3$ .

### 3.7.1 Complexity Analysis for Tolerating Second Link Failure

The following section analyzes the complexity of the sub-graph routing algorithm while ensuring complete dual-failure coverage. In order to route a connection  $R_i$  in the *base network*, the connection needs to be routed in all the  $|E| = L$  sub-graphs. The time complexity of routing a request  $R_i$  in a network is governed by the complexity of the routing algorithm. In our case, Dijkstra's shortest path algorithm can be used for routing the connections in each of the  $L$  sub-graphs. The complexity of the Dijkstra's shortest path algorithm is given by  $O(N \log N)$  [67], where  $N$  is the total number of nodes in the network. Thus, the overall complexity of routing these requests using Dijkstra's is  $O(L \cdot N \log N)$ . It is important to note that sub-graph routing is not limited to using only shortest path routing, but rather can accommodate any other desired routing metric.

After the failure of the first link  $e$ , the network makes a transition from the base network to the  $G_e^{th}$  sub-graph. Now to ensure restorability against failure of another link  $f$ , a sub-

set of connection requests need to be re-routed on the remaining  $L-1$  sub-graphs, that is all sub-graphs except the  $G_e^{th}$  graph. The requests that need to be re-routed on all the  $L-1$  sub-graphs in order to tolerate a second fault would require an additional worst case computation of  $O(L \cdot N \log N)$ . Thus the worst case complexity for routing each request for dual-failure survivability is  $O(L^2 \cdot N \log N)$ . However, in the following section we will show that the size of the sub-set of requests that have this worst case routing complexity is relatively small.

In [61], the concept of constrained sub-graph routing is presented. Constrained sub-graph routing requires that each sub-graph containing all of the links of a request's selected path in the base network use the same path. In other words, if a request's path contains  $l$  links, that request, if accepted, will be routed on the same path in the base network as well as  $L-l$  sub-graphs. Constrained sub-graph routing has been shown to increase network performance by decreasing blocking probability and the probability of reassignment. The probability of reassignment is the probability that an active connection in the network will have to be re-assigned in the event of a fault. Constrained sub-graph routing also lowers the time complexity of routing in sub-graph routed networks. Instead of a complexity of  $O(L \cdot W \cdot N \log N)$ , assuming the use of Dijkstra's, an overall time complexity of  $O((L+1 - (L-l)) \cdot W \cdot N \log N) \approx O((l+1) \cdot W \cdot N \log N) \approx O(l \cdot W \cdot N \log N)$ , where  $l$  is the length of the path and  $W$  is the total number of wavelengths in a link, is achieved because a path need only be selected for the base network and  $l$  sub-graphs that doesn't contain all of the links of the path selected by the base network. The path in  $(L-l)$  sub-graphs is already selected through constraining the path to be the same as in the base network.

As a result of sub-graph routing being a recursive technique, the time complexity of connection recovery from a link failure also changes.  $O(((L+1-1) - 1 - (L-l-1)) \cdot N \log N) \approx O(l \cdot N \log N)$  is needed for the recovery because the connection doesn't have to be routed on the  $G_e^{th}$  or the base network, and due to path constraining,  $L-l-1$  sub-graphs will route the connection exactly like the  $G_e^{th}$  sub-graph. This, along with the original routing time complexity discussed in the previous paragraph, yields an overall time complexity for a single overlapping sequential link failures of  $O(l^2 \cdot W^2 \cdot N \log N)$  instead of the  $O(L^2 \cdot W^2 \cdot N \log N)$

time needed in unconstrained sub-graph routing.

This formulation can be extended in a recursive fashion for any number of sequential overlapping link failures. Let  $r$  ( $r > 0$ ) be the recursive depth of the recovery, i.e. the number of sequential overlapping link failures. If  $r = 1$ , there have been no single link failures (100% link failure protection),  $r = 2$  there has been 1 link failure (heuristic best-effort overlapping sequential link failure protection), and so on. This yields the complexity  $O(l^r \cdot W^r \cdot N \log N)$ , and indicates a network capable of providing 100% single link failure protection for  $r = 1$  and heuristic best-effort protection for  $r$  overlapping sequential single link failures.

### 3.8 Results

The performance of both the backup multiplexing and the sub-graph routing schemes are evaluated through simulation. Three topologies were used: the 14-node, 23-link NSFNET; the 11-node, 22-link NJLATA; and a standard 9-node, 18-link 3x3 mesh torus.

The blocking probabilities for both schemes are computed in the absence as well as presence of faults in the system. The sub-graph routing strategy had shown considerably lower blocking in the absence of faults as compared to the backup multiplexing scheme [48]. In this work, we primarily focus on the blocking probabilities in the presence of faults for backup multiplexing, and the blocking probability for sub-graph routing with and without randomly occurring single-link faults. For simulation purposes, each link is assumed to be composed of two-unidirectional links, each with only one fiber. The total number of wavelengths used are  $W = 16$  for each fiber in each unidirectional link.

The performance of the network in the presence of faults has been assessed in two ways. In the first, an arbitrary link is failed randomly and repaired during the simulation time frame as a fault would occur in a real world situation. In the second scenario, the simulation is paused periodically, and the network state is tested against all possible link failures. The simulation then continues without the network state being altered by the occurrence of any fault.

The arrival of the requests at a node follows a Poisson process with rate  $\lambda$  and is equally likely to be destined to any other node. The holding time of the requests follow an exponential

distribution with unit mean. The capacity requirements of each request is unit wavelength. The random link faults are assumed to occur following a Poisson distribution.

Link load is a measure of the load placed on each link in the network at any given time. It is useful in providing a baseline for the comparison of the effectiveness of routing strategies across different network topologies. The link load can be calculated by the formula,  $\gamma = \frac{N \cdot \lambda \cdot H}{L}$ , where  $N$  is the number of nodes in the network,  $\lambda$  is the arrival rate of the requests per node,  $H$  is the average hop length of each connection and  $L$  is the total number of links in the network.

**Blocking Probability**, as illustrated in Figure 3.6, shows how the backup multiplexing and sub-graph routing performs with and without the presence of random faults. The blocking probabilities of the sub-graph routing strategy are extremely low compared to the backup multiplexing scheme and reasonably close to the blocking probability achieved in the presence of no faults.

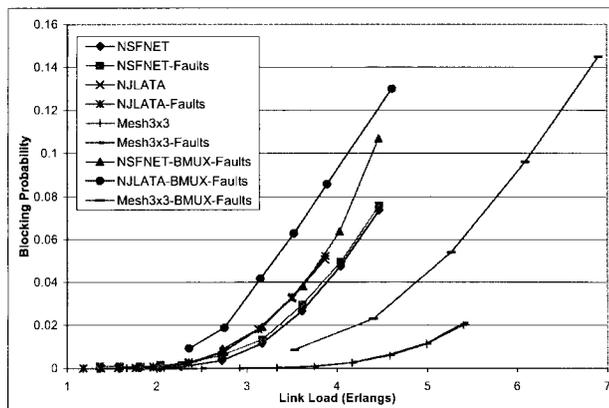


Figure 3.6 Blocking Probability vs. Link Load

Depicted in Figure 3.7, **Automatic Sequential Overlapping Fault Coverage**, indicates that around 72-81% of connections are automatically covered for all possible dual-failures, across different topologies, without being rerouted, in the sub-graph scheme as compared to 49-70% for the backup multiplexing routing strategy. The automatic dual-failure coverage in the sub-graph routing strategy is calculated as the number of connections in the final sub-graph  $G_e$  (reached by the failure in the link  $e$ ), that do not need to be rerouted in the other  $L-1$

sub-graphs, and hence are automatically covered for two link failures, the first failure being on link  $e$ .

High automatic coverage is important because it means that fewer connections will have to be rerouted in the event of a single link failure, in order to provide protection against a second overlapping failure. Section 4.8 discussed the time complexity of the proposed sub-graph routing scheme in terms of the amount of time required to recover from a single fault on a per connection basis. Having said this, the fewer connections, the less work that needs to be done to recover.

Additionally, higher automatic coverage means that active connections also have a better chance of being protected against a second link failure because the connection does not have to attempt rerouting. The total capacity reservation for tolerating a single fault in the backup multiplexing scheme has been shown to be around 150-160% [82]. Thus the probability of reserving a second path, in the event of a fault, to tolerate a second failure is extremely low either due to lack of capacity in the network or due to graph disconnection caused by the first failure.

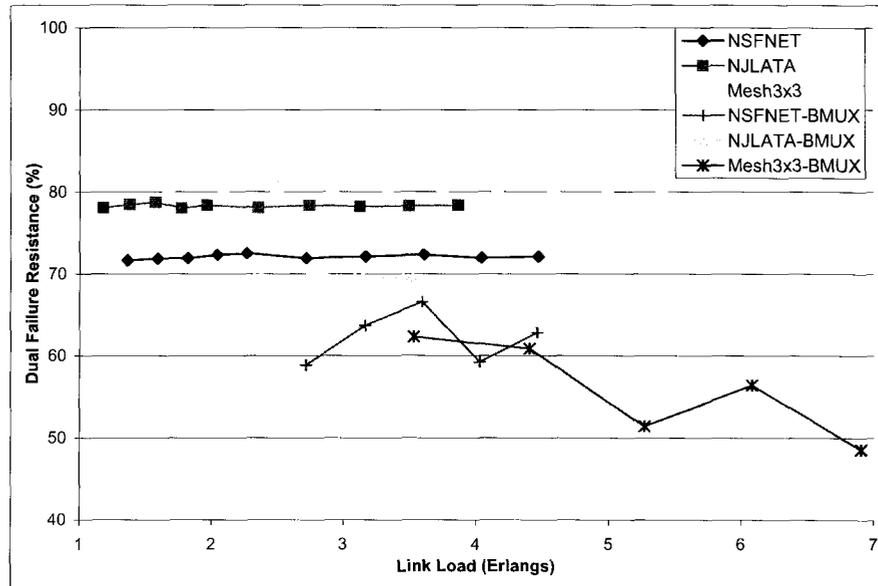


Figure 3.7 Automatic Dual-failure Coverage vs. Link Load for Periodic Testing

**Dual-failure Restorability In the Presence Of Random Faults** is shown in Figure 3.8 and is an indication of the degree of restorability that can be achieved by both algorithms in the event of random faults in the system. The sub-graph routing strategy achieves a significantly higher degree of restorability as compared to the backup multiplexing scheme. Although the backup-multiplexing scheme is able to achieve total restorability varying between  $\sim 60$ - $97\%$  across different topologies, the sub-graph routing scheme achieves a restorability over  $95\%$  for all topologies.

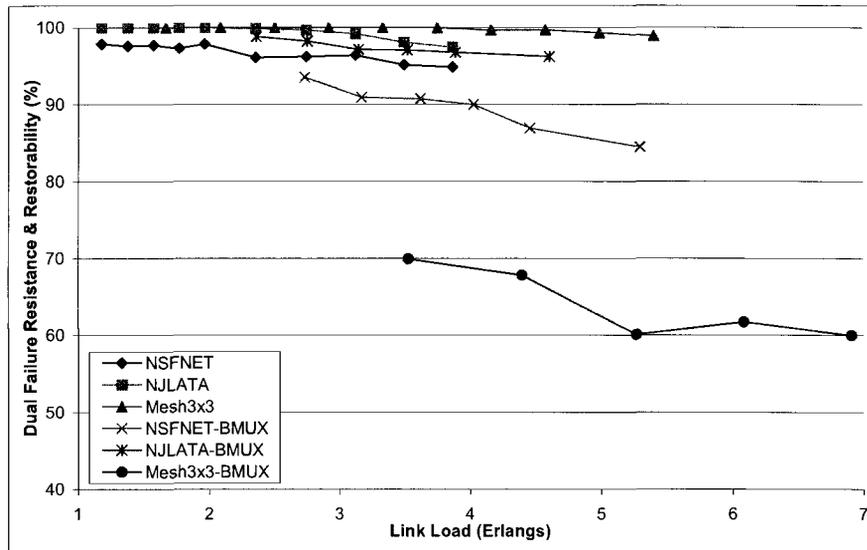


Figure 3.8 Total Restorability vs. Link Load for Random Testing

**Dual-failure Restorability In the Presence Of Periodic Faults**, depicted in Figure 3.9, indicates the complete network wide dual-failure restorability achieved by both the restoration algorithms. In the presence of periodic faults, restorability is computed by successively failing each link in the network, computing the coverage for a second failure, and averaging it over all possible dual-failure scenarios. The network is left in its original state. The total dual-failure restorability achieved by both the algorithms is quite high ( $\sim 62$ - $96\%$ ) except for MESH3x3 where the sub-graph routing strategy out-performs the backup multiplexing scheme.

Sub-graph routing provides a passive form of redundancy without any physical allocation of any redundant capacity in the network, by maintaining the state information of  $L$  distinct

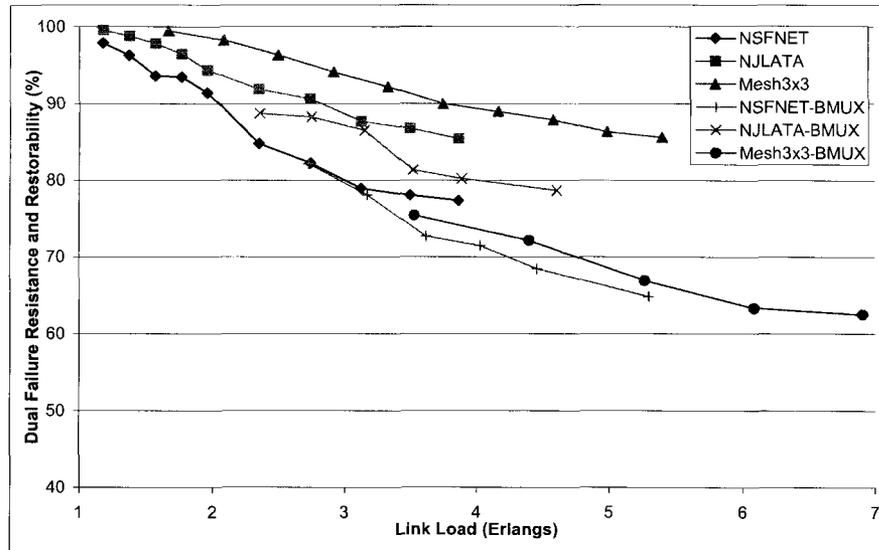


Figure 3.9 Total Restorability vs. Link Load for Periodic Testing

sub-graphs of the network. Effectively, there is a trade off between the physical redundant capacity that needs to be stored in the network to achieve fault-tolerance in the case of backup multiplexing, and the reconfiguration and redundant network states that need to be maintained in the sub-graph routing strategy. However, since network state information is always cheaper to maintain than physical allocation of spare capacity, the sub-graph routing strategy is a viable alternative routing methodology in WDM optical networks.

### 3.9 Chapter Summary

In this chapter the performance of the sub-graph routing strategy and the backup multiplexing scheme for tolerating a second link fault in a network is evaluated and compared. The sub-graph routing strategy attempts to maximize the number of connections covered for all second-link faults ensuing an arbitrary link failure, by allowing connections automatically covered against a second failure to remain uninterrupted and rerouting compromised connections. Summarizing, the following are the achievements in this chapter:

- We study the sub-graph based fault tolerant routing strategy for accommodating single

link failures.

- We study constrained sub-graph routing strategy which helps us to improve in performance over sub-graph routing.
- We perform a comparative study between sub-graph routing and shared mesh protection technique and evaluate its ability to restore against a sequential second link failure.
- The proposed reactive fault-tolerant strategy enables us to handle higher order recursive failures.

Proactive sub-graph fault tolerance has the ability to protect against all possible multi-link failures for which its sub-graphs are designed. It also has the advantage of having predetermined sub-graph states that the base network can emulate in the event of a failure. However, proactive fault tolerance has the drawbacks of not being able to handle all possible multiple link failure situations, as well as sequential overlapping link failures.

Reactive sub-graph fault tolerance addresses some of these pitfalls by employing a recursive method for tolerating numerous sequential overlapping failures. It can also tolerate simultaneous multiple link failures simply by serializing the handling of each individual fault. One of the drawbacks of reactive fault tolerance is that it can rarely provide 100% protection for all connections against subsequent link failures, although simulation results have shown that protection against a subsequent link failure is on the order of 75-96%. Another drawback is that it can't simply begin reconfiguring the network as soon as a multi-link fault occurs, but must first attempt to reroute all compromised connections for one fault, and then handle another. For example, if an SRLG were to fail in a reactive sub-graph fault tolerant network, each of the link failed in SRLG would have to be handled sequentially. Network reconfiguration cannot occur until all faults are processed and recovered from.

The best solution to multi-link fault tolerance would be to employ a hybrid of reactive and proactive sub-graph fault tolerance. Initially sub-graphs are defined taking into account link, SRLG, or node failures, and could, in the event of an unrelated or subsequent multi-link failure, incorporate the reactive form of sub-graph fault tolerance. Incorporating a hybrid

approach to fault tolerance using sub-graph fault tolerance provides a complete solution to the problem of multiple link failures in optical networks.

## CHAPTER 4. Multiple Link Failure Protection Using Subgraph Routing

In this chapter we address the design and provisioning of WDM networking for tolerating multiple link failures in the form of shared risk link groups. Multiple link failure models, in the form of Shared-Risk Link Group (SRLG) failures, are becoming critical in survivable optical network design. Most of the traditional restoration schemes are based on the single-failure assumption which is unrealistic. In our research, we propose a novel survivability approach that can tolerate multiple failures arising out of SRLG situations. We also study how restorability can be achieved for node failures and analyze the performance of our approach for different network topologies. Our proposed restoration architecture requires the storage of network state information corresponding to each of the possible failure scenarios defined by the sub-graphs. The proposed restoration model is novel and can be implemented in current WDM backbone networks.

The main contributions of this work are summarized as follows.

- We use the sub-graph based routing scheme to achieve restorability against failures caused by shared-risk link groups (SRLG's).
- We study the effects of node-based sub-graph routing, which can tolerate a single node failure in a network at any instance of time.

### 4.1 Sub-graph Fault Tolerance for Single-link Failures

In case of single-link failures, the fault set is  $F = E$ . For simplicity, let us assume that the network comprises of bi-directional links with a total capacity of one unit. The single link failure scenario is demonstrated in Section 4.4 and is exemplified in Figure 3.2. Let there be a

request between node 1 and node 2. This connection request attempts to find a path from 1 to 2 on all of the  $L$  sub-graphs of the base network. Let there be three requests in the network  $R_1 : 1 \rightarrow 2$ ,  $R_2 : 4 \rightarrow 5$  and  $R_3 : 3 \rightarrow 4$ . The request  $R_1$  can be routed successfully on all sub-graphs, as shown by the lighter shaded arrowhead. Thus connection  $R_1$  can be accepted for routing in the base network (Figure 3.2).

An attempt is made to find a viable path on all  $L$  sub-graphs, and since  $R_2$  can also be routed on all the sub-graphs it is also accepted in the base network. Finally  $R_3$  is attempted to be routed on all sub-graphs, but this attempt fail, as there is no possible path in sub-graphs  $G_2$ . Figure 3.3 shows the attempted routing of the connection between nodes 3 and 4 as the dotted line. Notice that in subnetwork  $G_2$  there is no free capacity.

On a link failure, the network can fully recover by accepting the sub-graph network state corresponding to the located link failure. For example, assume that there is an arbitrary failure on the link  $4 \rightarrow 5$ . To recover from this fault, the network re-routes all current connections to reflect the network state depicted by sub-graph  $G_7$ . Fault occurrence and recovery in the sub-graph routing scheme is illustrated in Figure 3.3.

## 4.2 Sub-graph Fault Tolerance for SRLG Failures

Sub-graph routing when  $F = S \cup E$  provides a means for protection against all single link and all SRLG failure scenarios in a given network. The methodology for protecting against all single link failures can be extended to tolerate specific multiple-link failure situations as shown in the next example.

