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Design and operation of mesh-restorable WDM networks

Murari Sridharan
Iowa State University

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Design and operation of mesh-restorable WDM networks

by

Murari Sridharan

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Program of Study Committee:
Arun K. Somani, Major Professor
Soma Chaudhuri
Manimaran Govindarasu
Ahmed E. Kamal
Murti V. Salapaka

Iowa State University

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Murari Sridharan

has met the dissertation requirements of Iowa State University

Signature was redacted for privacy.

Major Professor

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For the Major Program

DEDICATION

To my parents

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For all the graduate students slogging for their doctoral degree, I only have one thing to say, there is light at the end of the tunnel.

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ABSTRACT

The explosive growth of Web-related services over the Internet is bringing millions of new users online, thus creating a growing demand for bandwidth. Wavelength Division Multiplexed (WDM) networks, employing wavelength routing has emerged as the dominant technology to satisfy this growing demand for bandwidth. As the amount of traffic carried is larger, 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.

In this dissertation, we explore the design and operation of survivable optical networks. We study several survivability paradigms for surviving single link failures. A restoration model is developed based on a combination of these paradigms. We propose an optimal design and upgrade scheme for WDM backbone networks. We formulate an integer programming-based design problem to minimize the total facility cost. 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.

As part of network operation, we capture multiple operational phases in survivable network operation as a single integer programming formulation. This common framework incorporates service disruption and includes a service differentiation model based on lightpath protection. However, the complexity of the optimization problem makes the formulation applicable only for network provisioning and offline reconfiguration. The direct use of such methods for online reconfiguration remains limited to small networks with few tens of wavelengths. We develop a heuristic algorithm based on LP relaxation technique for fast, near optimal, online reconfiguration. Since the ILP variables are relaxed, we provide a way to derive a feasible solution from the relaxed problem.

Most of the current approaches assume centralized information. They do not scale well as they rely on per-flow information. This motivates the need for developing dynamic algorithms based on partial information. The partial information we use can be easily obtained from traffic engineering extensions to routing protocols. Finally, the performance of partial information routing algorithms are compared through simulation studies.

CHAPTER 1 Optical Networking: The story thus far

The Internet is growing faster than ever, with traffic across the core of the network quadrupling over the last year [1]. This tremendous growth in demand is fueled by many factors. The explosive growth of Web-related services over the Internet is bringing millions of new users online, thus creating a growing demand for bandwidth. With services ranging from video conferencing to large multimedia downloads, the per user bandwidth consumption has increased considerably. As witnessed recently, applications like Napster quickly consume the usable bandwidth in the network, leaving a lot of other important applications to choke. This trend continues, as many of today's businesses rely heavily on a reliable and continuously available high-speed communications infrastructure, for their day-to-day operations. These changing trends have caused fundamental shifts in traffic patterns. Major carriers in the United States announced that data traffic, for the first time, has overtaken voice traffic. With deregulation of the telecommunication markets in Europe and Asia, the pattern is similar, if not more significant.

To meet this growing demand for bandwidth, new technologies emerged from research labs, and companies have been quick to embrace such new technologies. Wavelength Division Multiplexed (WDM) optical networks is one such key technology which quickly moved from research laboratories to commercial deployment to meet the bandwidth challenge. With deregulation, the telecom revolution moved away from large monopolies to highly competitive new players. Competitive pressures in the telecom markets are forcing the players, big and small, to design and operate their networks more efficiently. With millions of wavelength miles laid out in typical global and nationwide networks, fiber optic cables are among the most prone to failures. TEN (formerly Hermes Europe Railtel), a pan-European carriers' carrier network, estimates an average of one cable cut every four days on their network [2]. Therefore, it is imperative to design networks that can quickly and efficiently recover from failures.

1.1 Telecom Network Evolution

There are different types of telecommunication networks present today. The evolution started in the mid-to-late 80s with the divestiture of AT&T, creating smaller regional bell operating companies (RBOCs). There were few competitive access providers back then, partly due to the exorbitant cost of leasing circuits from these companies and partly due to lack of market reforms to promote competition. The real dawn of telecom interconnection in the United States came with the passage of the Telecommunication Reforms Act of 1996. The Act deregulated most sectors of the communication market, throwing it wide open to competition. As a result, for the free market to thrive, incumbent local-exchange carriers (ILECs) had to give competitors access to their networks (which were already wired throughout the country), thus creating a whole segment of competitive local-exchange carriers (CLECs).

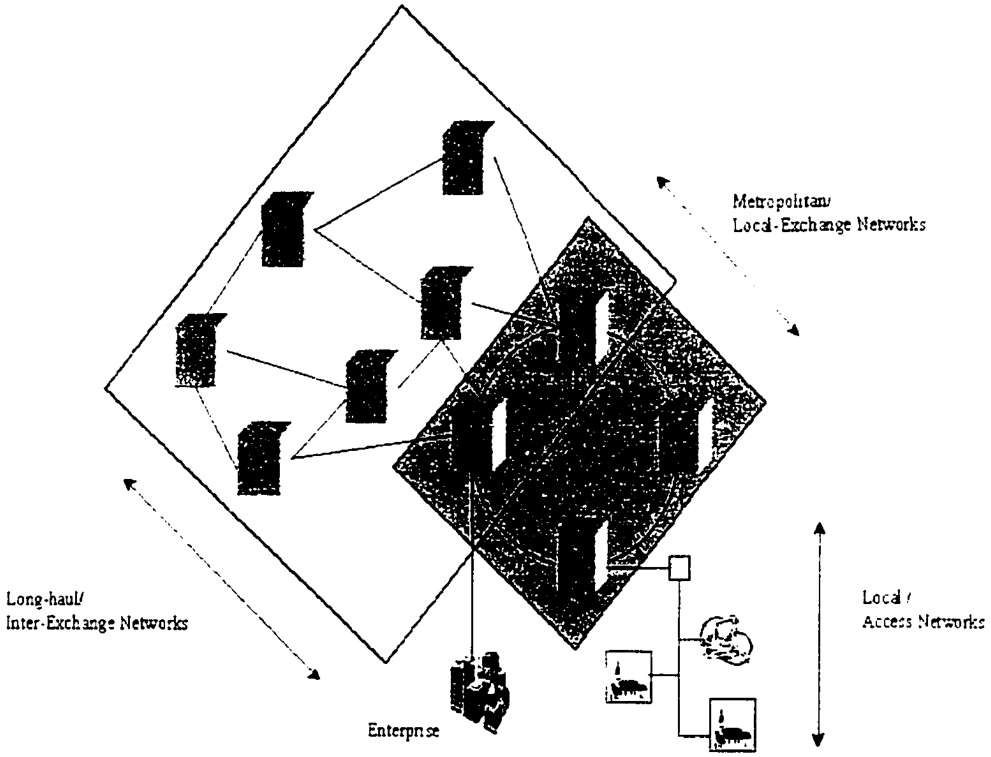


Figure 1.1 Public network hierarchy

Telecommunication carriers operate networks and provide services. Carrier networks have central offices which feed to the individual homes and businesses. These are the *access networks*. A *local-exchange network* interconnects different central offices in a metropolitan area. A *long-haul network* interconnects different cities. Then there are networks deployed by private enterprises called the *enterprise networks*. These can in turn be classified as *local-area networks* (LANs) which are networks within buildings, *metropolitan-area networks* (MANs) which are networks within a city, and networks that interconnect cities are called *wide-area networks* (WANs). Enterprise networks typically lease lines from the carriers. But the distinction between incumbents and competitors is not clear-cut. For instance, some ILECs have moved to the long-distance market, which means they are wholesalers when it comes to local services, but are new entrants in the long distance market. As a result today the market is increasingly crowded with voice and data service providers competing for revenue and operating over fixed-line, wireless, satellite, cable, and Internet Protocol (IP) data networks.

1.2 Optical Network Drivers

There are many key factors driving the need for optical networks. Some of the most important factors which have enabled different generations of optical network growth are discussed in this section.

1.2.1 Fiber Capacity

Optical fiber transmission has played a key role in increasing the bandwidth in telecom networks. In the first-generation implementations, optical fiber was used purely as a transmission medium, for increasing point-to-point capacity between sites. Optical fiber emerged as the preferred medium of transmission over copper cables mainly because optical fibers offered higher bandwidth than copper cables, they were less susceptible to various kinds of electromagnetic interferences, and provide lower bit error rates. Since the fiber is made of glass, it will not corrode and is unaffected by most chemicals. It can be buried directly in most kinds of soil or exposed to most corrosive atmospheres in chemical plants without significant concern. Fiber optic cables are ideal for secure communications systems because it is very difficult to tap but very easy to monitor. (Although most of the failures today are due to fiber cuts caused by digging [2], the trend is changing fast with a growing interest in preventing and managing coordinated attacks in an optical network [3].)

The main thrust was to develop technologies to transmit higher bit rates over longer distances.

The transmission speed has increased several orders of magnitude in the past 20 years, with a few megabits per second in the early 1980s, to gigabits per second for practical use in the 1990s. Perhaps the most significant way of increasing fiber capacity came in the form of broadband wavelength division multiplexed (WDM) in 1994. By fusing bionic tapered couplers, two signals could be combined on the same fiber. But limitations for further increase were caused because the signal frequencies had to be widely separated. Systems typically used 1310nm and 1550 nm wavelength signals for transmission. Although the performance is not comparable to today's technologies, broadband WDM provided twice the bandwidth out of the same fiber, which resulted in significant cost savings.

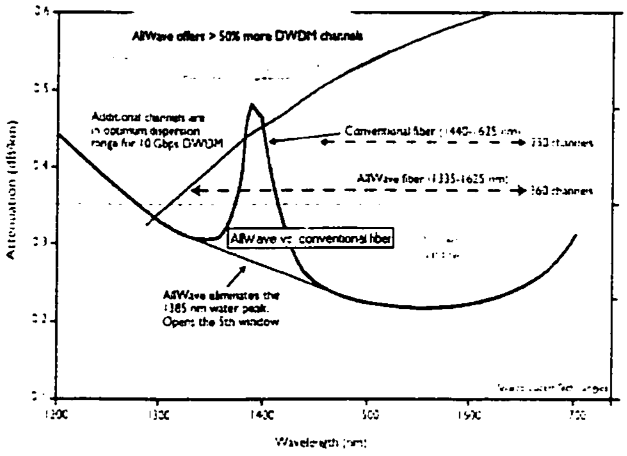


Figure 1.2 More usable optical spectrum: Lucent's AllWave vs conventional fiber

As optical filters and laser, fiber technologies improved, the ability to combine different wavelengths on a the same fiber became a reality. Dense wavelength division multiplexing (DWDM) combined multiple signals on the same fiber, providing upto 100 channels for signal transmission. Today some companies have made significant enhancements to DWDM transmission. Figure 1.2 compares the conventionally usable optical spectrum versus Lucent's AllWave fiber [4]. For the first time, AllWave fiber technology eliminated the water peak at 1390nm. This provided a way of harnessing previously untapped region in the fiber spectrum to provide 50 percent more usable wavelengths than the conventional fiber. Current state-of-the-art using DWDM technology can achieve up to 320 wavelengths per fiber with each wavelength carrying 10Gbps, for a total transmission capacity of up to 3.2Tbps [5].

1.2.2 Multiplexing Techniques

Faced with challenges from increased bandwidth needs and fiber exhaust, service providers needed to provide an economical solution. There are different ways of increasing transmission capacity. First is to lay more fiber, but this is not always the most economical solution. The second option is to increase the bit rate using Time Division Multiplexing (TDM). TDM increases the capacity of a fiber by slicing time into smaller intervals so that more bits can be transmitted per second. Although electronic TDM does not scale well beyond 10Gbps rates (commercially available), the Optical TDM (OTDM) technique, which multiplexes signal in the optical domain, provides alternatives to handle higher bit rates. However, these are not commercially available. OTDM also presents a problem of scalability. The service provider has to invest in more capacity than initially required, as there is no incremental way to add capacity. Based on the SONET hierarchy, the next incremental capacity upgrade step from 10 Gbps TDM is 40 Gbps TDM. Many experts believe it may not be possible for TDM technology to handle such high rates in the near future [6].

Another multiplexing technique is OCDM, based on the code-division multiplexing (CDM) scheme (also known as spread spectrum). This technique is not popular because of the problems of dispersion and synchronization. This technology is still a topic of research [7].

The more popular option these days is to combine multiple wavelengths onto a single fiber using the WDM technique. WDM increases the capacity of the fiber by assigning incoming optical signals to different wavelengths (specific frequencies) in a designated frequency band and the multiplexed signal is sent out onto a fiber. The primary difference between WDM and DWDM is the channel spacing. The channel spacing in DWDM is much smaller than in WDM. The International Telecommunication Union (ITU) has defined the allowed channel optical frequency grid based on 100GHz (moving towards 50GHz) spacing between neighboring channels. The equivalent wavelength spacing is around 1nm [8].

The most compelling advantages of DWDM are its transparency and scalability. Each signal can be at a different rate and use a different format as the signals are never terminated inside the core network. This provides bit rate and protocol transparency which is a key feature for any backbone network. Researchers have demonstrated error-free transmission of 1 terabit per second using 100 WDM 10-Gb/s channels with 50 or 100-GHz channel spacing [4]. There are 40-channel

DWDM systems commercially available [9], which can be upgraded to 96 channels, incrementally, on a channel-by-channel basis. These systems provide unprecedented scalability. Capacity can be upgraded on a per wavelength basis, this also means that the provisioning time is considerably reduced. These factors make DWDM, the transport of choice for long haul backbone networks of the future.

1.2.3 Component Technologies

The emergence of the optical network can be attributed to some significant advances in component technologies. The early telecommunication systems used multimode fibers along with light-emitting diodes (LEDs) as transmitters. These systems had to have regenerators every few km to improve the quality of the signal, degraded primarily due to a phenomenon known as modal dispersion. This hampered the bit rate advances heavily. The introduction of single-mode fiber paved a way for eliminating modal dispersion, thereby enabling dramatic increase in bit rates and distances between regenerators. Initially these single-mode fibers were commercially used to deploy systems in the 1.3μm window, the zero chromatic dispersion point of the fiber. These were the standard single-mode fiber. The next step was to deploy systems in the 1.55μm window to take advantage of the lower loss in this window as compared to the 1.3μm window. But impairments due to chromatic dispersion was the limiting factor in this region. This high chromatic dispersion at the 1.55μm window motivated the development of dispersion-shifted fiber, which were designed to have zero dispersion in this window. The wider the spectrum of the transmitted pulse, the greater the loss due to dispersion. The development of single-longitudinal mode (SLM) distributed feedback laser (DFB), with a narrow spectrum of transmitted pulse, increased the bit rates into more than a Gbps.

The most significant milestone in the evolution of the optical fiber transmission systems was the development of Erbium-doped fiber amplifiers (EDFAs). These amplifiers, for the first time, provided a way of amplifying signals at many wavelengths simultaneously, without converting them into electronic domain. The EDFA also provided bit rate and modulation format transparency. The link capacity could now be increased by increasing the number of operating wavelengths per fiber than increasing the bit rate.

1.3 Changing Trends

1.3.1 First Generation Optical Networks

First generation optical networks used optical fiber merely as a transmission medium replacement for copper cables, with all the switching and processing handled by electronics. 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 SONET (Synchronous Optical Network). A closely related standard adopted in Europe is SDH (Synchronous Digital Hierarchy). The private enterprise network standards include Fiber Channel, HIPPI, and FDDI [6]. For a more informative discussion on standards used in enterprise networks the reader is referred to [10].

SONET/SDH defines explicit multiplexing methods that make it easy to extract low speed streams from a high speed stream. This feature greatly simplified the multiplexer and demultiplexer costs, which were significantly complicated in the earlier standard plesiochronous digital hierarchy (PDH). All the clocks in the network are perfectly synchronized to a single master clock, and as a consequence, the bit rates defined in SONET/SDH were integeral multiples of the basic rate. SONET/SDH also provided standards incorporating extensive management information for monitoring the performance of traffic. Another significant step in first generation networks is interoperability. Prior to SONET/SDH there was no standard format on the transmission link. As a result different vendors used different line coding, optical interfaces etc. for their products, thus making it impossible for different vendor equipment to interoperate. SONET/SDH alleviated this problem by defining standard optical interfaces that enabled multi-vendor interoperability. They also provided specific protection schemes to provide high-availability of services, as a consequence, service restoration time after failure with SONET/SDH is significantly smaller, of the order of 50ms.

1.3.2 Second Generation Optical Networks

With the advances made in transmission speeds and multiplexing techniques, it soon became evident that optical networks were capable of providing more functions than just point-to-point transmission. As the speeds increased, the processing time in the electronic domain became a serious bottleneck. This was one of the key drivers for second generation optical networks, which looked to incorporate some of the routing and switching functions that were performed in the electronic domain into the optical domain. The following are the technologies that are competing to realize the all-optical switching dream.

- Micro-Electro-Mechanical systems (MEMS): Typically arrays of tiny tilting mirrors.
- Liquid Crystals: Depends on the polarization property of light for switching. When light passes though liquid crystals, the optical properties can be altered by applying an electric current.
- Bubbles: The surfaces of tiny bubbles formed by printer ink pens act like mirrors, glancing light onto alternative paths, thus realizing switching fabric.
- Thermo-Optics: By heating a passive splitter, the refractive index can be changed to alter the way in which it divides wavelengths between one output and another.

Recently, MEMS technology has generated a lot of excitement in the optical community [11, 12, 4] primarily because of better scalability, reliability, loss and power consumption as compared to its competing technologies. Although there are small 2-D MEMS commercially available [13], the large scale 3-D versions still remain a theoretical possibility. Currently 2-D MEMS switches are available with maximum 32×32 ports [13]. These smaller switches can be used to realize a larger core of upto 512×512 ports.

1.3.2.1 Services Perspective

The role of the second generation optical networks are defined by the services that can potentially be offered to users [6, 14]. The network can be viewed as consisting of many layers interoperating with each other, as shown in Figure 1.3. Different carriers, depending on their requirements, can choose different ways to realize their network. Incumbent carriers for example may use their large installed base of SONET/SDH gear, and extensive grooming and monitoring capabilities of the digital crossconnects. An Internet Service Provider offering internet services might choose to deploy IP over the fiber without the intervening SONET layer. Carriers who choose to provide Quality of Service (QoS) guarantees would prefer to use ATM as their transport technology. Below these layers is the emerging WDM layer or the optical layer. The basic service offered by the optical layer currently is the *lightpath* service, applicable to wavelength routed optical networks. Lightpaths are basically circuit switched pipes carrying traffic at very high bit rates (2.5Gbps to 10Gbps). The optical layer provides lightpath service to the higher layers which can be viewed as client layers that make use of the services provided by the optical layer. Our interest

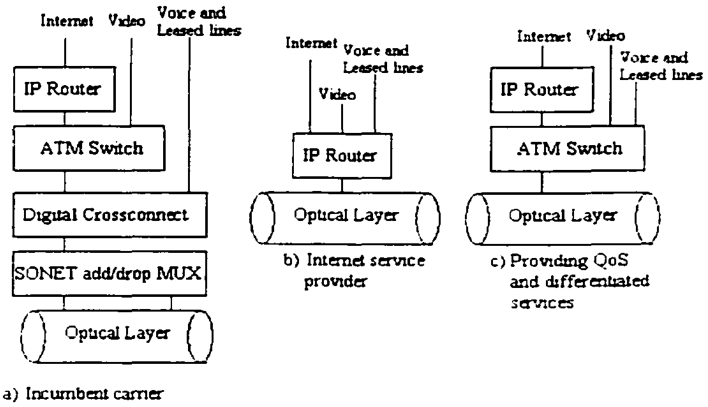


Figure 1.3 Network layering choices

here is to look at the optical layer from the protection services perspective that need to be provided by the optical layer to the higher layers (for further reading please refer to [14]).

The IP, ATM and SONET layers incorporate their own protection and restoration mechanisms.[1] These layers are designed to interoperate with other layers and can also operate directly over the fiber. As a result each layer has its own protection and restoration mechanism. We discuss some of the reasons why optical layer needs to provide its own set of protection and restoration mechanisms.