For this example, the network shown in Figure 4.1 is considered. There are 2 shared-risk link groups, each of size 2. Each link in the network is assumed to be a bidirectional link of total capacity one unit. The corresponding sub-graphs are generated through the removal of individual links, as well as links belonging to each SRLG, and are shown in the same figure. Let us consider three requests in the network  $R_1 : 1 \rightarrow 2$ ,  $R_2 : 4 \rightarrow 5$  and  $R_3 : 3 \rightarrow 4$ . The request  $R_1$  is routed in all the sub-graphs and hence it has been accepted for routing in the base network. The request  $R_2$  as shown in Figure 4.1 finds a route in all the sub-graphs

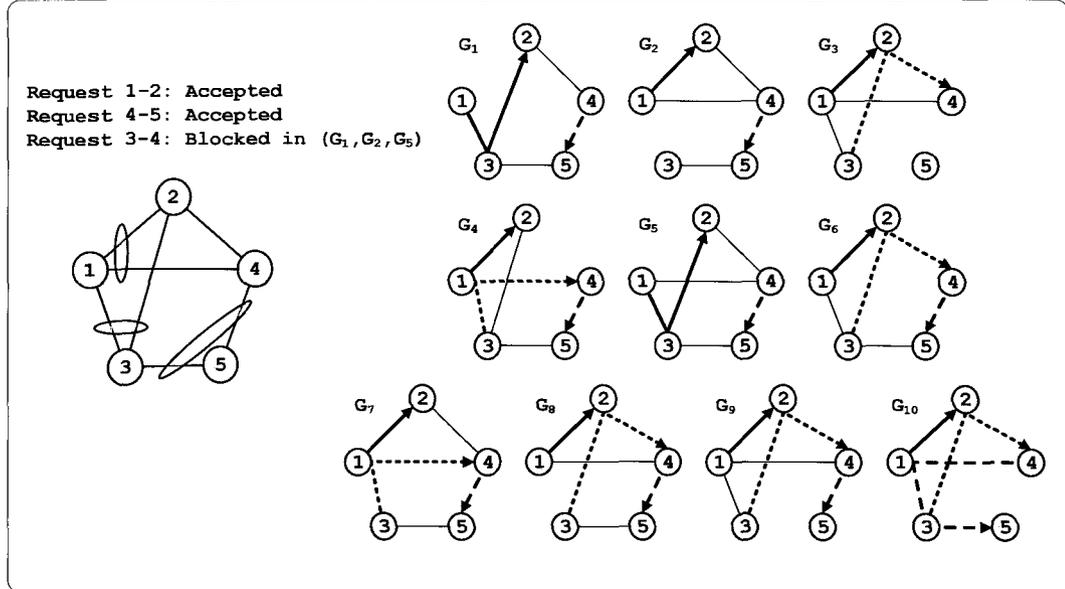


Figure 4.1 Sub-graph Routing for tolerating SRLG and Single-link failures

and hence is also accepted in the base network. The request  $R_3$  doesn't find a route in all sub-graphs except  $G_1$ ,  $G_2$  and  $G_5$  and hence it is rejected in the base network.

A request is accepted in a subgraph if there exists a route from the source to destination. A request is dropped if it has any intermediate nodes with degree 0 (outgoing or incoming degree in case of directed graphs), as such a request will have no alternate path under the failure scenario and will have to be dropped.

#### 4.2.1 Sub-Graph Fault Tolerance for Node Failures

Node based sub-graph routing is similar to sub-graph routing except that in this case, the sub-graphs are generated by the removal of each node,  $v_i \in V$ , one at a time, from the base network. Let us consider the network as shown in Figure 4.2. Each link in the network is assumed to be a unidirectional link of total capacity one unit. The sub-graphs after removal of each node is shown in the same figure. Let there be three requests in the network  $R_1 : 1 \rightarrow 2$ ,  $R_2 : 4 \rightarrow 5$  and  $R_3 : 1 \rightarrow 4$ . The request  $R_1 : 1 \rightarrow 2$  can be routed in all the sub-graphs and hence it is accepted for routing in the base network. Similarly the request  $R_2 : 4 \rightarrow 5$  finds

a route in all the sub-graphs except  $G_4$  but still it is accepted in the base network (since the source node has a degree of 0). A request is accepted on a sub-graph which has any node with a degree of zero, i.e. a free node, and if that node is either the source or destination of the request. The request  $R_3$  is accepted for routing in each sub-graph except in  $G_1$  where it cannot be routed because node 1 has a nodal degree of zero, however, since node 1 is the source node of the request, it is also accepted in the base network.

The node based sub-graph routing gives a lower bound on the routing performance that can be achieved because it is much more constrained than the sub-graph routing for tolerating SRLG failures. The sub-graphs for tolerating node failures are a special case of the sub-graph routing for tolerating SRLG failures, since it deals with SRLG groups consisting of all links incident on a common node.

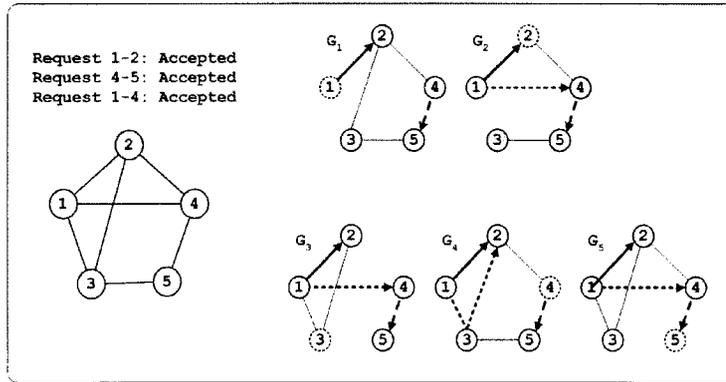


Figure 4.2 Sub-graph Routing for Node failures

### 4.3 Performance Evaluation of Sub-graph Routing

#### 4.3.1 Probability of Path Reassignment

Sub-graph fault tolerance depends on the network state's ability to be changed during a recovery. This may require some connections in the network to be reassigned to different paths. In order to quantify the amount of path reassignment taking place, path and trunk reassignment probability is measured. It is the probability that a connection's path or trunk

on the base network will have to be changed when the sub-graph state corresponding to the link failure is incorporated. Probability of path reassignment is calculated using Equations 4.1 and 4.2, where  $R$  and  $B$  are the total number of requests and the number of blocked requests and  $P_j(R_i)$  is 1 if the path of the request  $R_i$  in the base network is the same as the path (or path/trunk combination) in sub-graph  $j$ , and 0 if it is not.  $K$  defines the total number of failure scenarios  $\mathcal{F}$ . Equation 4.2 calculates the probability of reassignment of a backup multiplexed network and is expressed as the probability that a particular path contains the faulty link, thus necessitating the use of a backup connection.

$$P(\text{Sub-Graph}) = 1 - \frac{\sum_{i=1}^{R-B} \sum_{j=1}^K P_j(R_i)}{K \cdot (R-B)} \quad (4.1)$$

$$P(\text{Shared Mesh}) = 1 - \frac{\sum_{l=1}^{R-B} e_l}{L \cdot (R-B)} \quad (4.2)$$

### 4.3.2 Link Load

Link load is a measure of the load placed on each link in the network at any given time. Link load, represented by  $\gamma$ , is calculated using Equation 4.3, where  $L$  is the total number of links in the network,  $N$  is the total number of nodes in the network and  $\lambda_n$  is the arrival rate per node.  $H$  is the expected hop count of the primary connections in the topology calculated by simulating the topology at a very low arrival rate, very high link capacity and very low request hold time. Link load is expressed in units of *Erlangs* and is used to compare results between networks.

$$\gamma = \frac{\lambda_n \cdot N \cdot H}{L} \quad (4.3)$$

Three different network topologies, shown in Figure 4.3, Figure 4.4 and Figure 4.5 were simulated to assess the performance of sub-graph routing for tolerating SRLG failures. Each of the three topologies consists of links with 1 fiber per link, 16 wavelengths per fiber, and 1 timeslot per wavelength. Each link also consists of 2 unidirectional links that are treated as one link, meaning that if the link in one direction fails, the link in the opposite direction also fails because they would presumably be physically routed together. No nodes offer any

wavelength switching capabilities, thus the wavelength continuity constraint [70] is obeyed. The arrival of the requests at a node follows a Poisson process with rate  $\lambda$ , and is equally likely to be between any two nodes. The holding time of the requests follows an exponential distribution with unit mean. The capacity requirement of each request is a unit wavelength.

Three sub-graph formation techniques have been assessed, 1) sub-graphs based on all physical link failures,  $F = E$ , 2) sub-graphs based on arbitrarily chosen shared risk link groups,  $F = S \cup E$ , and 3) sub-graphs based on all single-node failures,  $F = V \cup E$ . For the 3x3 mesh torus, SRLGs were formed as the north and east links leaving a node and the south and west links leaving a node. The number of sub-graphs created for each base network is equal to the sum of the number of physical link faults and the number of SRLG's or nodes.

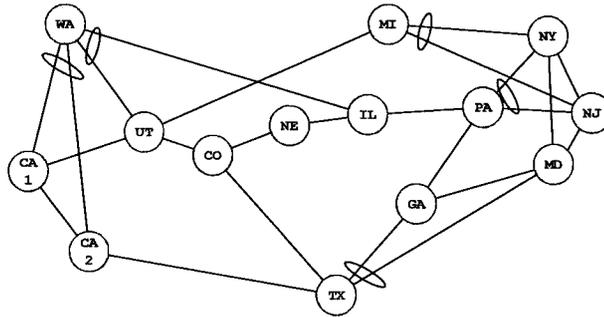


Figure 4.3 14-node, 23-link NSFNET network with SRLG's

In all sub-graph cases, protection against all single-link failures is 100% guaranteed, and in the cases of sub-graphs based on SRLG's and nodes, there is also a 100% restoration guarantee for all connections in the event of an SRLG or node failure, respectively.

The performance of each network topology is assessed using each of the three levels of constrained sub-graph routing. Results are obtained for path, trunk and unconstrained routing. As a basis for performance assessment, each topology is also simulated using no link failure protection technique, as well as backup multiplexing single-link fault tolerant strategy.

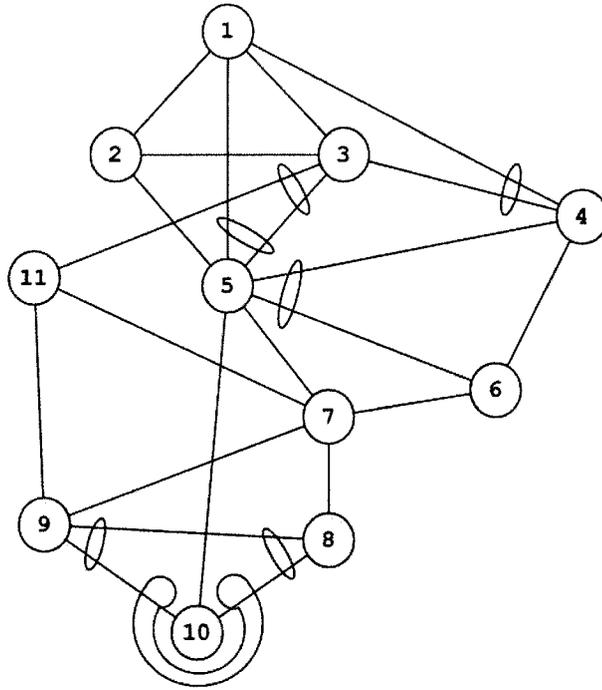


Figure 4.4 11-node, 22-link NJLATA network with SRLG's

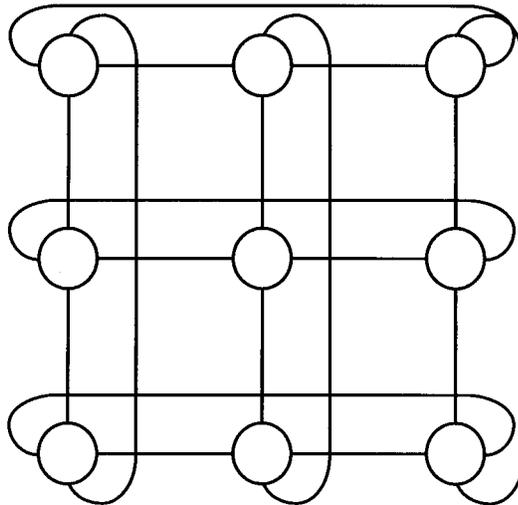


Figure 4.5 9-node, 18-link Mesh Torus network

#### 4.4 Results

Three different network topologies, shown in Figure 4.3, Figure 4.4 and Figure 4.5 are simulated to assess the performance of sub-graph routing for tolerating SRLG failures. Each of the three topologies consists of links with 1 fiber per link, 16 wavelengths per fiber, and 1 timeslot per wavelength. Each link also consists of 2 unidirectional links that are assumed to be part of the same shared risk link group, meaning that if the link in one direction fails, the link in the opposite direction also fails because they would be presumably physically routed together. No nodes offer any wavelength switching capabilities, thus the *wavelength continuity constraint* is obeyed. The arrivals of the requests at a node follow a Poisson process with rate  $\lambda$ , and are equally likely to be destined to any other node. The holding time of the requests follow an exponential distribution with unit mean. The capacity requirements of each request is of unit wavelength.

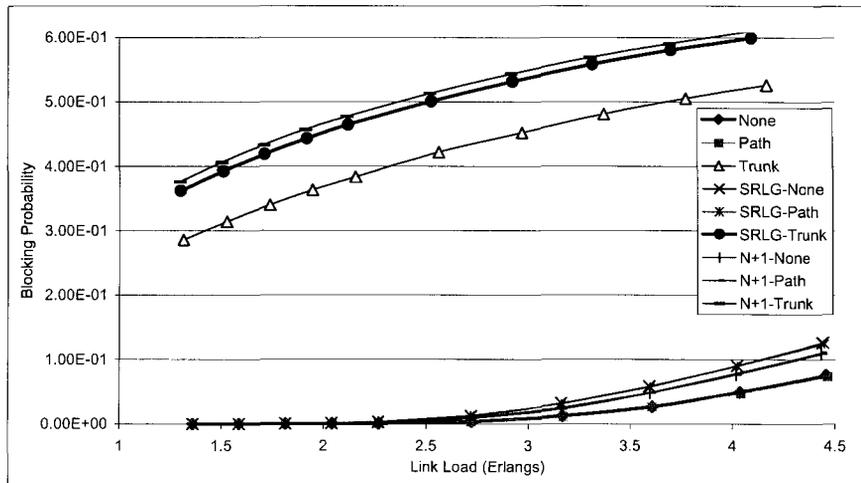


Figure 4.6 NSFNET Blocking Probability vs Link Load

Three different topologies have been assessed for sub-graph routing, based on link and node groups. The network topologies studied with various shared-risk link groups are shown in Figure 4.3, Figure 4.4 and Figure 4.5.

For the 3x3 mesh torus, SRLG's were formed as the north and east links leaving a node

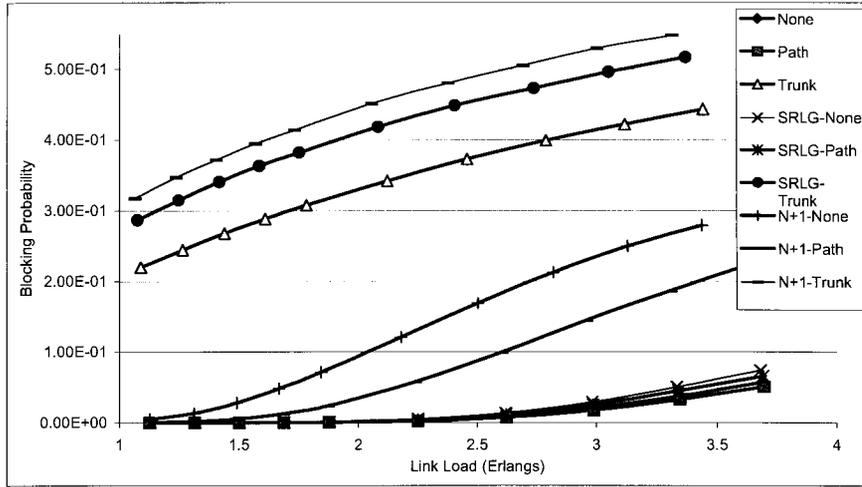


Figure 4.7 NJLATA Blocking Probability vs Link Load

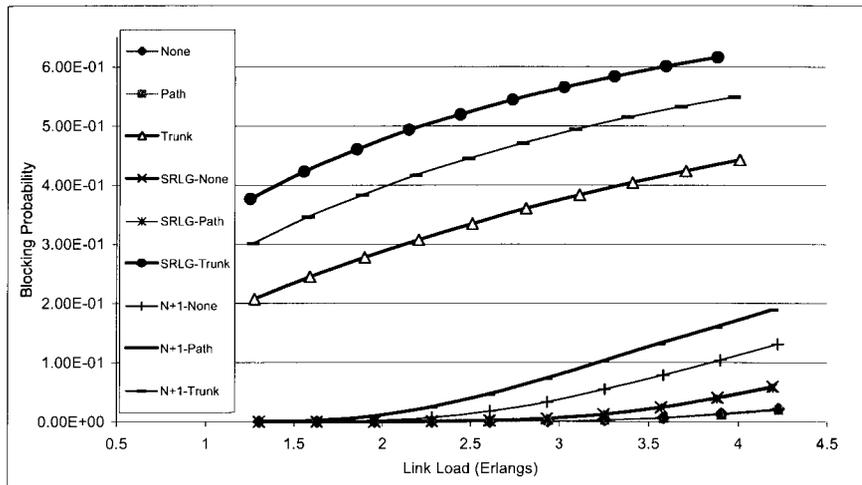


Figure 4.8 MESH 3x3 Blocking Probability vs Link Load

and the south and west links leaving a node. The number of sub-graphs created for each base network is equivalent to the sum of the number of physical link faults and the number of SRLGs. If a request's source or destination node is a stranded node (one with degree of 0) in a subgraph, a conditional acceptance on that subgraph is granted as discussed in Section III (source or destination nodes can be free, intermediate nodes cannot).

Conditional acceptance is allowed, because any connection formed between two nodes automatically incurs the risk of either the source or destination node failing. The intent of providing coverage for all single node faults is to protect against faults occurring at the intermediate nodes in the path of the connection request.