Network service providers can offer varying classes of services based on the choice of protection which can vary from full protection to no protection [14, 15, 16]. Based on the service classes, the traffic in the network can be divided into one of the three classes viz., full protection, no protection and best-effort. The first class comprises of high priority traffic which require full

---

[1] Note that protection refers to pre-planned recovery upon a failure and is expected to be very fast (≈ 50ms). It is the primary mechanism to deal with a failure. Restoration on the other hand takes over after the protection switching is completed. It is used to find either more efficient routes based on dynamic capacity recovery. Restoration is expected to be slow (seconds to minutes).

protection in the optical layer. Many carriers may have already invested hugely in their networks and their legacy equipment may not support protection and such applications have to rely on the optical layer for protection. The second class comprises of high priority traffic which require no protection in the optical layer, as they may already be protected by higher layers such as SONET. The best-effort class tries to provide protection for the connections based on the resources available. These may include IP traffic which have their own protection mechanisms that are slower, and as a result optical layer protection may be beneficial. Also, traffic which does not have any stringent protection requirements, but can pay for protection if the network has enough resources available.

In general, optical layer recovery typically tends to be faster and it can better utilize resources such as wavelengths. Certain failures like fiber cuts, which typically results in loss of traffic over multiple wavelengths, are restored sufficiently quickly and efficiently by the optical layer. If this failure for example were to be dealt by the higher layers like SONET, then several alarms are flooded into the network for every SONET stream that has failed, and the network management system can degrade sufficiently dealing with the large number of alarm messages. However, optical layer recovery mechanisms does have its limitations. For example it cannot handle failure of a laser in an IP router, or a SONET ADM attached to the network. These failures must be handled by higher layers. Optical layer may be transparent to the data (at variety of bit rates) that is carried on the lightpaths. As a result, it cannot monitor the signal to sense degradations. Optical layer protects traffic in units of lightpaths, but a more finer granularity of protection mechanisms may be desired for high priority streams that are carried on the lightpath.

1.4 Key Issues and Motivation

The challenge is to react quickly to these increasing bandwidth requirements while maintaining reliable service. The key is to design and operate networks to provide adequate capacity in the geographical areas where demand is growing fastest, without ever over provisioning to the point of reducing the network revenue.

Today's Internet is dominated by applications and services based on the ubiquitous Internet Protocol (IP). The trend is likely to continue as IP continues to provide a form of protection and restoration by enabling packets to be dynamically rerouted around link or node failures. With TCP providing a reliable transport service, it is very likely that IP based applications will continue to dominate the Internet traffic for years to come. It is therefore evident that the WDM backbone networks be optimized for IP services. These factors make it attractive to carry fast growing IP traffic directly over an optical network without the intervening SONET/SDH layer.

SONET has its own protection schemes providing fast recovery (50ms). The SONET recovery time is dictated by the fact that voice calls could be dropped if the restoration times were any longer. The study in [17] provides interesting comparisons on the impact of restoration times on various applications. To accommodate the changing trends, the entire network needs restoration strategies, that are different from the conventional SONET-like implementations [18]. Optical layer protection and restoration offers several advantages: a) recovery mechanisms provided by the optical layer are expected to be faster compared to those provided by the higher level service layers, b) optical layer can better optimize resources such as wavelengths, and c) provides protection to higher layer protocols that do not have their own recovery mechanisms. Restoration could be provided by either the service layer or the optical layer, and the relative benefits are being debated. However, carriers have made huge investments and the transition to a single optical layer providing all the services is expected to be slow. Considerable research needs to be done to understand the interactions of recovery protocols that operate at multiple layers in the event of a fiber cut. The outage duration in the event of a failure could be lengthened as recovery protocols from various layers may interfere with each other. The network could enter into a deadlocked state never converging to a new topology. As a result, protection interoperability studies for optical networks are gaining considerable importance in the research community [19, 20].

Survivable network architectures based on mesh-based (arbitrary) topologies have generated significant interest as the topology of choice in long-haul backbone networks, as they offer better capacity efficiency and efficient re-routing around failed links. This is a result of the route diversity in arbitrary topologies, which is highly sensitive to the average nodal degree. In such cases, the entire network needs a new protection and restoration strategy. In mesh-restorable networks, fast restoration is provided by using predetermined paths that are independent of failure location and uses backup multiplexing techniques for improving wavelength utilization. Mesh networks provide better capacity efficiency than ring networks. In long haul networks the greater distance related cost makes capacity efficiency much more important. Thus, there is continued interest in the design and operation of mesh-restorable backbone networks.

We will now discuss key issues of interest in the design and operation of mesh-survivable WDM optical networks. Several methods have been proposed for joint working and spare capacity planning in survivable WDM networks [21, 22, 23, 24, 25, 26]. These methods have considered a static traffic demand and optimized the network cost assuming various cost models and survivability paradigms. None of these methods however consider the problem of incremental upgrade. This is very important as it results in significant cost reductions for the network service provider.

As the traffic increases during the life time of the network, the resources that need to be budgeted to provide a cost effective upgrade scheme is of prime importance, and given the current market conditions, could determine the very existence of the network service provider.

Network design and static provisioning algorithms typically assume that all point-to-point demands are known *apriori*. While this is a valid assumption for such problems, it is impractical to do so for online routing. The static provisioning problems usually try to minimize capacity under the constraint that all connections have to be accommodated. This goal may yield optimal capacity usage, however, it may end up saturating some links. Once the network is provisioned and calls arrive dynamically, this will result in blocking connections which need to use some saturated links. A metric that minimizes the maximum link utilization is more practical in such cases. Such metrics can be added to the offline capacity minimization problems as a penalty cost to avoid saturating links during static provisioning.

Once the network is provisioned, the critical issue is how to operate the network in such a way that the network performance is optimized under dynamic traffic. The network reconfiguration and reoptimization to recover capacity has to be addressed as part of the operational phase. The optimal provisioning methods consider a static traffic demand and perform routing and wavelength assignment (RWA) to optimize network cost assuming different cost models and survivability paradigms. To the best of our knowledge, none of these design problems taking into account service disruption to working connections, which is a key aspect in the dynamic setting. Also, the application of these algorithms is restricted to network provisioning and offline reconfiguration due to their high computational complexity. For network operation under dynamic traffic scenarios, the direct use of such methods for online reconfiguration remains limited to small networks with few tens of wavelengths. This motivates the need for fast, near-optimal online reconfiguration techniques.

Changing trends in backbone and transport networks towards dynamic path provisioning and evolving optical technologies have brought considerable attention in developing a framework for the optical Internet [27]. It is interesting to study issues related to traffic engineering, network management, QoS, and restoration, in the context of Multi Protocol Label Switching (MPLS). The main motivation behind such an interest is the functional similarity between setting up wavelength switched paths and MPLS label-switched paths (LSP). Recent proposals have attempted to define a single control-plane for MPLS and optical channel routing [28]. These reasons motivate the need for dynamic online routing algorithms which are amenable for distributed implementation. As can be seen clearly, any algorithm which is centralized and requires complete per-flow information does not scale well with the increasing network size. This motivates the need for developing: (a) distributed algorithms with complete information, and/or (b) source based algorithms with partial information which can be easily obtained from traffic engineering extensions to routing protocols.

1.5 Outline of Dissertation

In Chapter 2, we review several survivability paradigms have been explored for surviving single link failures in mesh-based networks. These paradigms serve as a good framework for analyzing the different design methodologies. We also discuss our network model, discuss some technological issues in fault detection and localization, and present the restoration architecture adapted for our design. We introduce the notations that are used throughout the dissertation.

In Chapter 3 ([29]), we propose an optimal design and upgrade scheme for mesh-restorable DWDM backbone networks. We develop a cost model to map the cost resources in a WDM network, and formulate an integer programming based optimization problem to minimize the total facility cost. We also provide a cost optimal way of performing network upgrades. This results in significant cost reduction for the network service provider. 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 for which the network was designed for. The upgrade will take into account the technological advances, which can be input as design parameters in the problem formulation.

In Chapter 4 ([30, 31, 32]), we consider two important objectives of network operation: (i) capacity minimization and (ii) revenue maximization. For capacity minimization, we formulate three operational phases in survivable WDM network operation viz., initial call set up, short/medium-term reconfiguration, and long-term reconfiguration. All three phases are derived from a single ILP formulation. This common framework incorporates service disruption. We modify the framework for revenue maximization that includes a service differentiation model based on lightpath protection. We propose a multistage solution methodology to solve individual service classes sequentially and combine them to obtain a feasible solution. We provide cost comparisons in terms of increase in revenue obtained by various service classes with the base case of accepting demands without any protection. Results are provided to demonstrate the effectiveness of our framework.

The direct use of optimization methods for online reconfiguration remains limited to small networks with few tens of wavelengths. Our goal in Chapter 5 ([33]) is to develop an algorithm for fast online reconfiguration. We propose a heuristic algorithm based on LP relaxation technique to solve this problem. Since the ILP variables are relaxed, we provide a way to derive a feasible solution from the relaxed problem. The algorithm consists of two steps. In the first step, the network topology is processed based on the demand set to be provisioned. This pre-processing step is done to ensure that the LP yields a feasible solution. The pre-processing step in our algorithm is based on a) the assumption that in a network, two routes between any given node pair are sufficient to provide effective fault tolerance, and b) an observation on the working of the ILP for such networks. In the second step, using the processed topology as input, we formulate and solve the LP problem. Interestingly, the LP relaxation heuristic yielded a feasible solution to the ILP in all our experiments. We provide insights into why the LP formulation yields a feasible solution to the ILP. We demonstrate the use of our algorithm on practical size backbone networks with hundreds of wavelengths per link. The results indicate that the run time of our heuristic algorithm is fast enough (in order of seconds) to be used for online reconfiguration.

In Chapter 6 ([34, 35]), we develop dynamic algorithms for source based routing with partial information. The algorithms are classified based on the path selection approach used for the primary path. We compare the performance of various routing algorithms through simulation studies, based on metrics such as the call blocking probability, average path length of an accepted connections, capacity redundancy, and effective network utilization. Our studies show that dynamic routing algorithms perform better than static routing algorithms using pre-computed paths even when the path selection in static algorithms is based on optimizing a global network metric. The other interesting observation we make is that the performance improvement of dynamic routing algorithms using K pre-computed paths is significant even for small values of K.

The generalized version of the of the ILP formulation used in this dissertation, for K alternate paths, is presented in Appendix C.

CHAPTER 2 Restoration Architecture

Several survivability paradigms have been explored for surviving single link failures in mesh-based networks [16, 21, 22, 25, 36, 37]. They can be classified based on their route computation and execution mechanisms as centralized/distributed, by their re-routing as path/link based, by their computation timing as precomputed/real time, and their capacity sharing as dedicated/shared. This classification is shown in Figure 2.1. 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. Link based approach requires the ability to identify a failed link at both ends and makes restoration more difficult when node failures happen. The choice of restoration paths is limited and thus may use more capacity. The precomputed approach calculates restoration paths before a failure happens and real time approach does so after the failure occurs. The former approach allows fast restoration as the routes are precomputed while the latter approach is slow as the alternate route is computed after the failure is detected. Centralized restoration methods compute primary and restoration paths for all demands at a central controller where current information is assumed to be available. The routes are then downloaded into each node's route tables. These algorithms are usually path based. They may use precomputed routes or detect routes at real time.

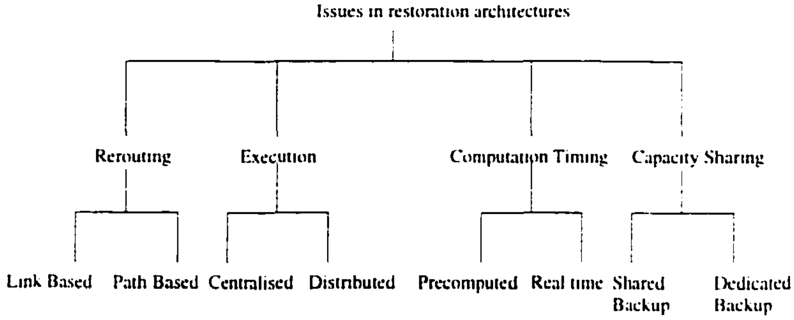


Figure 2.1 Issues in restoration architectures for survivable networks

As explained above, since this step needs to identify failure, ascertain the remaining topology and capacity and then find the best alternate route for the affected demands, the procedure is very slow. Given the importance of restoration speed and potential difficulty in fast failure isolation in optical networks, this approach is not very attractive. Centralized schemes which involve precomputed routes are more conducive for practical implementations. However, maintaining up-to-date information requires frequent communications between the nodes and the central controller. This overhead becomes a potential problem as the network size grows. Distributed methods may involve precomputed tables of discovered capacity and routes in real time. Real time capacity discovery is slow and the capacity utilization may be inefficient. Distributed precomputation of restoration route is an attractive approach. Capacity sharing among the primary and restoration paths can be dedicated or shared. The dedicated technique uses 1:1 protection where each primary path has a corresponding restoration path, and the restoration path is not shared among other demands. In the shared case several primaries can share the same backup path as long as the primaries are node and link disjoint. This scheme is sometimes called backup multiplexing technique [16]. These paradigms serve as a good framework for analyzing the different design methodologies, as each design methodology uses a restoration model which is a combination of the different paradigms just described. All the work in the following chapters assume this network model and restoration architecture discussed in this chapter.

2.1 Network Model

In this section, we discuss the assumptions in the network model, discuss some technological issues in fault detection and localization, and present the restoration architecture adapted for our formulation.

The optical layer model (shown in Figure 2.2) consists of nodes interconnected by links which can accommodate multiple fibers. In our formulation, we assume a single fiber model. Each fiber can carry multiple wavelengths. The number of wavelengths which can be carried on a fiber is a technological constraint, which is expected to increase from a few tens to a few hundreds in the coming years. A connection request between nodes is satisfied by establishing a lightpath from the source node to the destination node. A lightpath is an all optical channel which is assigned the same wavelength on all links along the route, to provide a circuit switched connection between the nodes. Each node consists of an optical cross-connect (OXC) and optical terminating equipment. This may not always be the case as some nodes may act as through nodes where optical channels are in transit. An optical channel passing through the optical cross-connect may be routed from an input fiber to an output fiber without undergoing O-E-O conversions. In our model we assume that

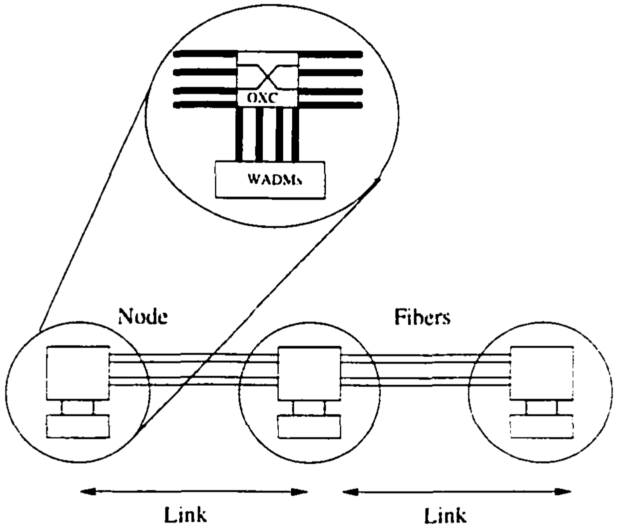


Figure 2.2 Optical layer model

the same wavelength is assigned on all links along the route. So no wavelength translation function is performed in the OXC, all cross-connects are wavelength-selective. An optical channel is terminated by optical terminating equipment such as Wavelength Add/Drop Multiplexers (WADMs). WADMs are used to add or drop selected wavelengths to and from the fiber. So any node can be a source or destination to a connection.

A dependable or a protected connection request between a source-destination (s-d) pair is provided a primary route and a backup route. A non-dependable or unprotected connection is provided with a primary route only. We assume that, each path, primary or backup, always accommodates an OAM (operation, administration, and maintenance) channel terminated by the same s-d pair as the path. The restoration model is shown in Figure 2.3. When a primary path fails, an alarm indication signal is generated by the node which detects the link failure and is transferred over this OAM channel. When the source receives the alarm signal in its OAM channel, it prepares to setup the precomputed backup path and sends messages to the controllers along the backup path to configure the ports accordingly. Since the backup is dedicated, the capacity is assumed to be reserved, so no run time link capacity search needs to be performed. We discuss these aspects of the restoration architecture in a little more detailed later in the section. Once the backup path is setup, the destination prepares to receive on that path. There is no restriction in our model for the choice of wavelength on the backup path. It may or may not be the same as the primary path. The

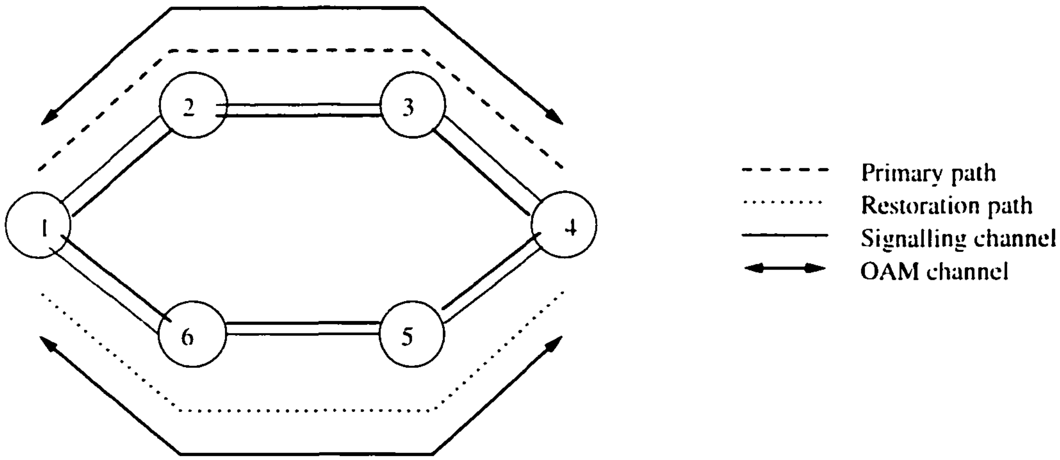


Figure 2.3 Restoration model

tuning time and the associated cost is assumed to be negligible.

2.1.1 Fault Detection and Localization

Current SONET/SDH systems use electronic data framing techniques to monitor overhead bytes to detect a loss of connectivity or bit error rates [6]. Recently new proposals for monitoring optical channel continuity and quality have been proposed in [38]. These optical monitoring techniques are expensive and may take time before they become affordable. Thus, these networks may continue to rely on some electronic framing techniques for per-channel monitoring. This implies some loss of transparency due to O-E conversions. This is already required for lightpath traveling large distances as they have to be dropped and regenerated. However, to reliably detect link/channel failures, some form of non-intrusive monitoring is required at all nodes [39]. Overall, networks which have precomputed routes and which rely on fast electronic or optical fault monitoring, can yield restoration speeds close to those of SONET.

2.2 Restoration Model

We consider 100% protection guarantee for any single node or link failure for dependable connections. This means that primary and restoration paths of protected connections are allocated the same capacity, and are node and link disjoint. We employ backup multiplexing technique to improve the wavelength utilization. This technique allows many restoration paths, belonging to demands of different node pairs, to share a wavelength λ on link l if and only if their corresponding primary paths are link and node disjoint. It should be noted that, although every primary lightpath, has a corresponding backup lightpath, wavelengths on a link can be shared by backup paths belonging to demands of different node pairs, as long as their primary paths do not share any common links. This improves wavelength utilization, while providing 100% guarantee under the single fault assumption. This is due to the fact that no single failure will cause two primary paths to contend for the same backup capacity. We have the following constraints in our restoration model.

- Number of connections (lightpath) on each link is bounded
- Levels of protection
  - Full protection: Every demand is assigned a primary and a backup path
  - No protection: Every demand is assigned only a primary path
  - Best-effort protection: (i) Every demand is assigned a primary path. A backup path is assigned if resources are available (ii) Accept as many demands as possible with or without backup.
- No backups are admitted without a primary i.e., for every node pair, the number of primaries accepted is equal to or greater than the number of backups.
- Primary path wavelength restrictions: Only one primary path can use a wavelength λ on link l, no restoration path can use the same λ on link l
- Restoration path wavelength restrictions: Many restoration paths can share a wavelength λ on link l if and only if their corresponding primary paths are link and node disjoint
- Primary and backup paths for a given demand should be node and link disjoint.

2.3 Notations

The network topology is represented as a directed graph $G(N, L)$ with N nodes and L links with W wavelengths on each link. We also assume that two alternate paths, which are node and link disjoint, for each s-d pair, are used to provide survivability. The following notation are used to develop the optimization formulations developed in successive sections.