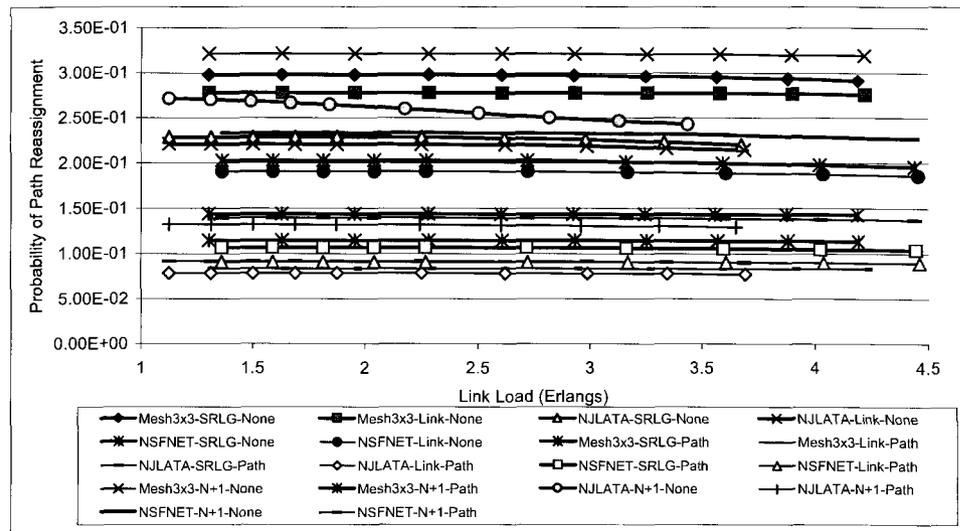


Figure 4.9 Probability of Path Re-assignment vs Link Load

Using the 14-node, 23-link NSFNET as an example, the previously described sub-graph formation techniques will be clarified. In the case of link sub-graph generation, an NSFNET base network creates 23 sub-graphs, each missing a pair of uni-directional links physically routed together. For SRLG sub-graph generation, a NSFNET base network creates 6 SRLG sub-graphs in addition to the 23 sub-graphs based on physical links, for a total of 29 sub-graphs. Finally, for node sub-graph generation, a NSFNET base network creates 14 node sub-graphs and 23 link sub-graphs for a total of 37 sub-graphs. Physical link failures are always considered

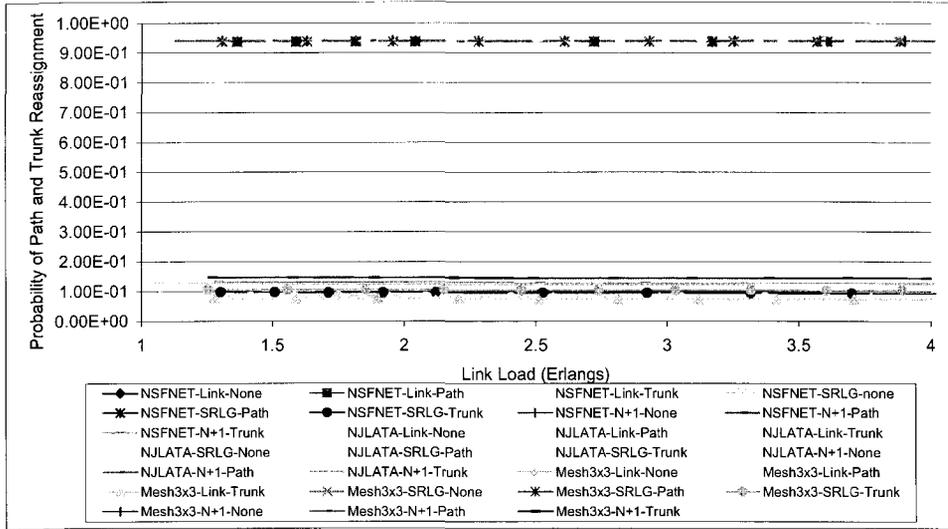


Figure 4.10 Probability of Path and Trunk Re-assignment vs Link Load

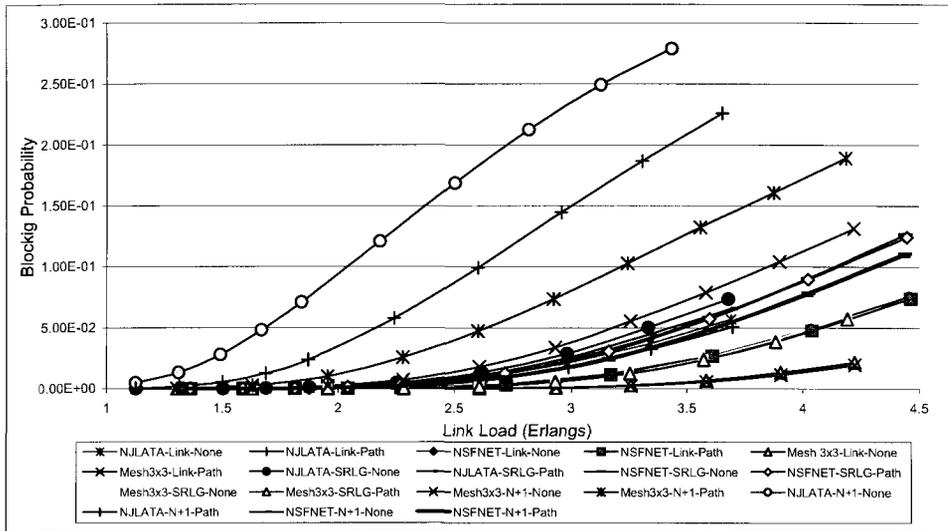


Figure 4.11 Blocking Probability vs Link Load for no Constraint and Path constraint

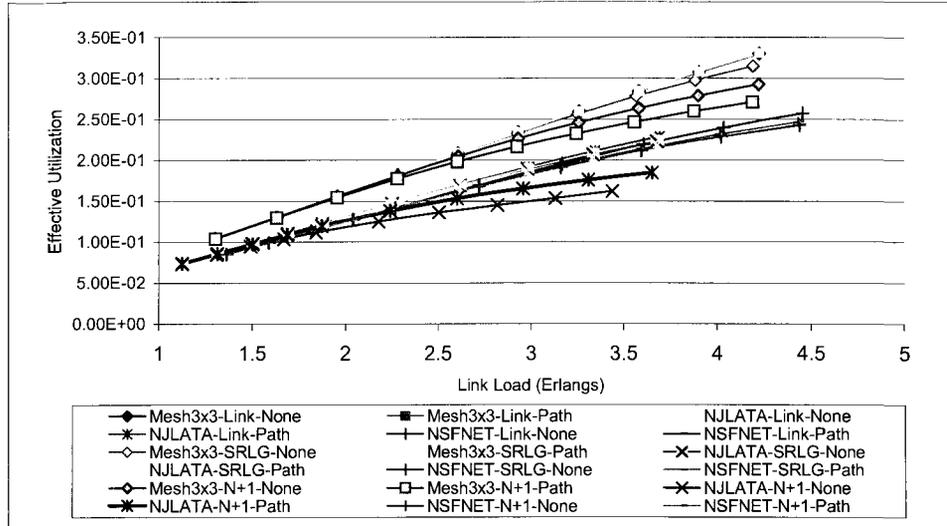


Figure 4.12 Effective Network Utilization vs Link Load

in each sub-graph generation because a physical link can fail in a location where it does not affect the other members of its SRLG.

In all sub-graph cases, all single-link faults are 100% guaranteed, and in the case of sub-graphs based on shared risk link groups, there is a 100% guarantee for all connections in the event of a shared risk link group fault. In the node based sub-graph case, 100% restoration is guaranteed for all intermediate node and single-link failures. The blocking probability results for all three topologies are shown in Figure 4.6, Figure 4.7 and Figure 4.8.

To assess the performance of constrained routing, the probabilities of reassignment to a different path and to a different path/trunk combination are shown in Figure 4.9 and Figure 4.10. In Figure 4.9 the probability of reassignment for unconstrained routing runs between 18-33%. This is in sharp contrast to the probability of reassignment for path constrained routing which ranges between 8-15%. In all cases, path constrained sub-graph routing offers lower probability of reassignment. According to [48], the calculated probability of path reassignment for backup multiplexing ranges between 8-15%, thus making constrained sub-graph routing roughly equivalent to backup multiplexing.

In Figure 4.10, the probability of path/trunk combination reassignment is about 93% for

path and unconstrained sub-graph routing. This is significantly higher than the probability of path and trunk reassignment for path/trunk combination constrained sub-graph routing, which ranges between 8-15%. This is an expected result because connections are more likely to choose same paths, in similar sub-graphs on any capacity available. In summary, in a recovery situation, a connection will more likely than not have to change its trunk if path/trunk combination constrained routing is not imposed.

In Figure 4.11 we observe that the blocking probability for path constrained sub-graph routing is less than the blocking probability for unconstrained sub-graph routing in all but two cases: NSFNET and mesh torus 3x3 node-based sub-graphs. In each topology, the blocking probability for node-based sub-graphs is higher than that for the SRLG, which in turn is higher than that for link-based sub-graphs. The only exception is observed in the results for NSFNET where node-based sub-graphs slightly outperforms the SRLG based sub-graphs.

Intuitively, one would expect that, in constrained sub-graph routing, forcing the connections to route on the same path on each of the  $L$  sub-graphs would increase the connection blocking probability. However in simulation, the reverse phenomenon was observed as shown in Figure 4.6, 4.7, 4.8. In most cases the blocking probability actually decreased slightly when following the path-constrained routing. Path/trunk constrained routing sharply increased overall connection blocking probability and is not seen as a viable solution unless minimization of probability of reassignment is more crucial than the minimization of blocking probability in a particular network.

In Figure 4.12 we study the effective utilization of the network for path constrained as well as unconstrained sub-graph routing. Path/trunk constrained routing is not considered due to its drastically higher blocking probability. For all the topologies, the network utilization for the SRLG sub-graph routing is slightly lower than that of link based sub-graph routing. However, the network utilization for the SRLG sub-graph routing is higher than node-based sub-graph routing since node based sub-graph routing offers a higher blocking probability than SRLG sub-graph routing for most topologies.

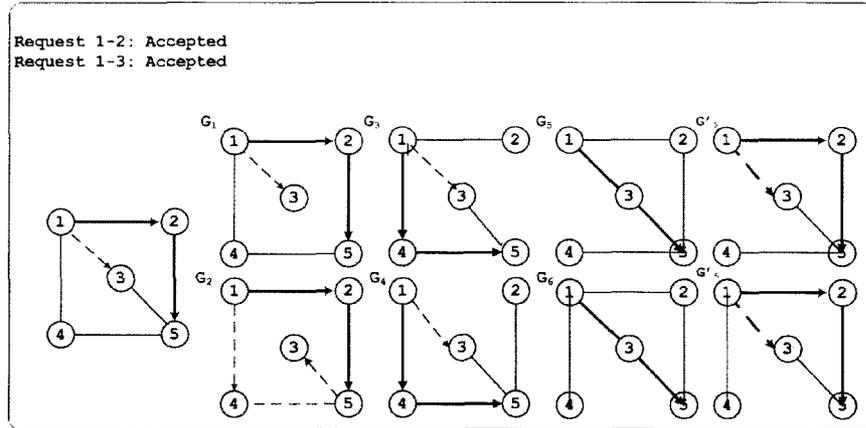


Figure 4.13 Sub-Graph Shadowing

#### 4.5 Discussion

The results obtained using path-constrained routing are very interesting. They indicate that constraining sub-graph routing to a path actually improves the blocking probability. One of the possible explanations for this phenomenon is the increased resemblance each sub-graph takes to the base network. If the path on a sub-graph is distinctly different from the base network, the request might have to traverse through links that a different request regularly utilizes. If a request cannot find the necessary resources available on such critical links, it is blocked with a higher frequency. If, however, each sub-graph is required to route each connection in the same way the base network does if the same path exists, the sub-graph utilization of critical links more closely resembles that of the base network. This increases the likelihood that an arbitrary request is accepted on all sub-graphs, and consequently accepted in the base network. This is referred to as sub-graph shadowing.

Sub-graph shadowing increases the performance of sub-graph routing because situations exist where there are several different equidistant paths from a source to a destination node. Each of these paths can be chosen to route the connection using the fewest hops routing strategy. Constraining the path actually creates sub-graph states that more closely resemble, or shadows, the actual state of the base network. It helps to reduce the occurrence of situations

where a connection gets blocked because the only possible path where it could have been routed is already occupied by some other connection that should have been routed elsewhere.

A sub-graph shadowing situation is depicted in Figure 4.13. In Figure 4.13, the base network consists of 6 links and sub-graphs are created based on single link failures, resulting in sub-graphs 1 through 6. Let us assume that each link in the sub-graphs has a total capacity of 1 unit. Let us assume that connection request  $R_1 : 1 \rightarrow 5$ , is routed on the base network along  $R_1 : 1 \rightarrow 2 \rightarrow 5$ . Similarly, connection request  $R_2 : 1 \rightarrow 3$  is routed on the base network along  $R_2 : 1 \rightarrow 3$ . Sub-graphs  $G_1$  and  $G_2$  have the option of routing connection  $R_1$ , from node 1 to 5, along the paths  $1 \rightarrow 2 \rightarrow 5$  or  $1 \rightarrow 4 \rightarrow 5$ . The path  $R_1 : 1 \rightarrow 2 \rightarrow 5$  is chosen. Connection  $R_2$  gets routed in sub-graphs  $G_1$  and  $G_2$ . In sub-graphs  $G_3$  and  $G_4$ ,  $R_1$  has the option to select from either of the two paths,  $R_1 : 1 \rightarrow 3 \rightarrow 5$  or  $R_1 : 1 \rightarrow 4 \rightarrow 5$ . The path  $R_1 : 1 \rightarrow 4 \rightarrow 5$  is chosen for routing connection  $R_1$  and connection  $R_2$  can be routed without any problem. In sub-graphs  $G_5$  and  $G_6$ , connection  $R_1$  has paths  $1 \rightarrow 2 \rightarrow 5$  and  $1 \rightarrow 3 \rightarrow 5$  to choose from. Without sub-graph constrained routing,  $1 \rightarrow 3 \rightarrow 5$  might be chosen as the path for routing connection  $R_1$ . If this path is chosen for routing  $R_1$  in sub-graphs  $G_5$  and  $G_6$ , connection request  $R_2$  cannot be accepted and must be blocked by the base network. However, if we constrain the routing on the same path, connection  $R_1$  is routed along  $R_1 : 1 \rightarrow 2 \rightarrow 5$  as shown in sub-graphs  $G'_5$  and  $G'_6$ . Furthermore, connection request  $R_2$  can be routed on node path  $R_2 : 1 \rightarrow 3$  and both connections can be accepted in the base network.

## 4.6 Chapter summary

The following are some of the main contributions of this chapter:

- In this chapter we developed a strategy that enables us to tolerate shared-risk link group failures.
- We proposed a methodology for tolerating node failures in a network, by creating node-disjoint sub-graphs from the base network. Designing for a node failure actually represents the worst-case SRLG failure involving all links at a common node.

- The proposed solution methodology enables us to handle certain specific multiple link failure scenarios in a WDM optical network.

The proposed technique needs to store only the network state information corresponding to the sub-graphs generated from the base network due to the SRLG failures. Hence it is aptly suitable for implementation for current WDM backbone networks.

Given the results that we have presented in this chapter, we have shown that sub-graph fault tolerance is a viable means for tolerating link, shared-risk link group and node faults in a wide variety of network topologies. The toleration of shared-risk link group faults is especially appealing in this strategy because the blocking probability doesn't significantly increase relative to single link failure situations. Additionally, path constrained routing further improves the performance of sub-graph routing.

## CHAPTER 5. Diverse Routing for Shared Risk Resource Groups (SRRG) Failures

In this chapter we address the design and provisioning of WDM networking for tolerating multiple link failures in the form of shared risk link groups. Multiple link failure models, in the form of Shared-Risk link and node groups (SRLG's and SRNG's), are becoming critical in survivable optical network design. In this chapter, we propose a graph transformation technique that helps to find out diverse routes between any given source and destination, in a network with a given set of shared risk resource groups. Diverse Routing in such multi-failure scenario essentially necessitates finding out two paths between a source and a destination that are SRRG disjoint. We study how restorability can be achieved for dependent or shared risk link failures and coordinated node failures and prove the validity of our approach for different networks.

We study how restorability can be achieved for node failures and analyze the performance of our approaches for different network topologies. Our proposed graph transformation technique gives polynomial time solutions and hence can be implemented in current WDM backbone networks.

The main contributions of this chapter are summarized as follows.

- In this chapter we propose a polynomial time graph transformation heuristic to solve a sub-set of the generalized version of the diverse routing problem in networks with shared risk resource groups.
- We also analyze the complexity of these routing methodologies and validate the correctness of the proposed algorithms.

The diverse routing problem is to find two paths between a pair of nodes in the optical layer such that no single failure in the physical layer may cause both paths to fail. The problem of finding diversely routed paths in optical networks is much more difficult than the traditional edge/node disjoint path problem in graph theory [40, 67].

In this chapter, we address the problem of diverse routing in SRLG situations as well as multiple failures arising out of nodes sharing a common risk of failure. We classify both these sub-problems under a generalized heading of shared risk resource group (SRRG) routing. In this work we propose a polynomial time graph transformation heuristic to solve a sub-set of the generalized version of the diverse routing problem in networks with shared risk resource groups. We analyze the complexity of these routing methodologies and also validate the correctness of these algorithms, thus making it feasible to be applied to large networks with huge traffic demands.

## 5.1 Shared-Risk Resource Groups (SRRG's)

An important class of SRRG's comprises of multiple links sharing a common component such as a duct, whose failure causes failure of all links in that group. Any physical failure of one of these ducts can invoke a logical failure of multiple links as illustrated in Figure 5.1(a). A single link can also be part of more than one SRLG. As shown in Figure 5.1(a) the link connecting nodes 1 and 3 is part of two SRLG's  $R_1$  and  $R_2$ . In our research, we concentrate on *co-incident SRLG's* [36], which are groups incident on a common node.

Another instance of a shared-risk resource failure (SRRG), is the failure of two or more nodes that are connected by a common channel or link and are often referred to as shared risk node groups (SRNG's) (Figure 5.1(b)) . In practice such a failure of one or more nodes may be due to some malicious signal that corrupts the transmission (laser's) at both end-points of the link or maybe due to power outage in an area, leading to simultaneous failure of some nodes in the network.

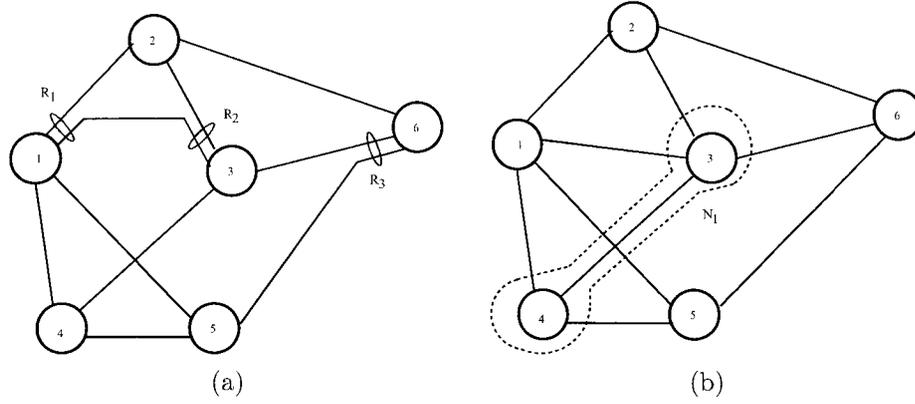


Figure 5.1 Network With (a) Shared-Risk Link Groups (SRLG's) and (b) Shared Risk Node Groups (SRNG's).

### 5.1.1 Graph Transformation Technique for Diverse SRRG Routing

In the following sections we present graph transformation techniques for finding out two shared-risk group disjoint paths to tolerate shared-risk resource group failures. We assume that there will be at most one SRRG failure at any given time.

### 5.1.2 Notations

The following notations would be consistently used in the following sections for describing the graph transformation algorithms.

- $G = (V, E)$ : Directed graph  $G$ , where  $V$  is the set of vertices and  $E$  is the set of edges.  $|V| = N$  and  $|E| = L$ .
- $\alpha_e$ : Weight of an edge  $e$  in the directed graph  $G$ . The weight of an edge is an indicator of the distance of the edge in miles. For bi-directional links,  $\alpha_{uv} = \alpha_{vu}$ .
- $\chi$ : Total number of Shared-Risk Link groups (SRLG's) in the network.
- $R_i$ : The  $i^{th}$  Shared Risk Link Group.  $i = 1 \dots \chi$ .

- $\psi$ : Total number of Shared-Risk Node groups (SRNG's) in the network.
- $S_i$ : The  $i^{th}$  Shared Risk Node Group.  $i = 1 \dots \psi$
- $d_i$ : A dummy vertex representing the  $i^{th}$  shared risk link group or a shared risk node group.
- $N(v)$ : The neighborhood of the vertex  $v$ .

## 5.2 SRLG Diverse Routing

We develop a graph transformation technique to identify two SRLG diverse routes, if they exist. The following are the assumptions under which the proposed transformation technique yields a polynomial time solution.

- There can be any number of shared-risk link groups in a network.
- Each shared risk link group is smaller in size than the degree of the node on which it is incident.
- A shared risk link group is not a proper subset of any other shared risk link group.
- An edge can be shared between utmost two shared risk link groups.

Each shared-risk link group  $R_i$  can be represented as

$$R_i = \{(u_i, v_{i1}), (u_i, v_{i2}), \dots, (u_i, v_{ik_i})\}.$$

where  $u_i$  is the vertex on which an SRLG is incident.  $|R_i| = k_i, i=1, \dots, \chi$

A *dummy vertices*  $d_i$  is used to represent each shared-risk link group  $R_i$  in the transformed graph  $G' = (V', E')$ .  $G'$  is derived from  $G$  using the vertex transformation:

$$V' := V \cup \{d_i\}, \quad i = 1, \dots, \chi.$$

Hence in the transformed graph  $G'$ , the total number of vertices is given by  $|V'| = N + \chi$ , where  $N$  is the cardinality of the set  $V$ . This is shown in Figure 5.3.