- $n = 1, 2, \ldots, N$: Number assigned to each node in the network
- $l = 1, 2, \ldots, L$: Number assigned to each link in the network
- $\lambda = 1, 2, \ldots, W$: Number assigned to each wavelength
- $i, j = 1, 2, \ldots, N(N - 1)$: Number assigned to each s-d pair
- $K = 2$ alternate routes between every s-d pair
- $p, r = 1, 2, \ldots, KW$: Number assigned to a path for each s-d pair. A path has an associated wavelength (lightpath). Each route between every s-d pair has W wavelength continuous paths. The first $1 \leq p, r \leq W$ paths belong to route 1 and $W + 1 \leq p, r \leq 2W$ paths belong to route 2
- $\bar{p}, \bar{r} = 1, 2, \ldots, KW$: if $1 \leq p, r \leq W$ (route 1), then $W + 1 \leq \bar{p}, \bar{r} \leq 2W$ (route 2) and vice versa
- (i, p) : Refers to the pth path for s-d pair i
- d_i: Demand for node pair i, in terms of number of lightpath request. Each request is assigned a primary and restoration route
- π_n^l: Link termination indicator which takes a value one if one of the termination ends of link l is node n, zero otherwise

The following cost parameters are employed.

- C_l: Cost of using a link l (data)
- C_w: Cost of disrupting a currently working path (data)
- C_{ND}: Cost of a primary path (data)
- C_D: Cost of a backup path (data)
- C_{lp}: Cost of provisioning a link (data)
- C_f: Fiber costs (data)
- C_λ: Cost per wavelength channel (data)
- C_{oxc}: Cost of a $\Omega x \Omega$ cross connect switch (data)

Information regarding whether two given paths are link and node disjoint

- $I_{(i,p),(j,r)}$ takes a value one if paths (i,p) and (j,r) have at least one link in common, zero otherwise. If two routes share a link, then all lightpaths using those routes have the corresponding I value set to 1, else 0. (data).

Design parameters and corresponding variables

- Ψ: Maximum number of wavelengths in each direction in a bidirectional fiber (technology dependent data)
- w_l: Number of wavelengths required in link l (integer variable)
- Ω: Size of the minimum crosspoint switching element (technology dependent data)
- Θ_n: Maximum allowable number of OXCs at node N (data)
- o_n: Number of OXCs required at node N (variable)
- F_l: Maximum number of fibers per link l (data)
- f_l: Number of fibers required per link l (integer variable)
- m_l takes a one if the link l is being used, i.e., atleast one fiber is being used ($f_l \geq 1$) in link l (binary variable)

The following notations are used for path related information

- $\delta^{i,p}$: Path indicator which takes a value one if (i,p) is chosen as a primary path, zero otherwise (binary variable)
- $\nu^{i,r}$: Path indicator which takes a value one if (i,r) is chosen as a restoration path, zero otherwise (binary variable)
- $\epsilon_l^{i,p}$: Link indicator, which takes a value one if link l is used in path (i,p), zero otherwise (data)
- $\iota_\lambda^{i,p}$: Wavelength indicator, which takes a value one if wavelength λ is used by the path (i,p), zero otherwise (data)
- $g_{l,\lambda}$ takes a value one if wavelength λ is used by some restoration route that traverses link l (binary variable)

- $\chi^{i,p}$: Path indicator which takes a value one if (i,p) is a currently working primary path, zero otherwise (data). We are only interested in the primary paths of the current working connection as the restoration paths can be re-assigned

CHAPTER 3 Design For Upgrade

3.1 Objective

In this chapter, we propose an optimal design and upgrade scheme for mesh-restorable DWDM backbone networks. In mesh-restorable networks, fast restoration is provided by using predetermined paths that are independent of failure location and uses backup multiplexing techniques for improving wavelength utilization. Mesh networks provide better capacity efficiency than ring networks. In long haul networks the greater distance related cost makes capacity efficiency much more important. Thus, there is continued interest in the design and operation of mesh-restorable backbone networks.

The following cost model is assumed for the network design. The cost resources can be mapped into a) link provisioning cost which may include digging cost, cable cost, leasing, right of way costs, maintenance costs etc. b) fiber cost, which is a combination of optical amplifier costs, multiplexer and demultiplexer costs for fiber terminations, cost of dispersion compensation components etc. c) per channel cost may include the cost of receiver and transmitter cards.

We assume that the network topology for a future traffic demand is given. For the current traffic demand, we formulate an integer programming-based design problem to minimize the total facility cost. The output of the design problem is the number of fibers and wavelengths on each active link, the number of OXCs required for each node, and more interestingly, a subset of links in the final topology that need to be activated for the current traffic demand. The objective of the optimization problem is to minimize the total facility cost. 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. The meaning in this case is 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. As the traffic increases during the life time of the network, more spans can be cost-effectively added to accommodate the increased traffic, thereby incrementally realizing the future topology for which the network was designed for. The upgrade will take into account the technological advances, which can be input as design parameters in the problem formulation.

Outline of the Chapter:

This chapter is organized as follows. Section 3.2 reviews prior work on survivable WDM network design. Section 3.3 introduces the network model, restoration model and cost model adopted for our formulation. The integer programming based design formulation is presented in Section 3.4. Section 3.5 presents the numerical results for design and evaluation. Section 3.6 presents our conclusions and observations.

3.2 Related Work

To date, design problems in mesh-survivable WDM network research have been studied in [21, 22, 23, 25, 24, 26, 40, 41, 42]. The study in [21] proposes an optimal design scheme for survivable WDM transport networks in which fast restoration can be achieved by using predetermined restoration paths. The study in [22] examines different approaches to protect mesh-based WDM optical networks from single-link failures. ILPs were formulated to determine the capacity requirements for a static traffic demand based on path/link protection/restoration survivability paradigms. Integer programming based design problems were formulated to optimally determine working paths together with their corresponding restoration paths, the number of fibers in each span, and the optical cross connects in each node.

In [23], ILP and simulated annealing (SA) were used to solve optimization problems for routing, planning of working capacity, rerouting, and planning of spare capacity in WDM networks. The purpose of the study was to design a fiber topology and optical path layer for WDM networks, with a fixed channel plan, minimizing the total cost for a given traffic demand. The work in [24] aims at providing design protection that is well adapted to WDM networks, where many channels share the same fiber. The design protection, however, does not guarantee carrying all the traffic that was carried prior to the failure. Instead, it aims at maintaining connectivity between all pairs of network ports following a single failure and lets the higher level network layers reconfigure itself so as to carry only the high priority traffic.

Joint optimization of primary and restoration routes to minimize the network capacity was studied in [25]. Given a network, a set of point-to-point demands, find a primary and a restoration route for each demand, such that the network capacity is minimized. The study also tried to determine the best restoration route for each wavelength demand, given the network topology, the capacities, and primary routes of all demands. The work in [26] mainly concerns connection provisioning for optical networks. An heuristic algorithm was developed for routing and wavelength assignment for a set of static connections and an adaptation of the algorithm was proposed to handle a set of failures. The study in [40] proposes a methodology for performing automatic protection switching in optical networks with arbitrary topologies in order to protect the network from fiber link failures.

The authors in [41] propose an ILP formulation to derive a minimal hop distance solution to the virtual topology design problem, studies resource budgeting tradeoffs and an exact reconfiguration procedure to move to a new virtual topology. The work studies tradeoffs between transceivers and switch sizes and demonstrates that an improperly designed network may have low utilization on any of these resources. The work in [42] studies the influence of modularity and economy-of-scale effects on the survivable network design. Results indicate that there are worthwhile savings by including modularity aspects directly in the design formulation. The significant research finding is the topology reduction arising spontaneously in optimized designs under the combined effects of high modularity and economy-of-scale.

3.3 Design Model

Several design models for WDM networks exist in literature [21, 23, 41, 43, 44, 45, 46]. The network model and restoration architecture adapted for our design problem was presented in Chapter 2. We present the cost model employed in the design problem.

3.3.1 Cost Model

The cost sources in a DWDM network can be mapped into the following four parameters: the link provisioning cost (C_{lp}), the fiber cost (C_f), the per channel cost (C_λ), 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 may include digging cost, cable 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 the 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 a significant design parameter. Since the number of wavelengths per fiber decides the amount of dispersion components required, the laser power required (hence the spacing between optical amplifiers), and the amount of regenerators needed, the network provider should set this design parameter appropriately. In ultra long haul DWDM backbone network design, the goal is to let the signal travel longer (thousands of kilometers) without 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 alleviated by using forward error correction (FEC) and dispersion compensation. The total fiber cost can be subdivided as follows. $C_f = A_f.C_a + C_{mux} + C_{demux} + C_{dc}$, 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_λ, includes the receiver and transmitter card costs per wavelength and power equalization required per channel. The power equalization is included as part of the transmitter cost. Since depending on the current demand, the network provider may sub-equip fibers, this cost depends on the number of wavelengths currently used. $C_\lambda = C_r.w_f + C_t.w_f$, where C_t, C_r are transmitter and receiver card costs and w_f is the number of wavelengths currently used in the fiber.

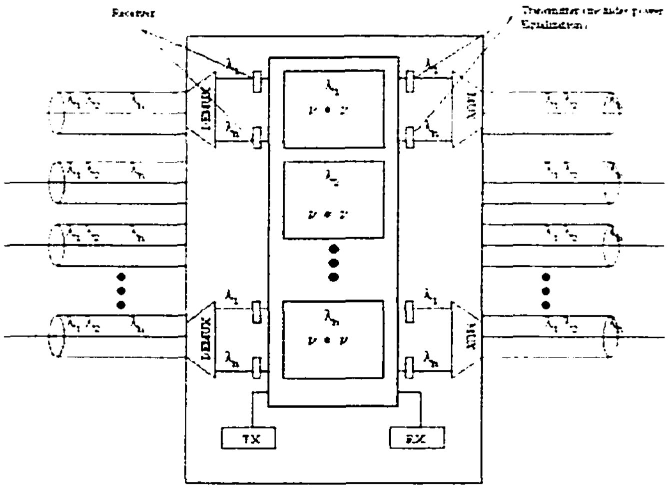


Figure 3.1 Wavelength routing switch architecture

The number of cross connects per node determines the switch size and hence the total facility cost. A typical wavelength routing switch architecture is shown in Figure 3.1. The size of the switch includes both origin/destination traffic for the node, and the transit traffic. 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 to the same output fiber port can use the same wavelength. Connections on different wavelengths, destined for the same output fiber port 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 2×2 ($\Omega = 2$) crosspoint switching element be C_{oxc}. The number of such switching elements required for a $v * v$ 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 $C_{oxc} * \frac{v}{2} \log_2 v$

The total facility cost is given by the sum of all the link and node costs.

$$\begin{aligned} Total facilitycost = & \sum_{l}^{L} (m_l C_{lp} + f_l C_f + w_l C_\lambda) + \\ & \sum_{n}^{N} (\Psi * C_{oxc} * \frac{(o_n)}{\Omega} \log_\Omega (o_n)) \end{aligned} \tag{3.1}$$

where $m_l = 1, 0$ denotes if a link l is used or not, f_l, w_l denote the number of fiber and wavelengths on a link l, respectively. o_n denotes the number of crossconnects needed in a node, and Ψ denotes the maximum number of wavelengths per fiber. The value of o_n is rounded off (ceil) to the nearest integral power of Ω. For the 2×2 case, the cost of 6×6 switch ($2 * (O_n = 3)$) is same as that of a 8×8 switch ($2 * (O_n = 4)$). In the second term in Equation (3.1), the cost of a MIN in each node is multiplied by Ψ, since there is a MIN switch for each wavelength.

3.4 Design Problem

In this section, we develop the design formulation to optimize the total facility cost. The output of the design problem is the links which need to be active to support the current traffic demand, the number of fibers and wavelengths on each active link, the number of OXCs required for each node.

For the ILP formulation, the following information is assumed to be given: the network topology, and a traffic matrix. We also assume that K alternate routes between each node-pair are precomputed and given. Information regarding whether any two given routes are link and node disjoint are also assumed to be given. Each route between every s-d pair is viewed as $F * W$ wavelength continuous paths (here F corresponds to the maximum number of dark fibers that are already laid, or expected to be available on a link, and W the maximum number of wavelengths that can be supported on a fiber), one path corresponding to every wavelength and therefore, we do not have an explicit constraint for wavelength continuity.

First the primary paths are assigned capacity on the shortest path between the node pair. This is under the assumption that, the shortest route (in our case it is the shortest in terms of link miles) between a node is the most cost effective to route demands, and is definitely likely to be used. Thus, these links are automatically active in the topology. Since the primary paths cannot be shared and the working capacity has to be assigned if demands exist, the key then is to optimize spare capacity allocation using techniques like backup multiplexing to improve wavelength utilization, thus optimizing the total network cost. This effective assumption greatly simplifies the problem formulation as explained here. Validating if backup multiplexing can be performed for two given connections, requires identifying where the primary paths for the connections are routed. For the case when there are exactly two disjoint alternate routes between any given node pair, formulating the backup multiplexing constraint is simplified as shown in [30, 32]. This decision if taken dynamically makes the problem formulation very complex and becomes computationally intractable. In this case, since there are K possible alternate routes, validation requires identifying the primary paths dynamically in the formulation. In order to make the problem more tractable, we made the assumption that the shortest route between two nodes is the most cost effective to route demands and hence the working capacity can be pre-assigned.

The ILP solution determines the links that need to be active, number of fibers and wavelengths required for each active link, the number of OXCs required for each node.

3.4.1 Problem Formulation

Objective: The objective is to minimize the total facility cost. This is the sum of all the link costs and the node costs as discussed in Section 3.3.1. Note that the actual cost of each node is computed using Equation (3.1), the objective here is to minimize the number of crossconnects (o_n) required per node, thereby reducing the switching cost

Minimize

$$\sum_{l=1}^{L} m_l C_{l_p} + \sum_{l=1}^{L} f_l C_f + \sum_{l=1}^{L} w_l C_\lambda + \sum_{i=1}^{N} o_n \tag{3.2}$$

Link provisioning constraint: Equations (3.3) and (3.4) set $m_l = 1$ one if $f_l \geq 1$

$$m_l \leq f_l \tag{3.3}$$

$$N(N-1)KFWm_l \geq f_l \tag{3.4}$$

$$1 \leq l \leq L,\ 1 \leq f_l \leq F_l$$

Link capacity constraint: The total capacity in a link depends on the total working and spare capacity assigned on the link. The following equations determine the number of wavelengths and fibers required on each link, given that the maximum number of wavelengths per link is Ψ

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{FW} \delta^{i,p} \epsilon_l^{i,p} + \sum_{\lambda=1}^{FW} g_{l,\lambda} \leq w_l \tag{3.5}$$

$$w_l \leq \Psi f_l \tag{3.6}$$

$$1 \leq l \leq L,\ 1 \leq f_l \leq F_l$$

Crossconnect constraint: Total number of OXCs required in node n to carry traffic, which includes both connections originated/terminated at node n and those that are in transit.

$$\sum_{l=1}^{L} w_l \pi_n^l \leq \Psi o_n \tag{3.7}$$

$$1 \leq n \leq N(N-1),\ 1 \leq o_n \leq \Theta_n$$

Restoration path wavelength usage indicator constraint: $g_{l,\lambda}$ takes a value one if wavelength λ is used by some restoration route (i, r) that traverses link l. Equations 3.9 and 3.10 set $g_{l,\lambda} = 1$, if $X_{l,\lambda} \geq 1$. $X_{l,\lambda}$ counts the number of paths using link l and wavelength λ for backup (Equation 3.8)

$$X_{l,\lambda} = \sum_{i=1}^{N(N-1)} \sum_{r=FW+1}^{KFW} \nu^{i,r} \epsilon_l^{i,r} \iota_\lambda^{i,r} \tag{3.8}$$

$$g_{l,\lambda} \leq X_{l,\lambda} \tag{3.9}$$

$$N(N-1)KFWg_{l,\lambda} \geq X_{l,\lambda} \tag{3.10}$$

$$1 \leq l \leq L,\ 1 \leq \lambda \leq FW,\ X_{l,\lambda} \geq 0$$

Demand constraints for each node pair: The primaries are mapped on the shortest route (route 1) between the given node pair. These constraints also implicitly satisfy topological diversity i.e., primary and restoration path of a given demand should be node and link disjoint

$$\sum_{p=1}^{FW} \delta^{i,p} = d_i \qquad 1 \leq i \leq N(N-1) \tag{3.11}$$

$$\sum_{r=FW+1}^{KFW} \nu^{i,r} = d_i \qquad 1 \le i \le N(N-1) \tag{3.12}$$

Primary path wavelength usage constraint: Only one primary path can use a wavelength λ on link l, no restoration path can use the same λ on link l

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{FW} \delta^{i,p} \epsilon_l^{i,p} \iota_\lambda^{i,p} + g_{l,\lambda} \le 1 \tag{3.13}$$
$$1 \le l \le L,\ 1 \le \lambda \le FW$$

Backup multiplexing constraint: If $I_{(i,1),(j,1)} = 1$, then the primary paths for node pairs i and j share links on its route. Note primary paths are already mapped on the shortest route. Thus, If $I_{(i,1),(j,1)} = 1$, only one of the restoration paths can use a wavelength λ on a link l as backup, since their primary paths share link(s) on their route

$$(\nu^{i,p} \epsilon_l^{i,p} \iota_\lambda^{i,p} + \nu^{j,r} \epsilon_l^{j,r} \iota_\lambda^{j,r}) I_{(i,1),(j,1)} \le 1 \tag{3.14}$$
$$1 \le i,j \le N(N-1),\ FW + 1 \le p,r \le KFW$$

3.5 Results

3.5.1 Experimental Design

We use CPLEX Linear Optimizer 7.0 [47] to solve our design formulations. The eligible routes, between any given node pair, for primary and backup routing were generated using shortest path routing algorithms. The primary paths for a given node pair are assigned using the shortest route mapping. Eligible restoration routes for a node pair were generated to be node and link disjoint from the shortest route where the primaries are mapped. To keep the problem sizes computationally manageable the number of eligible restoration routes were typically restricted to 3 or 4 per node pair. The design formulation has a choice of restoration routes for each node pair to better optimize the spare capacity using backup multiplexing techniques.

The following experiments are presented in the remainder of this section to demonstrate the practical utility of our design formulation. The objective of the optimization problem is to minimize the total facility cost. 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. The meaning in this case is that the cost optimal routing and capacity planning for the current traffic demand may be fully realized on a subgraph of the final topology. We provide a simple example to illustrate this topology sparsening effect in Section

3.5.2. In Section 3.5.3, we demonstrate the applicability of our design formulation to study the effect of various costs and technology trends on network design and upgrades as the network evolves. It is to be noted that the purpose here is to demonstrate the effectiveness of our formulation and how the various design parameters can be used to study different trends. The conclusions drawn here are not to be generalized, as the trends are highly dependent on the network traffic and the underlying topology assumed.

3.5.2 Topology Sparsening

The network topology we consider is shown in Figure 3.2. This network is derived by adding links to the NSFNET T1 backbone shown in [21]. Given that this network topology is designed for some future traffic demand, we design the network for the current traffic.

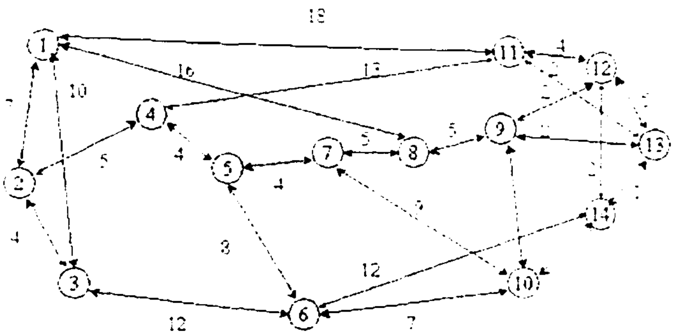


Figure 3.2 14 node 24 link network topology (span distance in hundreds of miles)

We show the topology sparsening effect for a traffic demand matrix consisting of 44 requests distributed over 16 node pairs. We assume the following cost values for the design $C_{l_p} = 100$. $C_f = 10$. $C_\lambda = 1$. The resultant 'sparse' topology is shown in Figure 3.3. This sparsening effect is due to the high cost for provisioning and operating a new link. The links used by the primary paths of a node pair are automatically active in the solution. The key then is to optimize spare capacity allocation among eligible restoration routes. The design formulation tries to maximize the use of a link which is provisioned by routing more demands through it. Identifying these links and backup multiplexing spare capacity to obtain a cost optimal result is the goal of the design problem. It is to be noted that resources such as fibers and wavelengths cannot be increased infinitely on a link. The increase is limited by restrictions such as maximum number of fibers per link l (F_l), maximum number of crossconnects (Θ_n), hence the maximum size of the switching fabric in the node n. These restrictions are captured in our design.