Let  $E = E_1 \cup E_2 \cup E_3$ . The modified edges in the transformed graph  $G'$  is given by:

$$E' = E_1 \cup E_4 \cup E_5 \cup E_6$$

where  $E_1 = \{e \in E \mid e \notin R_i \forall i\}$

$$E_2 = \{e \in E \mid e \in R_i, e \notin R_j, i \neq j\}$$

$$E_3 = \{e \in E \mid e \in R_i, R_j \text{ and } i \neq j\}$$

$$E_4 = \{(u_i, d_i) \mid R_i \text{ is an SRLG}\}$$

$E_4$  is set of edges of type  $(u_i, d_i)$  where  $u_i$  is the node on which there is an incident SRLG.

$E_5$  is a set of edges of type  $(d_j, v_j)$  replacing sets of edges in  $E_2$ .

$E_6$  is set of edges of the type  $(d_i, d_j)$  created to represent edges that are common to more than one SRLG.

Hence  $|E_2| = |E_5|$  and  $|E_3| = |E_6|$  and  $E_4$  are the new set of extra edges in  $G'$ . The graph transformation algorithm is described in Figure 5.2. In this graph  $E_1 = \{1-4, 1-5, 2-6, 3-4, 4-5\}$ ,  $E_2 = \{1-2, 3-2, 6-3, 6-5\}$  and  $E_3 = \{1-3\}$ .

**Input:** Graph  $G = (V, E)$ , SRLG Groups  $R_i$ 's and a traffic matrix  $T_{N \times N}$ .  
**Output:** The transformed graph  $G' = (V', E')$ .  
The following Data Structures are maintained:  
Arrange all SRLG's as  $R_i = \{(u_i, v_{i1}), (u_i, v_{i2}), \dots, (u_i, v_{ik_i})\}$ . where  $|R_i| = k_i, i=1, \dots, \chi$   
**Graph Transformation Algorithm:** Obtain the transformed graph  $G' = (V', E')$  by following the edge and node transformation rules.  
 $V' := V \cup \{d_i\}, i=1, \dots, \chi$ .  
Edges in  $E_1$  are kept as it is in the original graph.  
Connect edges in  $E_1$  with initial weight of zero.  
For each edge in  $E_2$  and  $E_3$  an alternate edge is created that includes the node on which the SRLG is incident.  
 $\forall e\{u_i, v_{ij}\} \in E_2$  create an edge  $(d_i, u_{ij})$  with  $\alpha_{(d_i, u_{ij})} = \alpha_{(u_i, v_{ij})}$  belonging to  $E_5$ .  
 $\forall e\{u_i, v_{ij}\} \in E_3$  the edge will be of the type  $\{u_i, u_j\}$  for some  $i, j = 1, \dots, \chi$ .  
Create an edge  $(d_i, d_j)$  with weights  $\alpha_{(d_i, d_j)} = \alpha_{(u_i, u_j)}$  and  $\alpha_{(d_j, u_j)} = H$ .  
where  $H \geq \{ \max(\alpha_{u_j, x}), \text{ where } x \in N(u_j) \}$ . This set of edges are represented as  $E_6$ .  
(Make a note that  $u_i, u_j$  can be of any order. The cycles hence computed might vary, but it is guaranteed that a cycle would be found if one such exists in the topology.)

Figure 5.2 Graph Transformation Algorithm

For example for the graph shown in Figure 5.1(a), there are three SRLG's  $R_1, R_2$  and  $R_3$ . The shared-risk link groups incident on node 1, 3 and 6 are  $R_1 : \{(1,2) (1,3)\}$ ,  $R_2 : \{(3,1) (3,2)\}$  and  $R_3 : \{(6,3) (6,5)\}$ . It is to be noted that the edge (1,3) is identical to the edge (3,1), since each link is assumed to be bi-directional. The explanations of each step of the

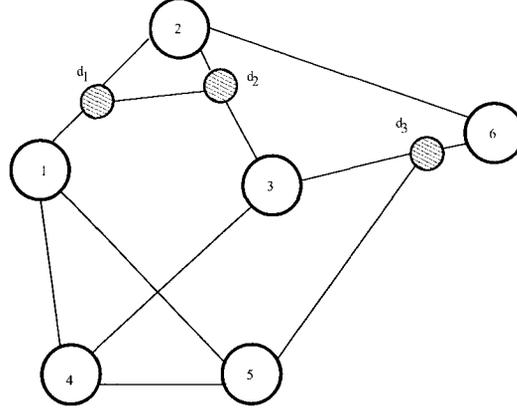


Figure 5.3 Graph Transformation using Dummy Nodes for Diverse SRLG Routing.

transformation are also given in Figure 5.2.

It is to be noted that, in instances where a link is common to two shared risk link groups, failure of any link in one group doesn't propagate to the other group. For example in Figure 5.1(a), failure of link  $1 \rightarrow 2$  doesn't imply failure of link  $2 \rightarrow 3$ .

In Figure 5.3 the dummy nodes  $d_1$ ,  $d_2$  and  $d_3$  are introduced to represent the three shared-risk link groups  $R_1$ ,  $R_2$  and  $R_3$ . As can be seen in Figure 5.3, there is a link between dummy nodes  $d_1$  and  $d_2$  to account for the edges in  $E_3$ . The transformed graph is shown in Figure 5.3. After the transformation, the edge sets are  $E_4 = \{1-d_1, 3-d_2, 6-d_3\}$ ,  $E_5 = \{d_1-2, d_2-2, d_3-3, d_3-5\}$  and  $E_6 = \{d_1-d_2\}$ .

**Input:** Graph  $G' = (V', E')$ , and a traffic matrix  $T_{N \times N}$ .  
**Output:** The shortest cycle for each  $t_{sd} \in T_{N \times N}$  in the transformed graph  $G' = (V', E')$ .  
**Cycle Computation Algorithm:** Obtain the cycles in the transformed graph  $G' = (V', E')$  using the following algorithm:  
*While* ( $t_{sd} > 0$ )  
 {  
 Obtain the Edge-Disjoint Shortest Cycle on the transformed graph  $G'$  for any traffic  $t_{sd} \in T_{N \times N}$   
 The paths of the shortest cycle have one or more segments of the following two types:  
 A.  $P_{G'}: (- \dots x - d_i - y - \dots -)$  or  
 B.  $P'_{G'}: (- \dots x - d_i - d_j - \dots - d_m - y - \dots -)$ , where  $1 \leq m \leq \chi$ .  
 }

Figure 5.4 Cycle computation in transformed graph  $G'$

**Computing Cycles:** In order to find out two shared-risk group disjoint routes between any s-d pairs, we apply the edge-disjoint shortest-cycle algorithm [67] on the transformed graph  $G'$  to find the two group-disjoint routes for a given s-d pair. The detailed algorithm for the cycle computation in the transformed graph is presented in Fig 5.4. Note that a path can have two kind of segments as described in Figure 5.4. The two group-disjoint paths between nodes  $1 \rightarrow 6$  in the transformed graph  $G'$  can be possibly the two paths corresponding to either of the following cycles shown in Table 5.1

Table 5.1 Different possible cycles in the transformed graph  $G'$

Cycle No.	Primary Lightpath	Backup Lightpath
$C_1$	1- $d_1$ -2-6	1-4-3- $d_3$ -6
$C_2$	1- $d_1$ -2-6	1-4-5- $d_3$ -6
$C_3$	1- $d_1$ -2-6	1-5- $d_3$ -6
$C_4$	1- $d_1$ - $d_2$ -2-6	1-4-5- $d_3$ -6
$C_5$	1- $d_1$ - $d_2$ -2-6	1-4-3- $d_3$ -6
$C_6$	1- $d_1$ - $d_2$ -2-6	1-5- $d_3$ -6

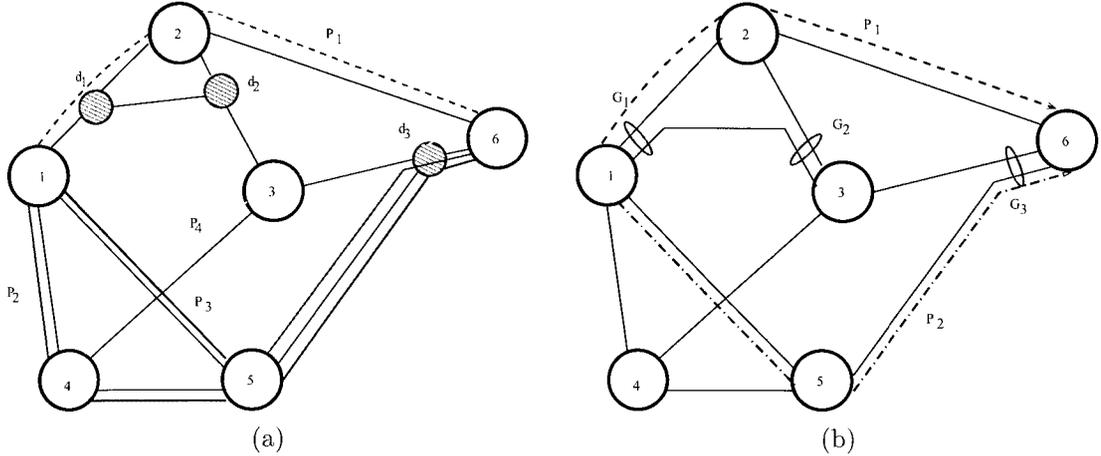


Figure 5.5 (a) SRLG Disjoint Routes on transformed Graph  $G'$ , (b)SRLG Disjoint Routes on the Original Graph  $G$ .

Some of these cycles are shown in Figure 5.5 (a). It will be shown that the two paths

derived out of the shortest-cycle on the transformed graph  $G'$  always provide us two SRLG disjoint routes in the original graph  $G$ .

**Reverse Mapping of Paths:** Once we obtain the shortest-cycle on the transformed graph  $G'$ , we need to map the two routes on the original graph  $G$ . The detailed algorithm for the reverse path transformation is presented in Figure 5.6.

As an example, if we choose the cycle  $C_3$  in Figure 5.5(a) to be the shortest-cycle (assuming equal weights of all links in the original graph  $G$ ) between nodes 1→6, then the two routes, obtained from the cycle are  $P_1$ : 1-2-6 and  $P_2$ : 1-5-6 as shown in Figure 5.5(b).

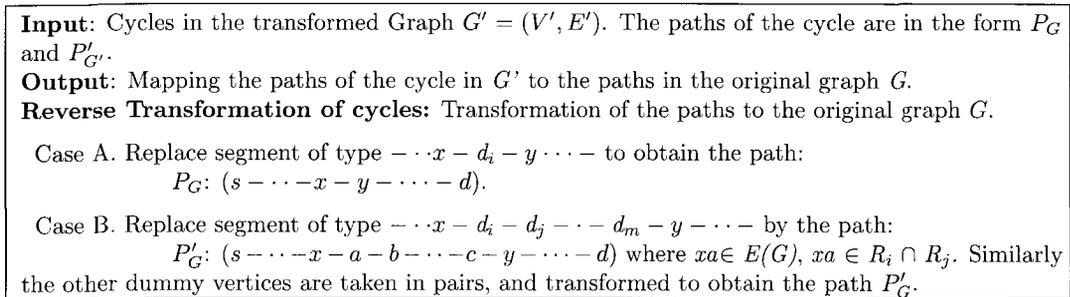


Figure 5.6 SRLG Disjoint Routing in original graph

**Lemma:** If there exists a cycle in the graph  $G$ , then the transformation guarantees that the cycle will be found.

*Proof.* A link in a graph can either belong to one SRLG, or it can be in one of the scenarios as depicted in Figure 5.7. Recall that a link can belong to utmost two SRLG's. If all the links in the graph, are in a single SRLG, then the transformation guarantees that the two disjoint paths between the source and destination will use any one of the two links  $u - d_i - v$  or  $u - d_i - w$ , and hence are SRLG-disjoint. If any link belongs to more than one SRLG, as depicted by Figure 5.7(a), the transformation would yield a graph  $G'$  as given in Figure 5.8. The weights on the links indicate the weights obtained after the graph transformation.

**Case I:** If the paths of the cycle includes the common edge 1-2 (equivalently edge  $d_1 - d_2$  in  $G'$ ), as shown in Figure 5.8, then it cannot include any of the other two edges 1-3 or 2-3.

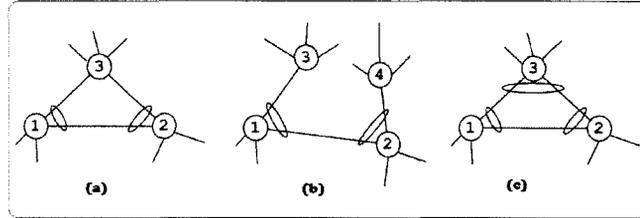
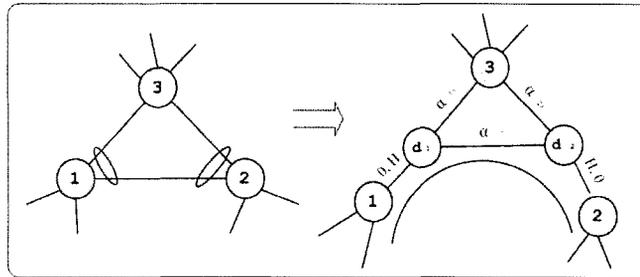


Figure 5.7 Different shared link scenarios

**Case II:** If the path happens to pass through one of the non-common edges 1-3 as shown in Figure 5.9, then the cycle cannot use the common edge 1-2. It to be noted that for an s-d pair it will not use the second non-common edge 2-3, because of the higher weight on  $d_jv$  or  $d_iu$  if another path exists to complete the cycle. This ensures group disjointness between the paths comprising the cycle. Note that each  $d_i$  has an odd degree of 3 and hence can only allow only two edges to be used in a cycle and hence both the common and uncommon edges cannot be used at the same time.

Figure 5.8 Path scenarios in cycle computation in  $G'$ 

In case of a network shown in Figure 5.7(b), the paths can be either in the format shown in Figure 5.10(a) & (b).

**Case I:** If the path of the cycle is as shown in Figure 5.10(a), then the cycle cannot consist of the edges 1-3 and 2-4 which is desired for ensuring group-disjoint paths.

**Case II:** If the path of the cycle is as shown in Figure 5.10(b), then the cycle can comprise of the edges 1-3 and 2-4 but cannot have the common edge 1-2, which again ensures that the

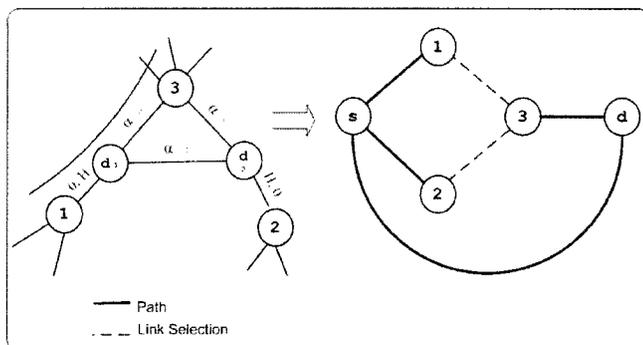


Figure 5.9 Path in a cycle, including a non-common edge

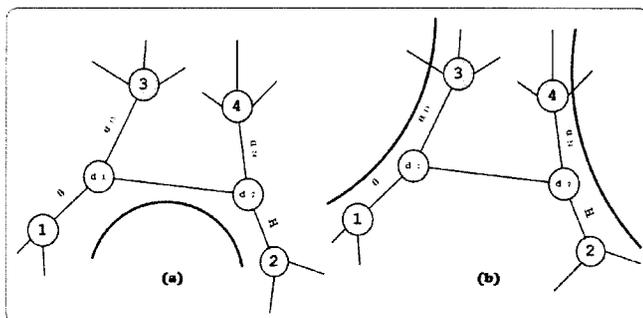


Figure 5.10 Path possibilities in a cycle for network instance Figure 5.7(b)

paths are group disjoint and a cycle be completed.

Now, let us consider a network with SRLG's as shown in Figure 5.11. The transformed graph is shown in Figure 5.11 (a) & (b).

**Case I:** If the edges  $1 - d_1 - d_2 - 2$  are selected as one of the paths of the cycle, then the edges 1-3 and 2-3 cannot be part of the cycle, thus ensuring group disjointness. If the path is as shown in Figure 5.11(a), then the edges 1-2 and 3-2 cannot be part of the cycle.

**Case II:** If the path is as shown in Figure 5.11(b), then the edge 1-3 cannot belong to the cycle. Hence a cycle can be always computed, if one such exists in the topology.

Furthermore we can have a network topology where the SRLG's are arranged in a cascaded manner as shown in Figure 5.12. The transformed network is shown in the same figure. As

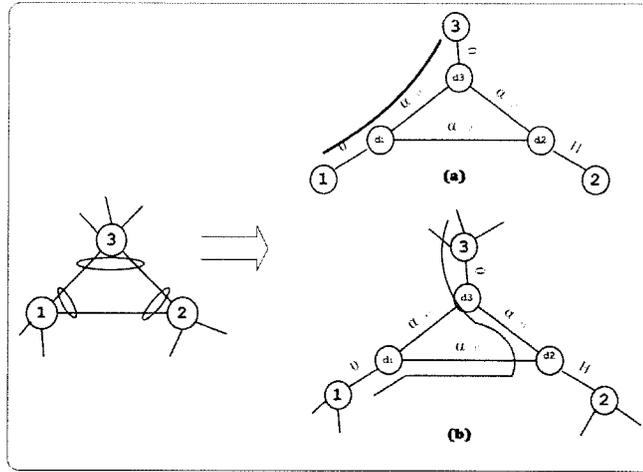


Figure 5.11 SRLG scenario depicting a cycle of sharing links

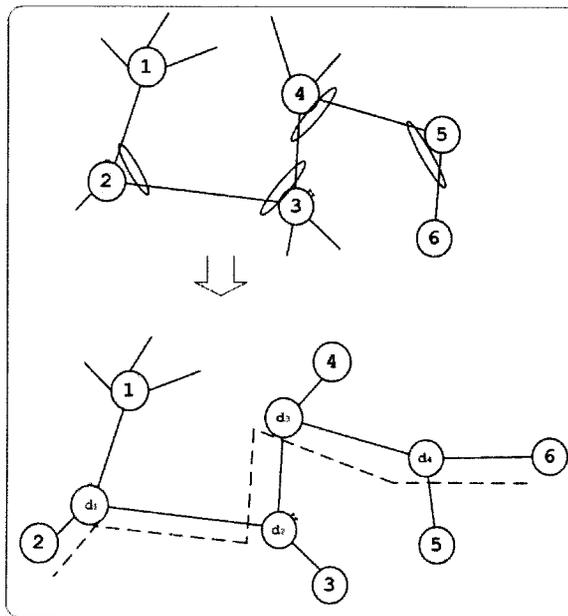


Figure 5.12 Cascading SRLG's

can be seen in the worst-case, the path would traverse all the dummy nodes.

**Case I:** If the edges  $2 - d_1 - 1$  is selected as one of the paths of the cycle, then the edge 2-3 cannot be part of the cycle, thus ensuring group disjointness.

**Case II:** If the path is of the type  $u - d_i - d_j - \dots - d_m$ , where  $1 \leq m \leq \chi$ , then the path in the original graph can be obtained by reverse transforming the dummy vertices pairwise to edges in  $G$ , as shown in Figure 5.6. Again this guarantees that a cycle can be found.  $\square$

**Lemma:** If there exists an edge-disjoint shortest cycle in the transformed graph  $G'$ , then using the above transformation, the paths  $P_1$  and  $P_2$  comprising the cycle can be always mapped to two SRLG disjoint routes in the original graph  $G$ .

*Proof.* If  $P_1$  and  $P_2$  comprises the two paths of the edge-disjoint shortest cycle in the transformed graph  $G'$ , then each dummy vertex  $d_i$  can appear utmost once in either of the paths  $P_1$  or  $P_2$ .

Thus the paths  $P_1$  and  $P_2$  consists of segments which maybe either in the form of  $P$ :  $(-\dots - u - d_i - v - \dots -)$  or  $P'$ :  $(-\dots - u - d_i - d_j - \dots - d_m - v - \dots -)$ , where  $1 \leq m \leq \chi$ . In case 1 (also shown in Figure 5.9), there is an exact mapping of the edges  $u - d_i - v$  in the transformed graph  $G'$  to the edge  $uv$  in the original graph  $G$ . This can be obtained by just dropping the dummy vertex from the path obtained in the transformed graph  $G'$  to obtain the path in the original graph. In case 2 (as shown in Figure 5.12), the edges  $d_i - d_j - \dots - d_m$  in the transformed graph, is mapped back to the edges in the original graph by taking the dummy vertices pairwise, and transforming it to the edges  $uv$ , such that  $uv \in E(G)$ ,  $uv \in R_i \cap R_j$  and  $ud_i, d_jv \in E'(G')$ . Since the primary and backup lightpaths do not have any overlapping  $d_i$ 's, the routes mapped back on the original graph are always SRLG disjoint.  $\square$

### 5.2.1 Complexity Analysis of SRLG Routing

We evaluate the overall complexity of the SRLG disjoint routing algorithm using the graph transformation technique. The computational complexity can be broken up into three parts, one the complexity involved in the transformation of the graph, second the complexity of finding out edge-disjoint shortest cycles in the transformed graph and finally the complexity of mapping the paths obtained on the transformed graph to the paths in the original graph.

As can be seen from the algorithm presented for graph transformation in Figure 5.2, the complexity involved in determining whether an edge belongs to more than one shared-risk

link group involves an exhaustive search, which is computationally of the order of  $O(L^2 \cdot \chi)$ . Depending on the outcome of this decision, the edges are transformed following the algorithm presented above. Thus the overall complexity of the graph transformation is  $O(L^2 \cdot \chi)$ .

The transformation of the graph from  $G \rightarrow G'$  adds  $\chi$  number of nodes. Two paths that are shared-risk group disjoint are computed using the shortest-cycle algorithm on the transformed graph as described in [67]. The computational complexity of the shortest-cycle algorithm is given by  $O(N \log N + L^2)$ . We have two distinct cases, one in which the SRLG's are such that there is no edge which belongs to more than one group and another scenario where an edge can possibly belong to two shared risk groups. In both the cases, the additional number of edges introduced in the transformed graph  $G'$  is  $\chi$ . Hence the complexity of finding two SRLG disjoint paths would be  $O(N \log N + L^2)$ .

Once the edge-disjoint shortest cycle are computed in the transformed graph, the paths comprising the cycle, is mapped back on the original graph  $G$ . This has a computational complexity of  $(L + \chi) \cdot L^2$  since a path can have a maximum of  $(L + \chi)$  edges in a transformed graph  $G'$  and determining the next hop vertex would involve an exhaustive search among all edge pairs. Combining the three above complexities, the overall complexity of the diverse SRLG routing is given by the dominant term, which is the complexity involved in finding the edge-disjoint shortest cycle on the transformed graph. Thus the overall complexity is given by  $O(L^3)$ .

### 5.3 Trap Avoidance in Diverse SRLG Routing

In a diverse SRLG routing, there might be instances where an algorithm fails to find a pair of SRLG disjoint routes for a given source and destination due to topologically induced *traps* also known as *unavoidable traps*[20]. *Unavoidable traps* are constraints imposed by the underlying topology, and cannot be worked around by any algorithm, i.e. there does not exist any SRLG disjoint paths between a source and destination node pair. For example if a network is not 2-edge connected then there is no algorithm that can guarantee the presence of two SRLG disjoint routes in the topology. *Avoidable traps*, however are traps that are not

imposed due to the underlying topology, but are due to the shortcomings of the underlying routing algorithm.

These traps can be easily avoided by choice of an appropriate routing algorithm. Some heuristic approaches have been studied in [20, 22] to work around avoidable traps in an underlying topology. The graph transformation techniques suggested in this paper attempts to find shortest cycles in a transformed graph, instead of using Dijkstra's shortest paths, and maps these cycles on the actual topology. Since the shortest cycle algorithm [67] inherently takes care of *avoidable traps* our approach always successfully finds SRLG disjoint routes in a given topology, if the topology is 2-edge connected and such disjoint routes exist in the topology.

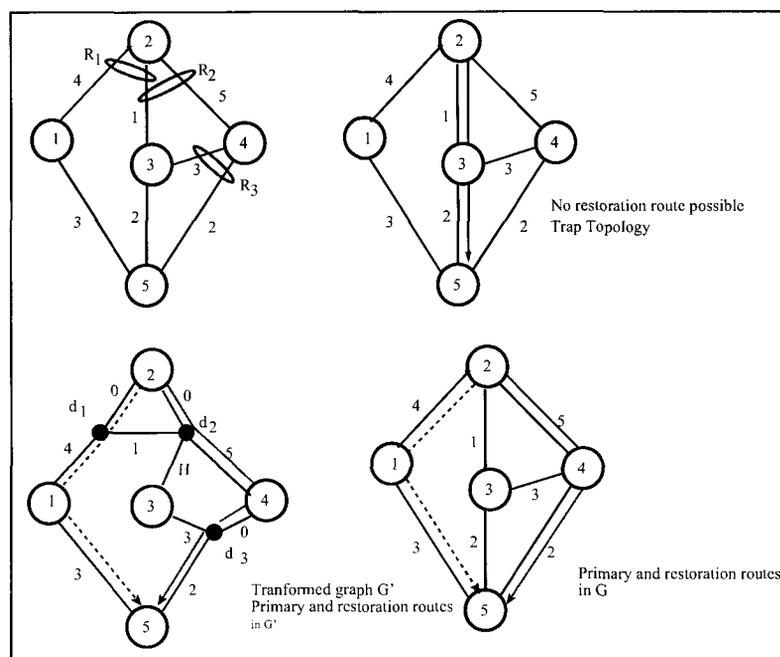


Figure 5.13 Trap Avoidance in Diverse SRLG Routing

One of the traditional approaches for computing diverse SRLG routes, is to compute the shortest path using the Dijkstra's algorithm from a node  $S$  to node  $D$ . For all the edges in the primary or service path, remove all the edges that share a common failure structure with these edges. The Dijkstra's algorithm is again run on the residual network to compute the second shortest path from  $S$  to  $D$ . When routing over a trap topology, the pre-selected

service path may not have a diverse restoration path, even though diverse paths exist in the network. For example, Figure 5.13 shows a network topology with the shared risk link groups and the edge weights. Computing the shared risk link group disjoint path using the traditional Dijkstra's algorithm would lead to selection of the path  $1 \rightarrow 3 \rightarrow 5$  as the primary path, thus making selection of a restoration route infeasible. However the proposed graph transformation transforms the graph as shown in Figure 5.13. The shortest cycles computed on the transformed graph are shown in the same figure. As can be seen, the graph transformation approach computes two shared risk diverse paths  $P_1: 1 \rightarrow 4 \rightarrow 5$  and  $P_2: 1 \rightarrow 2 \rightarrow 5$ .

#### 5.4 SRNG (Shared Risk Node Group) Diverse Routing

We propose a graph transformation technique for finding out two routes in scenarios where more than one node shares a common risk of failure. We identify such scenarios where more than one node shares a common risk of failure as shared risk node groups (SRNG's). We assume that the size of each SRNG is limited to two adjacent nodes sharing an edge between them.

Each shared-risk node group  $S_i$  can be represented as

$$S_i = \{(u_i, v_i) \mid u_i \in N(v_i)\}.$$

$$\text{where } |S_i| = 2, \quad i=1, \dots, \psi$$

A *dummy vertex*  $d_i$  is used to represent each shared-risk node group in the transformed graph  $G' = (V', E')$ .  $G'$  is derived from  $G$  by following the vertex transformation:

$$V' := V \setminus \{u_i, v_i\} \cup \{d_i\}, \quad i = 1, \dots, \psi.$$

Hence in the transformed graph  $G'$ , the total number of vertices is given by the cardinality of the set  $V'$ ,  $|V'| = N - \psi$ , where  $N$  is the cardinality of the set  $V$ . The edges in the transformed graph  $G'$  are represented as:

$$E' = E \setminus \{E_1 \cup E_2 \cup E_3\} \cup E_4$$

$$\text{where } E_1 = \{u_i v_i\}, \quad i = 1, \dots, \psi. \quad |E_1| = \psi.$$

$$E_2 = \{u_i x\}, \quad u_i \in S_i, \quad x \in N(u_i), \quad x \notin S_i, \quad i = 1, \dots, \psi$$

$$E_3 = \{v_i x\}, \quad v_i \in S_i, \quad x \in N(v_i), \quad x \notin S_i, \quad i = 1, \dots, \psi$$

$E_4$  are new edges from  $d_i$  to  $N(u_i) \cup N(v_i)$ ,  $i = 1, \dots, \psi$ .

The detailed graph transformation algorithm is presented in Figure 5.14.

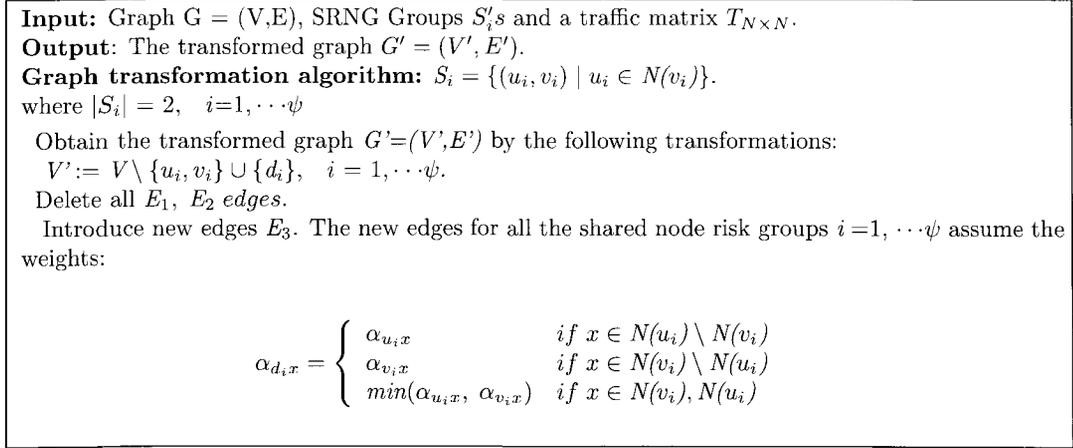


Figure 5.14 Graph transformation algorithm

As shown in Figure 5.15(a), the links between nodes 2→3, 1→3, 1→4, 6→3 and 5→4 are replaced by modified edges with adjusted edge weights as shown in the graph transformation algorithm.

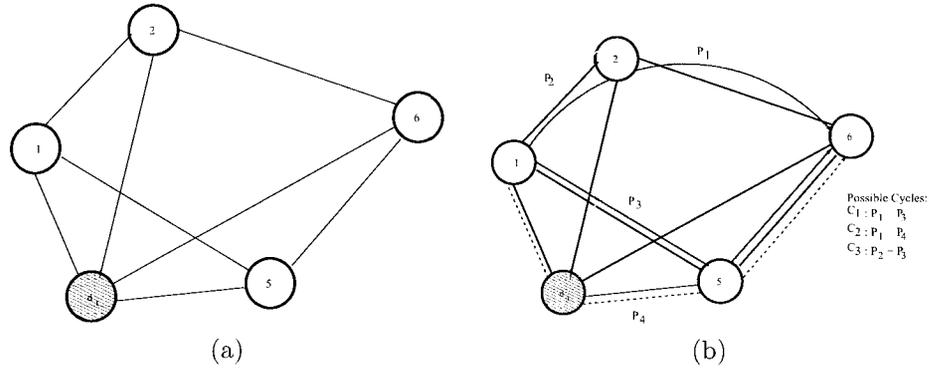


Figure 5.15 (a) Transformed Graph Indicating Shared Risk Node Groups, (b) SRNG Disjoint Routes in the transformed Graph  $G'$ .

**Input:** Graph  $G = (V, E)$ , SRNG Groups  $S'_i$ s and a traffic matrix  $T_{N \times N}$ .  
**Output:** The shortest cycle for each  $t_{sd} \in T_{N \times N}$  in the transformed graph  $G' = (V', E')$ .  
**Cycle computation algorithm:** Obtain the cycles in the transformed graph  $G'$  using the following algorithm

```

While ( $t_{sd} > 0$ )
{
  Obtain the Node-Disjoint Shortest Cycle on the transformed graph  $G'$  for any traffic  $t_{sd} \in T_{N \times N}$  using the node-disjoint shortest cycle algorithm presented in [67]. The paths of the shortest cycle have one or more segments of the following types:
  I.  $P_{G'}$ : ( $\dots - x - d_i - y - \dots$ ) or
  II.  $P'_{G'}$ : ( $\dots - x - d_i - d_j - \dots - d_m - y - \dots$ ), where  $1 \leq m \leq \psi$ .
}

```

Figure 5.16 Cycle computation algorithm

**Computing Cycles:** Two routes for a given s-d pair in the original graph  $G$ , that are node group disjoint is obtained by finding the node-disjoint shortest-cycle [67] in  $G'$  as shown in Figure 5.16 and Figure 5.15(b). Infact finding out a node disjoint shortest cycle on the transformed graph ensures that the two paths comprising the cycle, can guarantee fault-tolerance against failure of any single node on the path and also from node groups present in the topology. For example the two node disjoint paths between nodes  $1 \rightarrow 6$  can be possibly the two paths comprising either of the following cycles in  $G'$ :  $C'_1$ : {1-2-6, 1-5-6} or  $C'_2$ : {1-2-6, 1- $d_1$ -6} or  $C'_3$ : {1-2-6, 1- $d_1$ -5-6} and  $C'_4$ : {1-2- $d_1$ -6, 1-5-6} as shown in Figure 5.15(b).

**Reverse Mapping of Paths** After the node-disjoint shortest cycles are found, the paths corresponding to the cycles are mapped back to obtain the two node-group disjoint routes on the original graph  $G$ . The fact that the routes in  $G'$  are node-disjoint guarantees node group disjoint routes in the original graph  $G$ .

In the reverse mapping of the path  $P$  from  $G' \rightarrow G$ , we transform the edges in  $G'$  to obtain the corresponding edges in the original graph  $G$ . The details of the algorithm for the reverse mapping of edges to the original graph  $G$  is shown in Figure 5.17.

For example if the cycle  $C'_3$  is chosen, then the paths on the original graph would be 1-2-6 and 1-4-5-6 (and not 1-3-6 because, there is no link between 3 $\rightarrow$ 5). However if the cycle  $C'_4$  is chosen, then the two routes are 1-2-3-6 and 1-5-6. This is shown in Figure 5.19.

**Input:** Cycles in the transformed graph  $G' = (V', E')$   
**Output:** Mapping the paths of the cycle in  $G'$  to the paths in the original graph  $G$ .  
**Reverse transformation of cycles:** Transformation of cycles computed in  $G'$  to original paths in  $G$ .

Case I.  $P_G$ : At vertices  $x$  &  $y$  select vertex  $w$  s.t.  $w \in S_i, N(x), N(y)$ . For more than one choice of  $w$ , select  $w$  s.t. it minimizes  $\alpha_{xw} + \alpha_{wy}$ . The segment transformed back in the original graph, hence becomes  $(\dots - x - w - y - \dots)$ .

If no unique  $w$  exists, determine if  $u_i \in N(x), u_i \notin N(y), u_i \in S_i$ . The segment transformed back in the original graph, hence becomes  $(\dots - x - u_i - v_i - y - \dots)$ . Else the segment transforms to  $(\dots - x - v_i - u_i - y - \dots)$ .

Case II. Let  $e', e''$  denote the critical edges connecting the vertices in the node-groups  $S_i$  and  $S_j$  respectively. Let  $e$  denote the bridge link between  $S_i$  and  $S_j$ .

$P'_G$ : The reverse mapping of the segment  $x-d_i-d_j-$  leads to a selection of vertices  $w, w'$  such that  $w \in N(x), S_i$ , and  $w' \in N(w), S_j$ , and corresponding edges which satisfy that one of  $\alpha_{xw} + \alpha_e$  or  $\alpha_{xw} + \alpha_{e'} + \alpha_e$  or  $\alpha_{xw} + \alpha_e + \alpha_{e''}$  or  $\alpha_{xw} + \alpha_{e'} + \alpha_e + \alpha_{e''}$  is **minimized**, depending on choice of vertices. This is done for all successive pair of  $d_i - d_j$  vertices.

Figure 5.17 Reverse mapping of paths algorithm

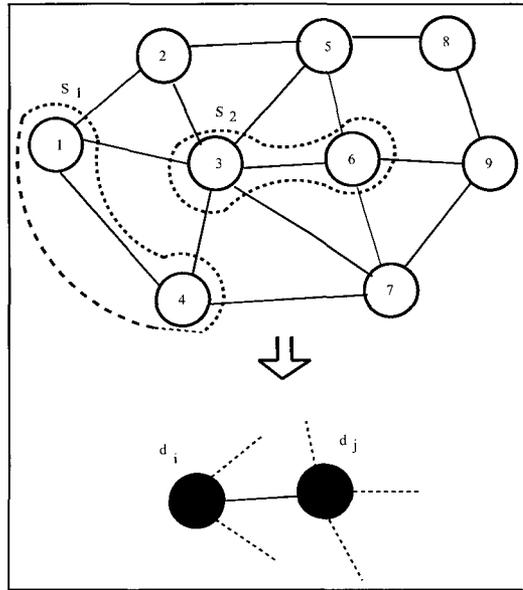


Figure 5.18 Example showing links between two dummy nodes and the reverse transformation.

**Lemma:** In a graph with SRNG's, if there exists a node-disjoint shortest cycle in the transformed graph  $G'$ , then using the above reverse mapping, the paths  $P_1$  and  $P_2$  composing the cycle always maps to two SRNG disjoint routes in the original graph  $G$ .

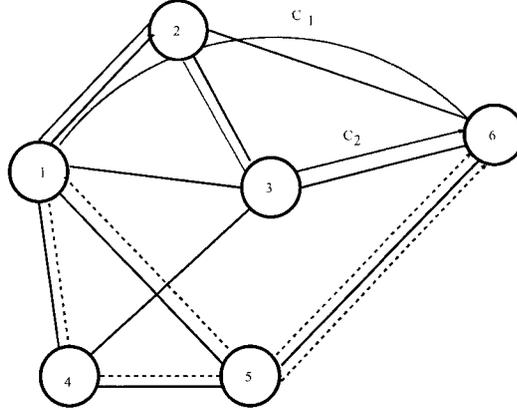


Figure 5.19 Shared Risk Node Group Disjoint Routes on the Original Graph  $G$ .

*Proof.* Each *dummy node* representing a shared risk node group can appear utmost once in any one of the two routes  $P_1$  or  $P_2$  of a cycle, and these routes are node-disjoint. The transformation of these routes on the original graph  $G$  hence guarantees that they are SRNG disjoint.  $\square$

#### 5.4.1 Complexity Analysis of SRNG Routing

This section evaluates the overall complexity of SRNG disjoint routing. The computational complexity can be broken up into three parts, the complexity involved in the graph transformation, second the complexity of finding out node-disjoint cycles in the transformed graph and finally mapping the paths obtained on the transformed graph to paths in the original graph.

The total number of shared risk node groups in the network is given by  $\psi$  and each group has two nodes. Thus the complexity involved in determining whether an edge has an end-vertex which belongs to an SRNG and transforming it involves an exhaustive search, which is computationally of the order of  $O(L\psi)$ . Depending on the outcome of this decision, the edges are transformed following the algorithms explained above. Thus the complexity of the graph transformation is  $O(L\psi)$ .

The transformation of the original graph  $G$  into the final graph  $G'$  reduces  $\psi$  number of nodes in the original graph. Two paths that are shared-risk group disjoint are computed using the node-disjoint shortest-cycle algorithm on the transformed graph [67]. The computational

complexity of the shortest-cycle algorithm is given by  $O(N \log N + L^2)$ . Following the graph transformation all the edges between the nodes of each node group gets deleted, hence leading to a deletion of total  $\psi$  number of edges. Let us denote the set of vertices which has an edge to both the nodes of an SRNG as the vertex set  $V_s$ . Let the cardinality of this set be denoted by  $|V_s|$ . Transition from  $G \rightarrow G'$  leads to a further deletion of  $|V_s|$  edges. Hence the complexity of finding two SRNG disjoint paths is  $O(N \log N + L^2)$ .