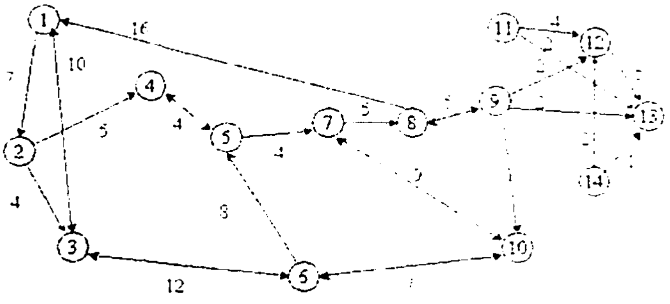


Figure 3.3 Active links for current traffic demand (span distance in hundreds of miles)

Note that in Figure 3.3, some of the active links are unidirectional. This is because we do not assume same traffic flowing across both directions of a node pair. This means that resources such as amplifiers are active only in one direction. For some designs, depending on the traffic, it may be cost effective to provision only one direction and when the network comes for upgrade, the other direction may need to be active. The digging and leasing costs can be avoided when considering the link for upgrade since only the fiber related investment like amplifiers, may be required.

The upgraded network for an increased traffic demand is shown in Figure 3.4. We introduce new traffic between two node pairs which did not have any direct traffic between them. This may provision some new links as shown in the figure. When the design problem is being solved for an increased traffic demand, the current topology and the resources already committed are input to the formulation. For example, resources like active links, number of fibers, wavelength cards which have already been committed, are input as lower bound values to the design problem when the network comes up for upgrade. These resources have already been budgeted and invested in the network.

3.5.3 Effect of Cost and Technology Trends in Network Evolution

We employ the following cost values for our experiments. C_{lp} = \$16000 per mile, C_f = \$10 per meter, C_λ = \$5000. The fiber laying costs or the leasing costs (in case dark fibers are available)

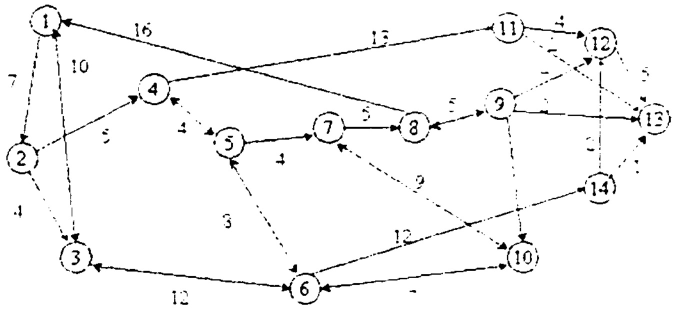


Figure 3.4 Upgraded network for increased traffic demand (span distance in hundreds of miles)

can vary a lot depending on the location. It may be cheaper to lay fibers in rural areas as against a business district in a metropolitan city. The cost values employed here are conservative estimates obtained from literature. The number of wavelengths per fiber, which is a technology constraint, may range anywhere from 4 to more than a 1000 [48]. Currently, commercial systems upto 40 wavelengths per fiber have been announced. For our experiments, we assume a set of $\Psi = \{4, 8, 12\}$ wavelengths per fiber.

A key factor is the economy-of-scale i.e., how the cost scales with increase in capacity. The cost of a fiber (C_f) may scale as $C \times kx$ (increasing capacity C times results in k times the cost). We assume $3 \times 2x$ scaling. This means that tripling capacity comes at twice the cost. The cost of a 2×2 ($\Omega = 2$) crosspoint switching element is $C_{oxc} = \$1000$. The total facility cost is computed using the formula in Equation 3.1.

We study the effects of the cost and technology trends on a 9 node 17 link network (derived from the NSFNET backbone network). The network evolution is studied for a period of six years. In the first year the traffic demand consists of 70 demands distributed uniformly over 20 node pairs. Every year the traffic is increased by a conservative growth estimate of 20-30%. Every two years, we introduce new traffic between four node pairs which did not have direct traffic between them. The total facility cost is plotted for different values of Ψ as the network evolves, as shown in Figure 3.5.

A network designer has to decide what technology to use for implementation, which links to provision, how many fibers and wavelength cards need to be put so that the network is cost effective. Over provisioning and wrong choice of technology can have an adverse effect as the

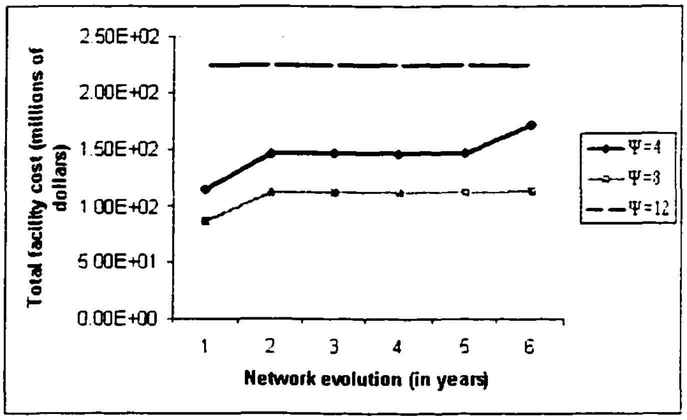


Figure 3.5 Technology and cost effects on network evolution (Note: The conclusions drawn here are not to be generalized, as the trends are highly dependent on the network traffic and the underlying topology assumed)

network may not incur any profits for years, till such a time when revenue exceeds the operation and maintenance cost. Looking at Figure 3.5, the following information can be obtained. It is evident that $\Psi = 8$ wavelengths per fiber is the most cost effective. The choice of technology (Ψ) is not obvious. It depends on the traffic patterns and the underlying topology. The network designer can also decide, based on the budget, how much to provision.

For the case $\Psi = 8$, which is cost optimal for the given traffic and topology, the difference between the network cost in year 1 and year 4 is about roughly $25 million. Depending on the budgeting constraints the designer may choose to provision the resources required to support year 1 and year 2 traffic and upgrade at the end of four years, or if the difference in cost is not significant, the designer may choose to deploy the resources required to support year 4 traffic at the beginning.

On the other hand, as in the $\Psi = 4$ case, the cost differences between the years are significantly high. The difference in cost between year 3 and year 1 is about $32 million and that between year 5 and year 3 is $250 million. It may not be feasible to provision the full topology with all the required capacity at once, hence the network is upgraded as it evolves.

The designer can also study the effect of different switch sizes on the cost. The total facility cost for two different crosspoint switching element sizes ($\Omega = 2, 3$) for the $\Psi = 8$ case is shown in Figure 3.6. The cost of $\Omega = \{2, 3\}$ is assumed to be $C_{oxc} = \{\$1000, \$3000\}$ respectively. The cost difference in this case is fairly less. So the designer may use 3×3 crosspoint switching elements to build the switching fabric.

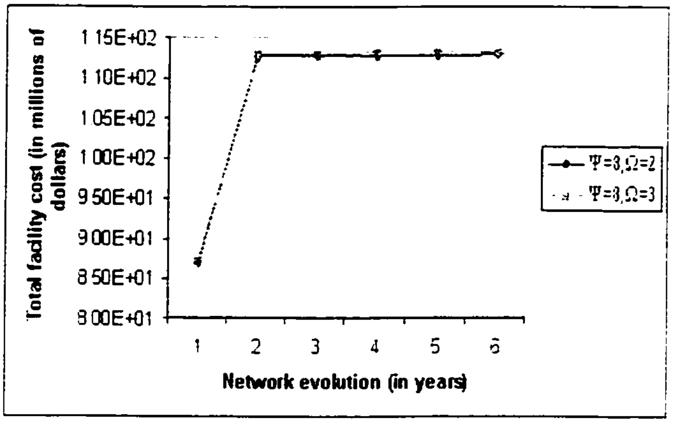


Figure 3.6 Effect of Ω on total facility cost for $\Psi = 8$

Figure 3.7 shows the total fiber length in the network versus number of wavelengths used per fiber Ψ for traffic in year 6. The fiber miles go down as Ψ increases. This does not necessarily means a reduction in network cost as the total cost depends on various other cost parameters as seen earlier.

3.6 Discussion

We formulated an integer programming-based design problem to minimize the total facility cost in a mesh-restorable optical network. The output of the design problem is the number of fibers and wavelengths on each link, the number of OXCs required for each node, and more interestingly, a subset of links in the final topology that needs to be activated for the current traffic demand. We showed illustrative examples to demonstrate this topology sparsening effect. As the traffic increases during the life time of the network, more spans can be cost-effectively added to accommodate the increased traffic, thereby incrementally realizing the future topology for which the network was designed for. The upgrade will take into account the technological advances, which can be input as design parameters in the problem formulation.

Validating if backup multiplexing can be performed for two given connections, requires identifying where the primary paths for the connections are routed. For the case when there are exactly two disjoint alternate routes between any given node pair, formulating the backup multiplexing

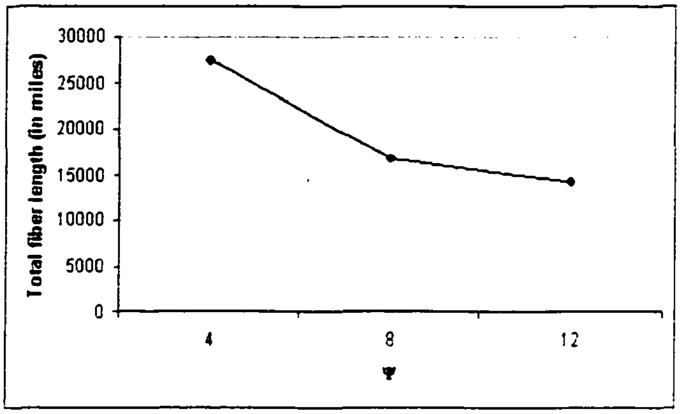


Figure 3.7 Total fiber length vs wavelength per fiber Ψ (based on year 6 traffic)

constraint is simple. This decision if taken dynamically makes the problem formulation very complex and becomes computationally intractable. In such cases, since there are K possible alternate routes, validation requires identifying the primary path routes dynamically in the formulation. In order to make the problem more tractable, we made the assumption that the shortest route between two end nodes is the most cost effective to route demands and hence the working capacity can be pre-assigned. Although this assumption greatly simplifies the problem formulation, there may arise situations when all the links in the final topology are automatically active when we pre-assign working capacity on the shortest path. To avoid such instances, we have developed a generalized formulation that can handle multiple path choices for assigning working capacity, and can dynamically compute backup multiplexing conflicts. However this formulation is fairly complex and we are working on simulated annealing heuristics to simplify the design problem. It is to be noted that the design formulation presented in this chapter can be easily extended to accommodate K= 2 or 3 shortest paths for assigning working capacity instead of pre-assigning on the shortest path. The backup conflicts can be handled by explicitly checking for the primary in one of these K paths.