Once the node-disjoint shortest cycles are computed on the transformed graph, the paths comprising the cycle, are mapped back to the original graph  $G$ . In cases where nodes belong to only one shared risk node group, we scan through each edge in the path and at the vertices  $x$  &  $y$ , we scan through its entire neighborhood and select the appropriate vertices as described in Section 6. Hence the complexity involved in this procedure is  $O(L^2)$ , since the maximum hop length of a path can be restricted to  $E' = L - \psi - |V_s|$  edges and we need to scan through all the neighbors and compare the path lengths in all cases.

Combining the three above complexities, the overall complexity of the diverse SRNG routing is given by the dominant term, which is the complexity involved in finding the node-disjoint shortest cycle on the transformed graph. Thus the overall complexity is given by  $O(N \log N + L^2)$ .

## 5.5 Capacity Minimization in Diverse SRRG Routing

In the previous sections we proposed graph transformation heuristics for solving the diverse routing problem in networks with shared risk resource groups. We proposed a methodology for tolerating dependent or shared risk link failures and coordinated node failures in a network. This methodology would help us answer the question, whether there is a feasibility of existence of such group disjoint routes in a given topology, once the dependent failure structures are defined in the topology.

Once a connection is routed on an optical network, one of the primary objectives is to not only route it over diverse paths but to also minimize the overall spare capacity thus utilized in the network. Some of the traditional approaches include the sharing of backup bandwidth

between multiple connections, that doesn't share the risk of failure at the same instance of time. Our attempt in this section would be to use our graph transformation methodology, such that we can route any incoming connection in the network ensuring that the primary and backup paths of the connections are link/node group disjoint and also uses the minimal amount of spare capacity.

An optical network can be modeled as a network having  $E$  links,  $F$  fibers per link,  $W$  wavelengths per fiber and  $T$  time-slots per wavelength. Hence the network can be represented by a 4-tuple  $(e, f, w, t)$ , where  $1 \leq e \leq E$ ,  $1 \leq f \leq F$ ,  $1 \leq w \leq W$  and  $1 \leq t \leq T$ . For simplicity we assume that the number of time-slots in each wavelength is equal to one. The multiplexing of backup bandwidth on a particular fiber-wavelength-timeslot combination is done by maintaining a *Backup Request List (BRL)* on each wavelength of each fiber at every link. The Backup request List is a link-list of all the requests whose backup paths are multiplexed on a particular fiber-wavelength at a link.

The primary path of the requests are routed using the *first-fit* fiber & wavelength assignment. The backup paths of the incoming connections are routed using the connection establishment methodology described previously in Section 3.4. The above framework for information collection and routing is also referred to as *MICRON* [71] and it helps in efficient bandwidth usage.

## 5.6 Results

Three network topologies, the 14-node, 23-link NSFNET and 11-node, 22-link NJLATA and 15-node, 24-link modified COST239 network with shared-risk link groups and shared-risk node groups as shown in Figure 5.20 & Figure 5.21, were simulated to assess the performance of the graph transformation heuristic for tolerating SRRG failures. Each of these topologies consists of links with 1 fiber per link, 20 wavelengths per fiber, and 1 timeslot per wavelength. Each link also consists of 2 unidirectional links that are assumed to be part of the same shared risk link group, meaning that if the link in one direction fails, the link in the opposite direction also fails because they would presumably physically routed together. No nodes offer

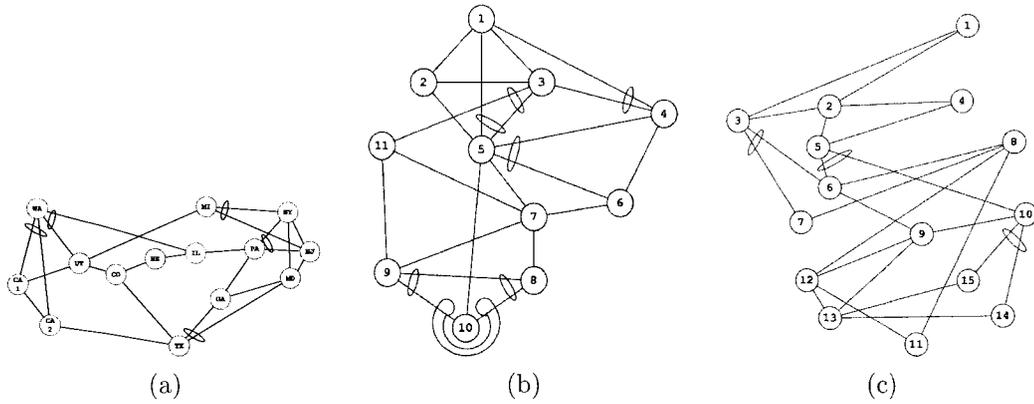


Figure 5.20 (a) 14 node, 23 link NSFNET; (b) 11 node, 22 link NJLATA; (c) 15 node, 24 link modified COST239 network

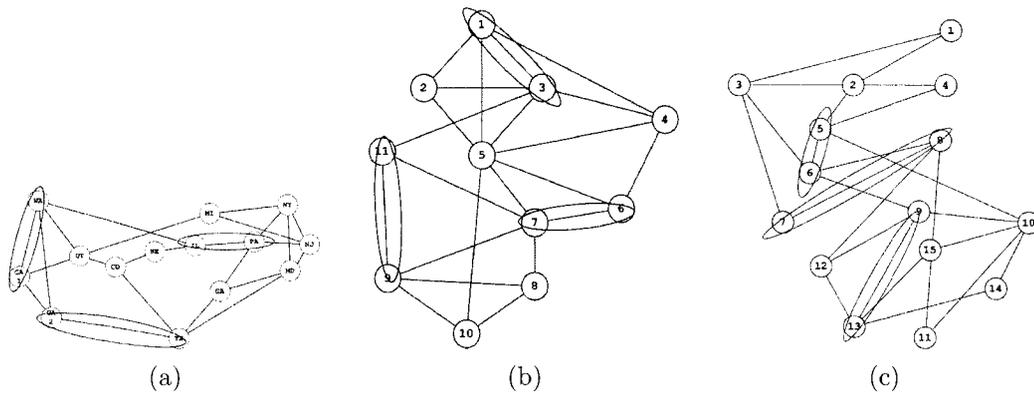


Figure 5.21 (a) 14 node, 23 link NSFNET with SRNG's; (b) 11 node, 22 link NJLATA with SRNG's; (c) 15 node, 24 link modified COST239 network with SRNG's

any wavelength switching capabilities, thus the *wavelength continuity constraint* is obeyed.

The arrival of the requests at a node follows a Poisson process with rate  $\lambda$ , and are equally likely to be destined to any other node. The holding time of the requests follow an exponential distribution with unit mean. The capacity requirements of each request is a unit wavelength. As can be observed from Figure 5.22 the blocking probability for all the three topologies using the proposed graph transformation technique and the shortest-path diverse routing technique

[26, 67].

The results indicate that the graph transformation techniques achieve much better blocking performance as compared to the techniques studied in literature [67]. The trend is similar in all topologies, however the maximum benefits are achieved in NJLATA, because it has a high average nodal degree of 4.0 as compared to 3.28 in NSFNET and 3.2 in case of the modified COST239 network. High nodal degree helps in the computation of diverse routes for an incoming connection.

Figure 5.23 demonstrates the blocking performance for all the three studied topologies using the graph transformation technique and the techniques studied in [26, 67] in the presence of shared-risk node groups (SRNG's). The blocking values computed are significantly higher for shared-risk node groups as compared to those for shared-risk link groups. The graph transformation techniques are however able to provide diverse routes for around 20-30% of the incoming requests, as compared to the traditional approach proposed in [67] which is unable to provide any diverse routes for the studied shared-risk node groups. Table 5.2 provides a detailed comparative analysis of blocking performance for both the studied algorithms under different topologies.

Figure 5.24 demonstrates the average path length for all the studied topologies in the presence of shared-risk link groups and shared-risk node groups using both the graph transformation technique as well as the shortest-node pair disjoint routing technique. As can be observed with increasing link load, and increasing blocking probability, the average path length decreases for all topologies.

The effective network utilization in the presence of shared-risk link groups (SRLG's) and shared-risk node groups (SRNG's) are represented in the graphs in Figure. 5.25 and Figure 5.26. As can be observed in these figures, the effective utilization of the network increases with increasing load. This is because, as the network load increases, there are more number of connections that are serviced by the network. As can be observed, the effective utilization varies between 18% -32% for both the graph transformation technique as well as the shortest-path heuristic in case of shared-risk link groups. It varies between 5% -14% for shared-risk

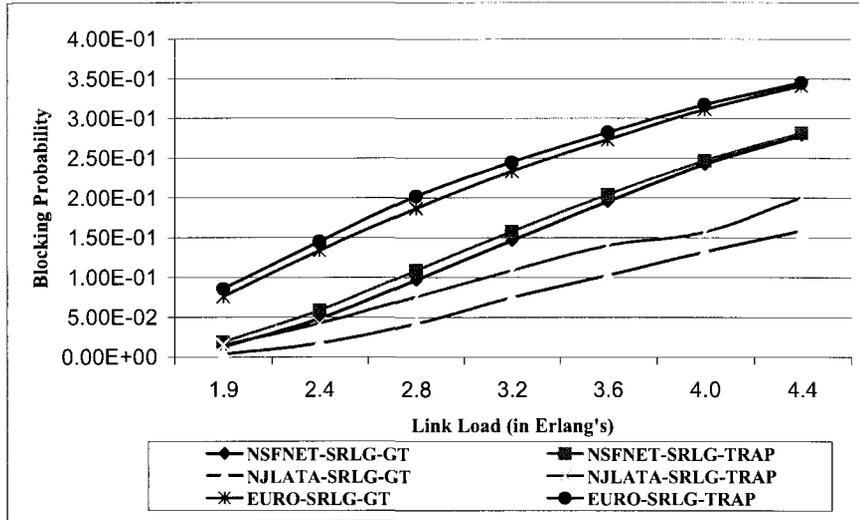


Figure 5.22 Blocking Probability vs. Link Load (in Erlang's) for SRLG's

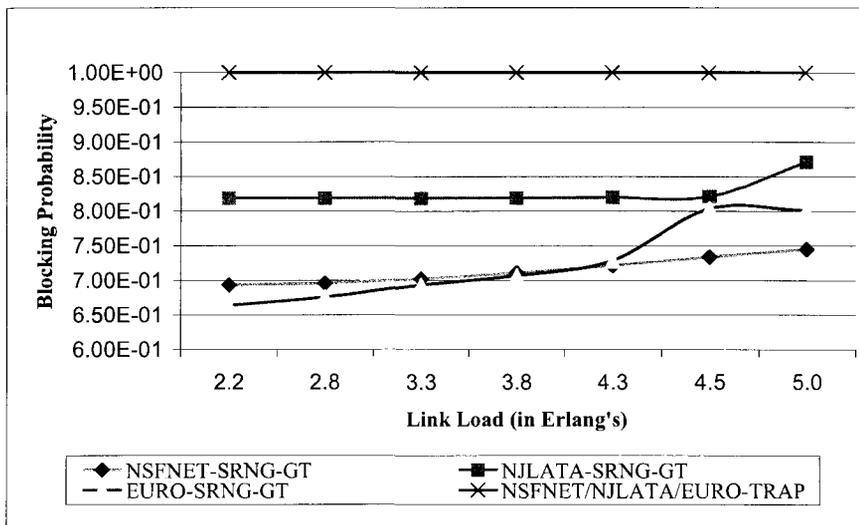


Figure 5.23 Blocking Probability vs. Link Load (in Erlang's) for SRNG's

node groups across different topologies using the graph transformation technique. The effective utilization is zero for shared node risk groups, using the shortest-path heuristic.

Table 5.2 Blocking performance for SRNG routing using graph transformation and shortest-path routing

Index	NSFNET			NJLATA			EURO		
	GT	SP	%Impv	GT	SP	% Impv	GT	SP	% Impv
40	69%	100%	31%	81.9%	100%	18.1%	66.4%	100%	33.6%
50	69.5%	100%	30.5%	81.9%	100%	18.1%	67.6%	100%	32.4%
60	70.2%	100%	29.8%	81.9%	100%	18.1%	69.4%	100%	30.6%
70	71.1%	100%	28.9%	81.9%	100%	18.1%	70.7%	100%	29.3%
80	72.2%	100%	27.8%	82.0%	100%	18.0%	72.9%	100%	17.1%
90	73.4%	100%	26.6%	82.1%	100%	17.9%	80.4%	100%	19.6%
100	74.5%	100%	25.5%	87.1%	100%	12.9%	80.7%	100%	19.3%

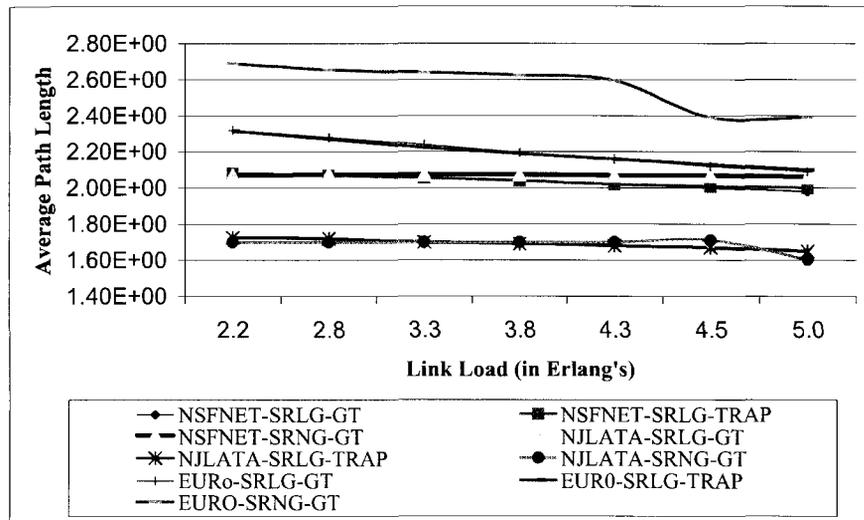


Figure 5.24 Average Path length vs. Link Load (in Erlang's)

## 5.7 Chapter summary

The following are the main contributions of this chapter:

- In this chapter we proposed graph transformation techniques for solving the diverse routing problem in networks with shared risk resource groups.

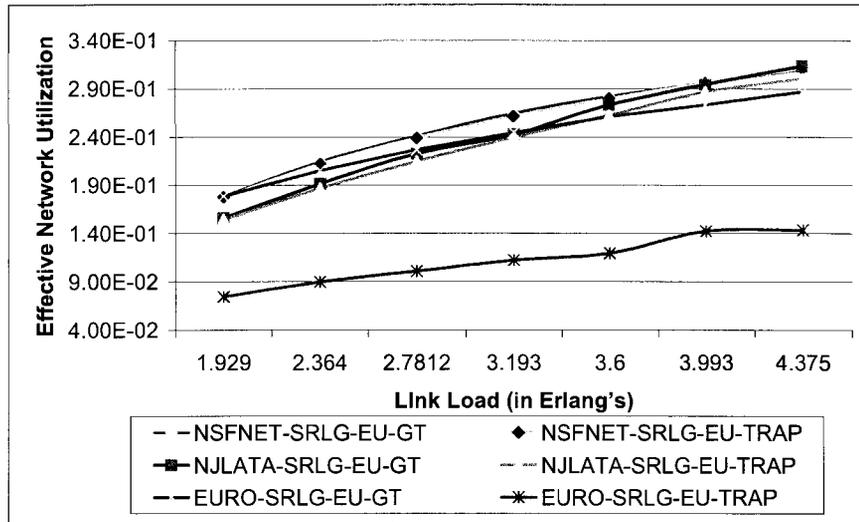


Figure 5.25 Effective utilization vs. Link load for Shared-Risk Link Groups

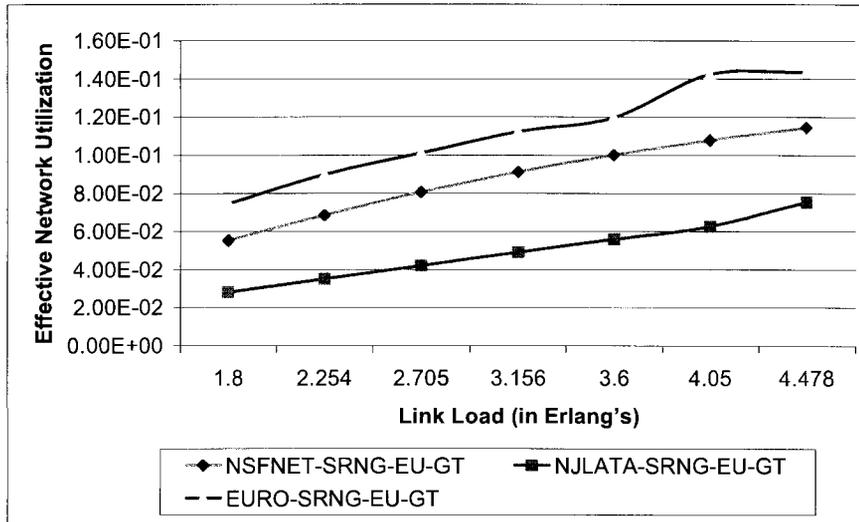


Figure 5.26 Effective utilization vs. Link load for Shared-Risk Node Groups

- We proposed a methodology for tolerating dependent or shared risk link failures and coordinated node failures in a network, by creating different graph transformations, routing on the transformed graph and transforming the routes on the modified graph to the original graph.
- The proposed methodology enables us to identify if 100% guarantee can be provided for any single SRLG or SRNG failure in a network.
- The proposed graph transformation algorithm only needs addition of a small number of edges and vertices to the original graph, and computation of link-disjoint or node-disjoint shortest cycles in the transformed graph (both of which are polynomial time algorithms [67]). It provides a polynomial time solution for the diverse routing problem for certain specific shared resource groups.

We validate the correctness of our proposed transformation approach, and illustrate how this technique always guarantees to yield shared risk group disjoint routes, if such a route exists in the graph. This approach for diverse routing under multiple failure scenarios is extremely elegant and can be applied to large networks with huge traffic demands.

## CHAPTER 6. Network Planning and Evolution

In this chapter we discuss a design and upgrade methodology for mesh-restorable WDM networks. We present a heuristic approach which minimizes the number of links used in the network, link provisioning cost, number of components used such as optical amplifiers, multiplexers, demultiplexers and dispersion compensation components. What sets this work apart from other work on design of mesh-restorable optical networks, is that it provides an innovative mapping of a well established optimization heuristic to the design and upgrade scenario in optical WDM mesh restorable network.

In the first step, we design a network which accommodates the traffic while minimizing the possible number of links, fibers utilized, and different optical components used. We, therefore, propose an approach to route the traffic in such a way that reduces the total number of required wavelengths and lightpath's, thus minimizing the overall network cost.

In the second step we adapt a design methodology so that it can accommodate incremental traffic demands across multiple generations of network evolution. We add traffic demands across different source-destination pairs, in a linear trend and demonstrate the efficacy of the proposed technique through a large number of experiments. We also compare our solutions with those obtained through ILP formulations, and demonstrate the proximity of the solutions obtained.

The main contributions of this chapter are summarized as follows:

- We develop a generic model for near optimal design and upgrade scheme for WDM backbone networks. In mesh-restorable networks, fast restoration is provided by using pre-determined paths and it uses backup multiplexing techniques for improving wavelength utilization. We assume the following cost model for network design and operation. The

total network facility cost is mapped to a) link provisioning cost which includes digging cost, leasing cost, right of way cost, maintenance cost etc; b) fiber cost, which includes optical amplifier cost, multiplexer and demultiplexer cost, cost of dispersion compensation components etc; and c) per channel cost which includes cost of receiver and transmitter cards.

- We assume that the network topology and the current traffic demand is given. For a given static traffic demand we need to find an optimal routing that minimizes the total network facility cost for the current generation of the network. Hence the output of the problem is the number of fibers and wavelengths on each active link, the size of the OXC's required at each node, and the links that need to be activated for realizing the current traffic demand.

Once the current demand set is realized, more spans are cost effectively added as the traffic increases during the lifetime of the network, such that the total network facility cost is minimal at each evolutionary stage of the network. The proposed routing methodology can be also used as part of network operation to optimally route the ever increasing traffic demands from one generation to the next.

## 6.1 Network Model

In this section we define the network model of a WDM network which comprises of switching nodes interconnected by one or more optical fibers. We assume a homogeneous network architecture i.e. all the node architectures are identical throughout the network. Each fiber carries a certain number of wavelengths. The number of wavelengths supported in a fiber is a technological constraint, which is expected to increase from few hundreds to higher numbers in the coming years. A lightpath is defined as an all optical channel from a source to a destination that provides a circuit switched connection between two nodes.

Each node consists of an optical cross-connect (OXC) and some optical terminating equipment. Some of the nodes however act as *pass-through* nodes, where optical channels are in transit. An optical channel passing through an cross-connect node maybe routed from an input

fiber to an output fiber without undergoing optical-electronic-optical (O-E-O) conversions. In our model, we assume that the wavelength continuity constraint is satisfied on all the links along the route. We assume that there is no wavelength conversion capabilities at any node in the network.

All the cross-connects are wavelength selective. An optical channel can be terminated by an optical line terminating equipment such as Wavelength add/drop multiplexers (WADM's). WADM's are used to add or drop selected wavelengths to and from the fiber. Any node can be a source or destination to a connection. We also assume switching required to route an incoming wavelength on one fiber to go to any output fiber on the same wavelength. The architecture of a typical wavelength routing switch employed at each node is shown in Figure 6.1.

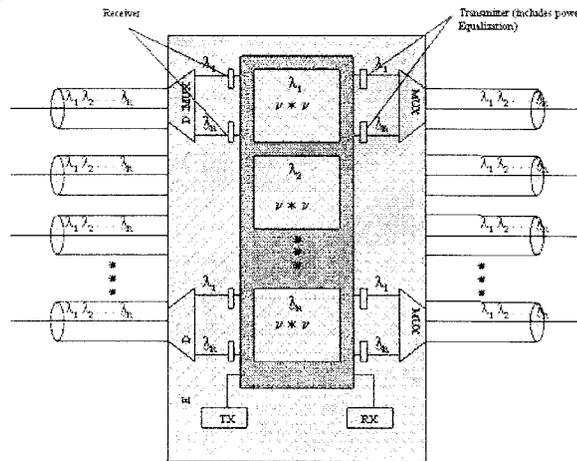


Figure 6.1 Wavelength Routing Switch Architecture

The network state information is collected at a node by link state vector. In link-state protocols every node transmits its node and link specific information to every other node in the network. Each node in the network is assumed to maintain a global state information through a link state protocol. Hence every node in the network has a complete view of the entire network state at any given point of time. Since our network model is homogeneous in nature we develop an efficient framework for information collection and routing which is

described in detail in Section III. Thus every link in the network is denoted by a *link state vector*. The vector consists of a set of properties associated with the link, such as available bandwidth on individual wavelengths, hop length, fiber length etc. Each of these entities in the vector can be referred to as *metric*. Every path from a source to a destination can be represented by a *path vector*, which is obtained by combining the link state vectors of all the links in the path.

A connection request between each source-destination pair is provided a primary lightpath and a backup lightpath. We assume that, each lightpath, primary or backup, always accommodates an OAM (operation, administration and maintenance) channel terminated at the same s-d pair as the lightpath. We also assume that wavelength continuity constraint is satisfied on all links along the route. When a primary lightpath fails, an alarm indication signal is generated by the node that detects the link failure, and is transferred over the OAM channel. When the source receives the alarm signal in its OAM channel, it prepares to setup the backup lightpath and sends messages to the controllers along the backup path to configure the ports accordingly.

The primary and backup paths for each request is found by the ShortestCycle(SC) algorithm as described in [67]. The shortestcycle algorithm basically finds out the shortest vertex or link disjoint cycle which minimizes the sum of the path lengths in a given network in the presence of shared link-, node group failures in the network. The primary is routed along the shorter of the two paths of the cycle and the backup along the alternate path. Since the backup path is pre-computed for a given primary and capacity is assumed to be reserved, so no run time link backup search needs to be performed. Once the backup path is setup, the destination prepares to receive on the backup path.

## 6.2 Restoration Model

We consider 100% protection guarantee for surviving any single link failure in the network. This means that the primary and backup paths of a demand are allocated the same capacity, and has to be node or link disjoint. In this work, we employ backup multiplexing technique to

improve the wavelength utilization. This allows multiple backup paths, belonging to demands of different node pairs, to share a wavelength  $\lambda$  on link  $l$ , if and only if their corresponding primary paths are link-disjoint.

It should be noted that, although every primary lightpath has a corresponding backup lightpath dedicated to it, wavelengths on a link can be shared by restoration paths belonging to demands to different node pairs, as long as their primaries do not share any common links. This improves wavelength utilization, while still providing 100% guarantee under the single fault scenario. This is due to the fact that no single failure will cause both the primary paths to contend for the same backup capacity.

The network is assumed to have  $L$  links,  $F$  fibers per link and  $W$  wavelengths per fiber. Hence the network can be represented by a 3-tuple  $(l, f, w)$ . The backup multiplexing is done by maintaining a *Backup Request List (BRL)* on each wavelength of each fiber at every link. The Backup request List is a link-list of all the requests that are backup multiplexed on a particular fiber-wavelength at a link. The details of how the Backup Request List is used for the channel assignment is described in the subsequent sections.

### 6.3 Cost Model

The cost sources of a WDM network can be mapped to the following four parameters: the link provisioning cost ( $C_{lp}$ ), the fiber cost ( $C_f$ ), the per channel cost ( $C_\lambda$ ) and the cross connect cost ( $C_{oxc}$ ). The link provisioning cost captures the investment required before any capacity on the link can be used. This includes digging cost, leasing cost, right of way cost, maintenance cost etc. Multiple fibers may be laid out as part of the initial investment, some of them may be lit and dark fibers used for future upgrades.

The fiber cost,  $C_f$  is a combination of optical amplifier costs, multiplexer and demultiplexer costs for fiber terminations, cost of dispersion compensation components. The maximum number of wavelengths per fiber is an important design parameter. Since the number of wavelengths per fiber decides the amount of dispersion components required, the laser power required and the amount of regenerators needed, the network provider should choose these

design parameters appropriately.

In ultra long haul WDM backbone network design, the goal is to let the signal travel longer (thousands of kilometers) without any regeneration. Since regenerators make up a significant part of the facility cost, reducing the number of regenerators results in a direct reduction in the total facility cost. Longer distances without regeneration typically means that the signal to noise ratio is low, as each amplifier add noise to the signal. The noise can be reduced using forward error correction (FEC) and dispersion compensation.

Hence the total fiber cost can be subdivided as follows  $C_f = A_f \cdot C_a + C_{mux} + C_{dmux} + C_{dc}$ , where  $C_a, C_{mux}, C_{demux}, C_{dc}$  are costs of optical amplifiers, multiplexers, demultiplexers and dispersion compensation components respectively and  $A_f$  is the number of amplifiers along the fiber.

The per channel cost  $C_\lambda$  includes the receiver and transmitter card cost per wavelength and power equalization required per wavelength. The power equalization is included as part of the transmitter cost. Since depending on the current demand, the network provider may equip a certain number of wavelength cards out of the possible maximum, this cost depends on the number of wavelengths currently used.  $C_\lambda = C_r \cdot w_f + C_t \cdot w_f$ , where  $C_t, C_r$  are transmitter and receiver card costs and  $w_f$  is the number of wavelengths currently used in the fiber.

The number of cross-connects per node determines the switch size and hence the total facility cost. At each fiber port, the incoming wavelengths are demultiplexed and sent to a space switch where they can be switched and sent to any output fiber port. The only constraint is that no two connections going on the same output fiber can use the same wavelength. Connections on different wavelengths, destined for the same output fiber are multiplexed and sent out. The cost of the space switch for each wavelength depends on the size of the minimum crosspoint switching element ( $\omega \times \omega$ ) available in the market. Let the cost of a  $2 \times 2$  crosspoint switching element be  $C_{oxc}$ . The number of such switching elements required for a  $(v \cdot v)$  switch is  $\frac{v}{2} \log_2 v$  (assuming the switches are implemented as a multistage interconnection network (MIN)). Hence the cost of each MIN is  $C_{oxc} \cdot \frac{v}{2} \log_2 v$ . The number of incoming and outgoing ports on a fiber is decided by the maximum number of wavelengths and fibers that needs to be

activated at a particular stage of network evolution. The total network facility cost is hence given by the sum of all the links and node costs.

$$\begin{aligned} \text{Total Network Facility Cost} &= \sum_l^L (m_l C_{lp} + f_l C_f + w_l C_\lambda) \\ &+ \sum_n^N (\psi \cdot C_{orc} \cdot \frac{(o_n)}{\omega} \log_\omega(o_n)) \end{aligned}$$

where  $m_l = 0, 1$  denotes if a link  $l$  is used or not.  $f_l, w_l$  denotes the number of fibers and wavelengths on a link  $l$  respectively.  $o_n$  denotes the number of cross-connects needed in a node, and  $\psi$  denotes the maximum number of wavelengths per fiber. The value of  $o_n$  is rounded off to the nearest higher integral power of  $\omega$ . In the second term of the above equation, the cost of a MIN in each node is multiplied by  $\psi$ , since there is a MIN switch for each wavelength.

#### 6.4 Connection Establishment

When a connection is routed on an optical network, one of the primary objectives is to not only route it over diverse paths, but also minimize the overall spare capacity utilized in routing the incoming request. One of the traditional approaches involves sharing of backup bandwidth between multiple connections, that do not share risk of failure at the same instance of time.

The network is modeled as having  $E$  links,  $F$  fibers per link, and  $W$  wavelengths per fiber. Hence the network can be represented by a 3-tuple  $(e, f, w)$ , where  $1 \leq e \leq E$ ,  $1 \leq f \leq F$ , and  $1 \leq w \leq W$ . The multiplexing of backup bandwidth on a particular fiber-wavelength combination is done by maintaining a *Backup Request List (BRL)* on each fiber-wavelength at every link. The Backup request List is a link-list of all the requests whose backup paths are multiplexed on a particular fiber-wavelength at a link.

The primary path of the requests are routed using the *first-fit* fiber & wavelength assignment. To ensure multiplexing of backup bandwidth, a Backup Request List (BRL) is maintained on each wavelength on each fiber at every link. Hence the BRL on a link is de-

noted by  $\{e_i, f_j, (w_1, w_2, \dots, w_W)\}$ , where  $e_i$  denotes the link or edge id,  $f_j$  denotes the fiber id and each of  $w_i$  denotes the BRL on that fiber and wavelength. When an incoming request  $R_i$  arrives, the link disjoint paths are computed using the shortestcycle algorithm.

A check is made on its backup path on each fiber and wavelength to see if there is any conflict with the existing requests in the BRL. After the check a vector *Backup Availability Matrix*  $B_{l_1}^{f_1} : \{m_1, m_2 \dots m_W\}$  is computed on each fiber and wavelength on the links of the backup path of the request. The Backup Availability Matrix is filled up with 0 if there are no free backup possible at that fiber-wavelength combination or if that wavelength on that fiber is used up by a primary connection. It is filled up with a 1 if the incoming request has no conflict with any of the requests on the BRL. Hence the information stored on the Backup Availability Matrix helps us in determining whether the incoming request can share backup bandwidth on any fiber-wavelength combination.

A vector called *Routing-Info Matrix* is computed by combining the Backup Availability Matrix vector on all links along the path of the backup request. The *Routing-Info Matrix* is computed by the operation  $RI_{f_i} = B_{l_1}^{f_i} \otimes B_{l_2}^{f_i} \dots \otimes B_{l_k}^{f_i}$ ,  $1 \leq i \leq F$  and  $k$  is the number of hops in the path. The operator  $\otimes$  simply denotes a binary **OR** operation. Once the *Routing-Info Matrix* is computed, the requests are assigned channels (wavelengths) by scanning through the *Routing-Info Matrix* and using the *first-fit* wavelength assignment algorithm. The above channel establishment procedure ensures minimum fiber usage and multiplexing of backup bandwidth while routing an incoming connection in the network. This methodology can be applied in general for any heterogeneous wavelength routed network.

In Figure 6.2, let us assume that we have two requests  $R_1$  and  $R_2$  both from  $1 \rightarrow 2$ . Hence the primary and the backup paths computed by shortest-cycle would be  $1 \rightarrow 2$  and  $1 \rightarrow 8 \rightarrow 2$ . Let us assume that  $R_1$  and  $R_2$  are the first two requests. According to the above algorithm when the backup of  $R_1$  is routed the Backup Availability matrix is computed to be  $\{1, 1, 1 \dots 1\}$  since there is no conflict.

The  $RI_{f_i}$  matrices obtained are  $\{1, 1, \dots 1\}$ ,  $1 \leq i \leq F$ . Hence backup path of the first connection  $R_1$  gets routed using the first fiber and wavelength. When the backup of the second

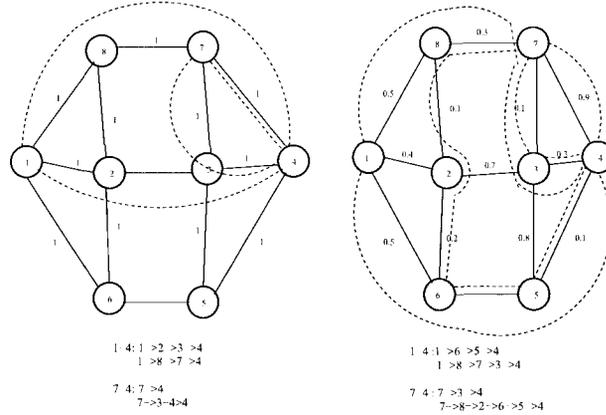


Figure 6.2 Path Mutation in Simulated Annealing

connection is routed the  $RI_{f_i}$  matrices are computed as  $\{0, 1, 1 \dots 1\}$  for the first-fiber and  $\{1, 1, 1 \dots 1\}$ , for  $2 \leq i \leq F$  since  $R_2$  has a conflicting primary path with  $R_1$  and  $R_1$  is routed using the first fiber & wavelength. Hence  $R_2$ 's backup gets routed using a different wavelength than  $R_1$  but they reuse the same fiber.

The above framework for information collection and routing is referred to as *MICRON*-Methodology for Information Collection and Routing in Optical Networks [71]. This can be applied in general for any heterogeneous wavelength routed networks.

## 6.5 A Simulated Annealing Approach for Routing Static Connections

*Integer Linear Programming (ILP)* formulations have already been attempted for the design and upgrade problem of mesh restorable optical networks in [54, 79, 83] and it has been observed that ILP is an effective optimization technique only for small networks with moderate amount of services or demand sets[54]. The complexity of the optimization problems grows exponentially as the size of the network grows or the demand sets increases. Under such scenarios simulated annealing can be an elegant technique to solve the same problem in a reasonable amount of time.

Simulated annealing (SA) is a Monte Carlo approach for minimizing multivariate functions. The simulated annealing progresses by lowering the temperature slowly until the system

"freezes" and no further changes occur. At each temperature the simulation should run long enough for the system to reach a steady state or equilibrium. This process is known as thermalization. The sequence of temperatures and the number of iterations applied to thermalize the system at each temperature comprise an annealing schedule.

Simulated annealing is used as a network design tool to optimize the total network facility cost used to route static connections. To achieve 100% survivability each request is assigned a primary path and a backup path computed using the cycle computation algorithm presented in Chapter 5. The primary and backup paths for each arriving request is calculated dynamically based on the current link weights of the network.

After all the requests of the demand matrix are routed, the total network facility cost is computed. This total cost becomes the initial solution for the annealing process. In the thermalization stage (which comprises of multiple sub-transitions at the same temperature), the request set is shuffled based on different parameters. These steps are repeated until the system reaches a stable state.

To apply simulated annealing to the problem at hand, the following steps are used.

1. First the system is initialized with a particular initial solution configuration.
2. A new configuration is constructed by imposing a displacement by shuffling.

Three different shuffling metrics were considered, random shuffling, one based on the descending hop length of connections, and another on the ascending hop length required to route the connection. The request set considered for shuffling could be the complete initial request set or a sub-set of the initial demand matrix.

If the energy of this new state is lower than that of the previous one, the change is accepted unconditionally and the system is updated. If the energy is greater, then the new configuration is accepted probabilistically. This ensures the system to move consistently towards lower energy states, yet still *jump* out of local minima due to the probabilistic acceptance of some upward moves. It also allows the search to explore a larger search space without being trapped in a local optima prematurely.

3. The shuffling of request demands is repeated for a fixed number say ( $X$ ) times at a particular temperature. At the end of each such sub-transition, the objective function is re-computed. If the total network facility cost used to route the shuffled set of connections is less than the initial cost, the latest solution is used as the best objective function, else no update is made.
4. After  $S$  sub-transitions at a particular temperature, an equilibrate state is obtained wherein all the requests of the demand matrix are routed obeying a particular metric such that the overall network cost is minimized. At the end of each such  $S$  sub-transitions the link utilization on all links are computed. The link utilization of the  $i^{th}$  link, given by  $L_i$  is the total primary capacity used on the link divided by the total capacity available on a link.
5. At the end of  $X$  sub-transitions the link weights used for the computation of the cycle is mutated by a factor of  $\gamma(1 - L_i)$  during the first transition boundary. This is done such that the shortest cycle explores different possible primary and backup path combinations for each request during each transition boundary at a fixed temperature. This process is repeated for a fixed number of say ( $Y$ ) times.
6. The temperature is scaled down linearly and the thermalization process restarts again. The objective function is recomputed after the routing of the pre-determined set of static requests. If the objective function is reduced from the optimum value the new solution is used to update the objective function value. If the objective function value is greater than the optimal value it is accepted with a certain probability which depends on two parameters, the difference between the objective values  $\delta$  and the control temperature  $T$  at that point of time.
7. The probability of acceptance is generally given by  $p_a = \exp^{-\delta/KT}$  where  $K$  is the *Boltzman's Constant* and  $T$  is determined by so called annealing or cooling scheme described in the next section. If this calculated probability at any point given by say ( $X_i, Y_j$ ) is greater than a particular random number  $R_k$  (varying between 0 and 1),

then the inferior solution is accepted and is used to update the current solution, else it is rejected. Initially  $p_a$  is very high, (i.e close to 1 and hence greater than  $R_k$ ), so all bad solutions are also accepted. This facilitates SA to explore bad solution states in the beginning.  $T$  decreases as the search proceeds, thus gradually decreasing  $p_a$ , the probability of acceptance of a bad solution. As  $T$  approaches zero, the search reduces to a greedy search and is trapped in the nearest local optima.

As can be seen in Figure 6.2, the initial primary and backup routes selected by the cycle computation algorithm for the requests  $1 \rightarrow 4$  and  $7 \rightarrow 4$  for uniform link weights is just the shortest paths between each source and destination. But as the edge weights are mutated between two transitions based on the link utilization, the shortest-cycle gave two new primary and backup paths for the same connection demand. Hence the routing through successive edge mutations is equivalent to exploring large number of route sets as part of the shortest cycle algorithm.

The fact that we try also different arrangements helps us get the best possible backup multiplexing and in turn improves capacity efficiency, and also for a given node pair, this in-effect emulates the  $K$  generalized shortest cycles because of edge weight mutations. The above search can be terminated by either repeating the annealing process for some predetermined number of iterations or if the search experiences no improvement in the best objective value for some pre-defined  $\psi$  number of annealing steps.

There are different possible annealing schemes to update the temperature  $T$ . We may use an annealing scheme where the temperature varies as  $T_n = \alpha \times T_{n-1}$ , where  $T$  is the temperature at the  $n^{th}$  temperature update, and  $\alpha$  is an arbitrary constant between 0 and 1. The parameter  $\alpha$  decides how slowly  $T$  decreases. Typical values of  $\alpha$  lie between 0.9 and 0.95. The parameters  $Y$ ,  $\alpha$  and the initial value of  $T$  plays a critical role for the performance of the simulated annealing. We have an annealing scheme where the temperature update is made as  $T_n = T_0/(1 + \alpha \times T_{n-1})$ . The typical values of  $\alpha$  can be of the order of 0.01 to 0.1 in-order to have a graceful degradation of the temperature.

## 6.6 Methodology for Network Upgrade

The method of routing static connections using the simulated annealing technique is extended for upgrade of networks. As network evolves over time, the challenge lies in how to route the incremental traffic demands over pre-existing network such that the total network facility cost is minimized at every instant in the process of network evolution. The main idea is to re-use most of the resources from the previous generation of the network and evolve out of it to accommodate the additional traffic set.

Each link in the network maybe used to realize the working and spare capacity requirements. The objective would be to incur a one-time *fixed charge* for the acquisition and have an incremental step-wise increase in cost with increasing capacity as additional transmission systems are turned up.

In the most generalized model we assume a traffic model given by  $\{R_l, R_a\}$ , where  $R_l$  is the number of connections that leaves the system during transition from one generation to the next generation and  $R_a$  defines the number of connections that arrive in the next generation.

For our experimental studies we consider two scenarios, one in which all the demands from the first generation gets carried over to the next generation i.e.  $\{|R_l| = 0, |R_a| \geq 0\}$  and secondly another scenario wherein  $\{|R_l| \geq 0, |R_a| \geq 0\}$  and  $|R_a| \geq |R_l|$  hence the network going for an upgrade. In the second scenario the traffic matrix might be entirely or partially different from the previous generation. The routes of the demands which do not carry onto the next generation are removed but the installed capacity in the network (in terms of the no. of fibers, cross-connects at nodes etc.) are taken as lower bounds for the simulated annealing framework in the next generation.

In our work the static connections of the first generation are optimally routed using the simulated annealing approach. The total optimal network state at the end of the first generation is taken as the lower bound of the SA while routing the connections during the second generation of network evolution. The same process is repeated for each successive generation of network evolution.

Hence the final topology we arrive at, would have a subset of links that needs to be

activated, a subset of fibers that need to be lit up, some number of wavelength cards that need to be installed and cross-connects that need to be configured to realize the traffic.

## 6.7 Performance Evaluation

The 14-node, 22-link NSFNET network as shown in Figure 6.3, is used for our experimental studies. Each of the links in the network are assumed to be bi-directional. The maximum number of fibers  $F$  in the network is assumed to be 5, since fibers are expensive components and we should try to minimize installation of fibers. The maximum number of wavelengths considered per fiber is 40. Each node in the network is assumed to be strictly homogeneous i.e. they employ the same switching architecture. A connection at a node is assumed to be switched between an incoming wavelength on one fiber to the same wavelength on the same or different outgoing fiber. We employ the following cost values for our experiments. The link provisioning cost  $C_{lp} = \$160$  per mile, the fiber provisioning cost is kept at  $C_f = \$1000$  per mile, the wavelength cost is kept at  $C_\lambda = \$1$  and the cost of a  $(2 \times 2)$  ( $\omega = 2$ ) cross-connect is kept at \$1000. The cost values employed here are conservative estimates obtained from literature [54].

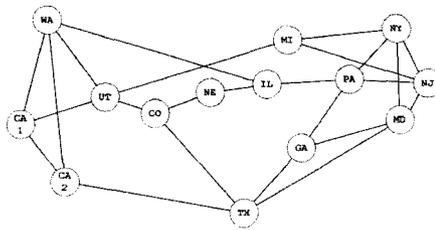


Figure 6.3 NSFNET backbone network

The total facility cost is computed using the equation derived in the cost model. The Boltzman's Constant was taken to be of the order of 5000 to 10000 such that,

$$0 \leq \exp^{-\delta/(K \times t_i)} \leq 1$$

where  $t_i$  is the temperature at the  $i^{th}$  iteration. The temperature mutation parameter  $\alpha$  is taken to be between 0.005 and 0.01 so that the temperature does not drop abruptly. Higher

values of  $\alpha$  leads to a fast convergence for the simulated annealing procedure. The edge weight mutation parameter  $\gamma$  is chosen to be between 0.5 and 1.0.

The MICRON routing algorithm is used to generate the initial solution to the SA process in the first generation. The network evolution is considered for a period of six years. In our model of network evolution the initial number of requests considered for the first generation are 75, 100, 150 and 200 distributed uniformly over the 22 node pairs. Every year the traffic is increased by a conservative growth estimate of 15% to 20%. For the second model of traffic upgrade some connections from the first generation were probabilistically terminated so that they are absent in the next generation and new connections were added in such that the overall connections increases across generations.

## 6.8 Results

Various observations are made from the study of the simulated annealing approach for routing static connections.

- Figure 6.4(a) shows an simulated annealing progress curve for all the three different shuffling schemes. As can be observed from the figure the higher values of the objective function were seen by each scheme because SA was trying to explore a bad solution, which would not have never been explored in all the previous studies done till far. So the claim is that simulated annealing actually tries to emulate the K-shortest paths (K-shortest-cycles in our case) and does so in an much more unconstrained manner as compared to our previous studies [54].

The total number of sub-transitions at a given temperature considered for SA was 10 and the transition across different temperatures was considered to be 20. This numbers were chosen because they were moderate enough for the chosen demand sets, for the simulated annealing to show different possible solution sets.

- As an expected trend the mutation scheme based on the descending hop length of connections gave us the best optimal solution for routing connections as can be seen from

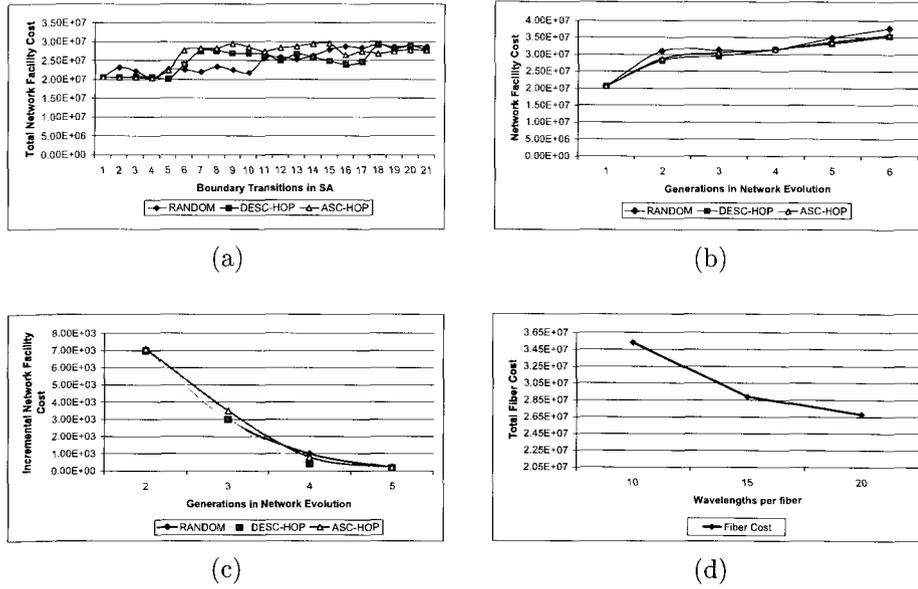


Figure 6.4 Performance Results of SA on NSFNET: (a) Behavior of Simulated Annealing within one generation, (b) Network Facility Cost across generations when initial demand set remains intact, (c) Incremental Network facility cost when we have entirely new traffic pattern in future generations and (d) Fiber Cost Vs Wavelengths per fiber

Figure 6.4(b).

This was an intuitive result as the network would ideally like to see higher hop connections getting routed prior to shorter hop connections, such that all the requests can get ideally packed in. The schemes based on ascending hop length and the one based on random mutation performed significantly poorer as compared to the first scheme. In fact as we progress to higher and higher generations, a few longer hop connections starts getting blocked due to infeasibility of a route.

- Figure 6.4(c) shows the incremental costs that are incurred for the second model of upgrade. This figure shows that simulated annealing is actually successful in routing the connections in successive generation over the facility installed in the initial design itself. As can be seen, the descending hop length scheme performs the best. In future

generations, the ascending hop length scheme performs almost similar to the random mutation scheme.

The point to be noted here is that the initial design solution for the first generation itself is an inexpensive one and tries to route traffic using a sub-set of links out of the complete topology. The successive incremental costs that comes in future generations just tries to re-use the resources from the previous generation and sometimes dimensions new links to accommodate new connections. This is a significant point as every network designer would like to build a network, which not only accommodates current traffic, but can also carry a significant amount of future workload.

- Figure 6.4(d) shows the decrease in fiber cost across six generations as the number of wavelengths per fiber is increased for handling the same traffic demand.

Table 6.1 Comparison Of Different SA Mutation Schemes

Metric	DESC Hop Length			ASC Hop Length			Random		
#Req	Object	CPU	E, F	Object	CPU	E, F	Object	CPU	E, F
75	3.23E7	54	14, 1	3.58E7	56	14, 1	3.77E7	54	14, 1
100	3.53E7	100	18, 2	3.63E7	104	19, 2	3.81E7	104	19, 3
150	3.63E7	183	22, 3	4.16E7	187	22, 4	3.97E7	191	22, 3
200	4.50E7	288	22, 4	4.61E7	294	22, 4	4.73E7	296	22, 4

Table 6.2 Comparison of Simulated Annealing with ILP

No.Of Reqs	Simulated Annealing (Objective Value)	ILP (Objective Value)
72	$1.1687 \times 10^8$	$1.14 \times 10^8$
92	$1.684 \times 10^8$	$1.46 \times 10^8$
112	$1.8256 \times 10^8$	$1.72 \times 10^8$

- Table 6.1 represents the performance of the different mutation techniques for different initial traffic demands. #Req represents the initial number of requests to start with at the beginning of the first generation. The traffic demands are assumed to grow by an

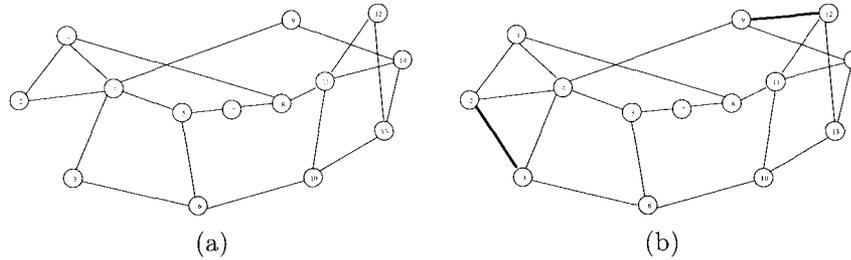


Figure 6.5 Sparsening Effects in Simulated Annealing

conservative estimate of 20% in between two successive generations. Object represents the optimal value of the Objective function i.e the total network facility cost found at the end of the final generation. CPU represents the total CPU time needed to arrive at the solution for the complete design problem for six generations when the simulations were performed on a Sun Sparc III machine supporting OS-5.8 with a processor speed of 750Mhz. E represents the number of edges that were activated after finding a solution and F fibers represents the total numbers of fibers needed. As can be observed from the table the descending hop length metric scheme performs significantly better than the other two schemes when we consider lower traffic demands. But as the traffic demands increases the solutions given by all the schemes tend to merge.

- Table 6.2 represents the performance of simulated annealing as compared to an ILP solution. It can be seen that simulated annealing objective value is within 10% of the ILP optimal value. For the above chart we considered a demand set of 72 requests in the first generation and followed by an incremental demand of the order of 20 for the next two generations. The traffic demand used for this comparison is different from the traffic demand used for the previous experiments with SA.

Another interesting observation was the effect of topology sparsening, which happens in our design study as shown in Figure 6.5(a) which illustrates some missing links during a certain generation and Figure 6.5(b) indicates the links that gets added on to accommodate traffic

that could not be facilitated on the existing links. Simulated annealing was able to show that the topology needed to route a set of connections for any given generation was actually the proper sub-set of the topology obtained for routing a future generation traffic.

## 6.9 Chapter Summary

In this chapter, a framework is presented for designing networks for a given static traffic matrix. The following are the main contributions of this chapter:

- We present a framework for designing networks for a given static traffic matrix using the simulated annealing approach.
- We defined a methodology for upgrade using the simulated annealing approach which minimizes the incremental costs needed for network upgrade.
- This framework can be used as a heuristic technique to arrive at near optimal solutions in design problems involving complex demand sets and moderately large networks, where the run-time of an ILP becomes practically intractable.
- The simulated annealing framework is a more generalized approach as compared to most ILP studies, since we try to explore different alternative path sets during the search of an optimal solution.
- The proposed scheme is very inexpensive, fast and can be ideally employed in all backbone networks.

The simulated annealing approach explores different possible solution sets and hence can be mapped on to the generalized K-alternate shortest path approach proposed in literature. The proposed framework has been implemented in networks that collect information through link-state protocols and employ source-based routing. This methodology can be extended for heterogeneous networks, and allows us to study the impact of switching architectures on route selections.

## CHAPTER 7. Conclusions and Future Work

Wavelength Division Multiplexed (WDM) networks, employing wavelength routing has revolutionized wide-area networks. As the amount of traffic carried is larger, any single failure can be catastrophic. Survivability has become indispensable in such networks. The primary focus of this dissertation is to explore different restoration approaches for surviving multiple failures in optical networks.

In Chapter 3, we considered sub-graph based routing strategy for mesh-restorable WDM networks. The sub-graph based routing strategy for tolerating single link failures in a network was first introduced in [48]. In this dissertation we attempt to study subgraph-based routing for providing resilience against all possible failure scenarios  $\mathcal{F}$  besides single link failures, such as a single node failure or a group of nodes or link failures.

There are several ways to improve the performance of sub-graph based fault tolerance. Sub-graph based routing is flexible in that it is immediately portable to other network strategies. One way to exploit the flexibility of the sub-graph strategy is to assess the operation of different routing strategies such as those studied in [7, 72]. Possible algorithms include shortest widest path, shortest maximum path, maximum shortest path or any other algorithm designed to more efficiently manage capacity in networks.

Another challenging aspect that needs attention is to assess how different routing algorithms can be used in conjunction with one another for connection establishment. For example, shortest hop routing, which is used exclusively for our research, can be used to route connections on the base network, while several other metrics such as shortest maximum path can be used to better manage capacity while routing connections on the subgraphs. The routing strategy used on one subgraph can be completely independent of the strategy used on another

subgraph. The proposed sub-graph based fault tolerance, is studied only for homogeneous networks. However it has the capability to be extended to more generalized heterogeneous network architectures with grooming capabilities at each node of the network.

We develop a novel survivability approach that can tolerate multiple failures arising out of SRLG situations in Chapter 4. The sub-graph based restoration paradigm necessitates storage of complete network information at each node of the network. It would be interesting to develop sub-graph based network models which can tolerate higher order failures, with minimal or partial network state information stored at each node of the network.

In Chapter 5, we develop a graph transformation technique for shared component failures in WDM optical networks. The diverse routing problem for generalized SRLG failure structures have been proved to be NP-complete. We propose a polynomial time algorithm for solving the diverse routing problem for certain specific SRLG failure sets. Currently we are working on a more generalized framework which can accommodate SRLG's that are not only incident on a common node, but can involve any arbitrary set of links in a given network topology.

In long haul networks the greater distance related cost makes capacity efficiency much more important. Thus, there is continued interest in the survivability of mesh-restorable backbone networks. In Chapter 3, we developed a simulated annealing based design scheme for WDM networks and provide a cost optimal way of performing network upgrades. We showed that since the cost of provisioning and operating a link can be significantly high, the current traffic demand, which is a subset of the future traffic demand, may avoid using some links in the final topology. This implies that the cost optimal routing and capacity planning for the current traffic demand may be fully realizable on a subgraph of the final topology. This results in significant cost reduction for the network service provider.

In the future we plan to conduct more experiments to study the effects of bottleneck nodes in the network. One of the primary assumptions made in one of the incremental network upgrade traffic model, where connections depart from the system and new connections arrive in the next generation, is that the design methodology doesn't account for cost penalties for service disruption during such a network upgrade. The effect of these cost penalties should be

studied to see what effects it has on the results obtained.

The simulated annealing design methodology is implemented for homogeneous networks. We should also implement this design technique in heterogeneous networks and study the impact of different switching architectures at each node in the network. The comparative results obtained from the simulated annealing technique indicate that the solutions obtained were about 5-8% away from the optimal results obtained from the ILP for moderate demand sets. We have explored three different path mutation techniques, and we would also like to explore newer path computation variants using other heuristic techniques such as genetic algorithms, tabu search and ant-colony optimization.

The simulated annealing methodology was studied for design and evolution of networks that are tolerant to single failures. As part of our future study, we would like to extrapolate this study to networks that are tolerant to multiple link or node failures in the form of shared-risk resource group failures or independent multiple failure scenarios.

## APPENDIX A. Edge-Disjoint Shortest Cycle Algorithm

<p><b>Input:</b> Graph <math>G = (V,E)</math>, and a traffic matrix <math>T_{N \times N}</math>.</p> <p><b>Output:</b> The edge-disjoint shortest cycle for each <math>t_{sd} \in T_{N \times N}</math>.</p> <p><b>Algorithm:</b> Let the edge weight of each edge <math>uv</math> be <math>\alpha_{uv}</math>. Let <math>\kappa</math> be the sum of all edge weights in <math>G</math>, i.e., <math>\kappa = \sum_{i=1}^L \alpha_i</math>. <math>a</math> is the weight given to the forward direction of all edges on the shortest path.</p> <p><i>While</i> (<math>t_{sd} &gt; 0</math>)</p> <p>{</p> <p>I. Sum all edge weights then weight <math>a</math> and <math>b</math> as follows:  <math>a = 2 * L + 1</math>. These values will let the algorithm degrade to minimal edge overlapping cycles, if a set of disjoint paths does not exist.</p> <p>II. Run the Bread-First-Search algorithm, to find the shortest path in graph <math>G</math>. Store the shortest path.</p> <p>III. For all nodes on the shortest path set the edge weight to the next node on the path to <math>a</math>, and change the sign of the edge weight between the current node and the previous node.</p> <p>IV. Run the Bread-First-Search on the modified graph to get the second path. Store the second shortest path.</p> <p>V. If there are any common edges between the two shortest paths remove the interlacing edges between the paths.</p> <p>VI. Restore the network.</p> <p>}</p>
---

Figure A.1 Edge-Disjoint Shortest-Cycle Computation Algorithm

## APPENDIX B. Vertex-Disjoint Shortest Cycle Algorithm

**Input:** Graph  $G = (V,E)$ , and a traffic matrix  $T_{N \times N}$ .

**Output:** The vertex-disjoint shortest cycle for each  $t_{sd} \in T_{N \times N}$ .

**Algorithm:** Let the edge weight of each edge  $uv$  be  $\alpha_{uv}$ . Let  $\kappa$  be the sum of all edge weights in  $G$ , i.e.,  $\kappa = \sum_{i=1}^L \alpha_i$ .  $a$  is the weight given to the forward direction of all edges on the shortest path.  $b$  is the weight of the edge connecting two nodes in  $G$ , that were one node in  $G$ . The values of  $a$  and  $b$  are somewhat arbitrary as long as  $a \geq b \geq L$  for this algorithm.

*While* ( $t_{sd} > 0$ )

{

- I. Sum all edge weights then weight  $a$  and  $b$  as follows:  
 $a = 2 * L + 1$ .  $b = L + 1$ . These values will let the algorithm degrade to minimal vertex overlapping paths, if a set of disjoint paths does not exist in the topology.
- II. Run the Bread-First-Search algorithm, to find the shortest path in graph  $G$ . Store the shortest path.
- III. For all nodes on the shortest path set the edge weight to the next node on the path to  $a$ , and change the sign of the edge weight between the current node and the previous node.
- IV. For every node in the shortest path, create a dummy node and transfer all outgoing links from the node on the shortest path to the dummy node. Add an edge with weight  $b$  going from original node to the dummy node.
- V. Run the Bread-First-Search on the modified graph to get the second path. Store the second shortest path.
- VI. Remove dummy nodes from the second shortest paths. This could also be described as merging the dummy vertices back together.
- VII. If there are any common edges remove the interlacing edges between the paths.
- VIII. Restore the network.

}

Figure B.1 Vertex-Disjoint Shortest-Cycle Computation Algorithm

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