We showed the applicability of our design formulation to study the effect of various costs and technology trends on network design and upgrades as the network evolves. We performed experiments studying the effects of various costs and technology choices on the total facility cost in a network. The design can be used to identify the technology that is best suited for implementation and how much resources to budget and when to perform the upgrades. A key factor we considered is the economy-of-scale i.e., how the cost scales with increase in capacity. We assumed $3X2x$ scaling i.e., tripling capacity comes at twice the cost.

In the future we plan to conduct more experiments to study the effects of bottleneck nodes in the network and for different economy-of-scale values. We assumed that the whole network scales uniformly in our experiments. This may not be the case always. For example, when coast to coast traffic increases, the intermediate nodes have to invest more as the transit traffic through them also increases. This increase in transit traffic may not be cost effective for all nodes in the network. Some nodes may have their own budgeting constraints and may not want to scale up at the same rate as the rest of the nodes. This means that some connections have to be routed away from these nodes which may result in increased cost.

CHAPTER 4 Network Operation

4.1 Objective

In this chapter, we consider two important objectives of network operation: (i) capacity minimization and (ii) revenue maximization. For capacity minimization, we formulate three operational phases in survivable WDM network operation viz., initial call set up, short/medium-term reconfiguration, and long-term reconfiguration. All three phases are derived from a single ILP formulation. This common framework incorporates service disruption.

We modify the framework for revenue maximization that includes a service differentiation model based on lightpath protection. We propose a multistage solution methodology to solve individual service classes sequentially and combine them to obtain a feasible solution. We provide cost comparisons in terms of increase in revenue obtained by various service classes with the base case of accepting demands without any protection. Results are provided to demonstrate the effectiveness of our framework.

Outline of the Chapter:

This chapter is organized as follows. The network model and restoration architecture are as presented in Chapter 2. Section 4.2 discusses various issues in survivable network operation. The capacity and revenue optimization problems are formulated in Section 4.3, Section 4.4 discusses techniques for problem size reduction, in Section 4.5, we present a solution methodology for solving the combined problem for all classes of demands, Section 4.6 discusses the results and Section 4.7 concludes the chapter.

4.2 Network Operation

Typically, the design problems in optical networks have considered a static traffic demand and tried to optimize the network cost assuming various cost models and survivability paradigms. Fast restoration has been a key feature addressed in most of the designs. Once the network is provisioned, the critical issue is how to operate the network in such a way that the network performance is optimized under dynamic traffic. In this section, we present two important objectives of network operation, capacity minimization and revenue maximization.

4.2.1 Capacity Minimization

For capacity minimization we decompose network operation into three phases, a) initial call setup b) short/medium term reconfiguration and c) long term reconfiguration. The initial call setup phase is a static optimization problem where the network capacity is optimized, given the topology and a traffic matrix to be provisioned on the network. Once demands arrive dynamically, they are admitted based on a routing and wavelength assignment algorithm. The network cannot afford to run optimization procedures to route every call that arrives dynamically. As a result, the utilization of the network capacity slowly degrades to a point where calls may get blocked. This triggers various reconfigurations stages, which try to better utilize the network capacity. In short/medium term reconfiguration, the goal is to optimize resource consumption for backup paths while not disturbing the primary paths of the currently working connections. Backup paths are used only when the primary path fails, so reconfiguring backups causes no hit in service. If further optimization is required, a long term reconfiguration is triggered.

The long term reconfiguration problem can be treated as a static formulation by allowing rerouting of all working connections and optimizing the network capacity for the complete demand set, comprising of both the current working demands and the new demands. On the other hand, we could avoid disrupting any of the currently working demands (by removing the capacity used by the current working demands) and optimizing the network capacity for the new demands. The former treatment provides the best capacity optimization. However, it is possible that all the current connections may be disrupted, which may not be acceptable. The latter case avoids disruption to the current working paths, which may result in poor capacity utilization. To address this tradeoff in the long term reconfiguration problem, we capture service disruption by adding a penalty term for disrupting existing connections as explained in Section 4.3. To the best of our knowledge, none of the existing formulations include the service disruption aspect into the problem formulation. Although the need for different stages in network operation and their corresponding triggering mechanisms are of research importance, we do not address them in this dissertation. We assume that the network control and management monitors the network dynamics and triggers different reconfiguration stages. We use the terms demands and connections interchangeably.

4.2.2 Revenue Maximization

Network service providers can offer varying classes of services based on the choice of protection which can vary from full protection to no protection [14, 15, 16]. Based on the service classes, we divide the traffic in the network into one of the three classes viz., full protection, no protection and best-effort. The first class comprises of high priority traffic which require full protection in the optical layer. Many carriers may have already invested hugely in their networks and their equipment may not support protection and such applications have to rely on the optical layer for protection. The second class comprises of high priority traffic which require no protection in the optical layer, as they may already be protected by higher layers such as SONET. The best-effort class tries to provide protection for the connections based on the resources available. These may include IP traffic which have their own protection mechanisms that are slower, and as a result optical layer protection may be beneficial. Also, traffic which does not have any stringent protection requirements, but can pay for protection if the network has enough resources available. The network typically relies on the best-effort traffic for maximizing revenue. We modify the framework for revenue maximization, which includes a service differentiation model based on lightpath protection. We consider two variations on the best-effort class, variation 1) every demand is assigned a primary path. A backup path is assigned if resources are available 2) Accept as many demands as possible with or without backup. The objective is to maximize revenue. Since the network typically relies on best-effort traffic for revenue, we compare the increase in revenue obtained by the two variations of the best-effort class with the case of accepting demands without any protection.

One of the difficulties in adapting the above formulation for online reconfiguration in larger and more practical networks arises due to the combinatorial nature of the optimization problem. These problems typically take hours to solve for a few hundred demands in small networks with few tens of wavelengths. This is still acceptable in the present scenario, as it takes a few weeks to provision a new connection. We present techniques to prune the size of the ILPs for problem size reduction. Several heuristics and decomposition techniques [25, 33, 49, 50, 51] are being explored to significantly reduce the computational complexity of the original problem.

4.3 Formulation of the Optimization Problems

In this section, we present the ILPs for network capacity minimization and adapt the formulation to include service differentiation based on lightpath protection, for revenue maximization in wavelength routed optical networks.

The following information is assumed to be given: the network topology, a demand matrix consisting of the new connections to be established for each class, and the set of current working connections. We assume that a two alternate routes between each node-pair is precomputed and given. Each route between every s-d pair is viewed as W wavelength continuous paths (lightpaths), one for each wavelength and therefore, we do not have an explicit constraint for wavelength continuity. Information regarding whether any two given routes are link and node disjoint are also assumed to be given. The ILP solution determines the primary and backup lightpaths for the demand set and hence determines the routing and wavelength assignment.

4.3.1 Problem Formulations

4.3.1.1 Capacity Minimization

Objective: The objective is to minimize the network capacity. The first term in objective function (Equation (4.1)) denotes the capacity consumed by primary paths, and the second term denotes the capacity consumed by backup paths. The last term is a penalty term. If a currently working connection ($\chi^{i,p} = 1$) is re-assigned in the final solution ($\delta^{i,p} = 0$), then the objective value is penalized by adding a cost C_w to it.

Minimize

$$\sum_{i=1}^{N(N-1)}\sum_{p=1}^{KW}\delta^{i,p}\sum_{l=1}^{L}\epsilon_l^{i,p}C_l + \sum_{l=1}^{L}\sum_{\lambda=1}^{W} g_{l,\lambda}C_l + \sum_{i=1}^{N(N-1)}\sum_{p=1}^{KW}\chi^{i,p}(1-\delta^{i,p})C_w \tag{4.1}$$

Restoration path wavelength usage indicator constraint: $g_{l,\lambda}$ takes a value one if wavelength λ is used by some restoration route (i,r) that traverses link l. Constraints (3) and (4) set $g_{l,\lambda} = 1$, if $X_{l,\lambda} \geq 1$

$$X_{l,\lambda} = \sum_{i=1}^{N(N-1)}\sum_{r=1}^{KW}\nu^{i,r}\epsilon_l^{i,r}\iota_\lambda^{i,r} \tag{4.2}$$

$$g_{l,\lambda} \leq X_{l,\lambda} \tag{4.3}$$

$$N(N-1)WKg_{l,\lambda} \geq X_{l,\lambda} \tag{4.4}$$

$$1 \leq l \leq L,\ 1 \leq \lambda \leq W,\ X_{l,\lambda} \geq 0$$

Link capacity constraint:

$$\sum_{i=1}^{N(N-1)}\sum_{p=1}^{KW}\delta^{i,p}\epsilon_l^{i,p} + \sum_{\lambda=1}^{W} g_{l,\lambda} \leq W \qquad 1 \leq l \leq L \tag{4.5}$$

Demand constraints for each node pair

$$\sum_{p=1}^{KW} \delta^{i,p} = d_i \qquad 1 \le i \le N(N-1) \tag{4.6}$$

$$\sum_{r=1}^{KW} \nu^{i,r} = d_i \qquad 1 \le i \le N(N-1) \tag{4.7}$$

Primary path wavelength usage constraint: Only one primary path can use a wavelength λ on link l, no restoration path can use the same λ on link l.

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \epsilon_l^{i,p} v_\lambda^{i,p} + g_{l,\lambda} \le 1 \tag{4.8}$$

$$1 \le l \le L, 1 \le \lambda \le W$$

Backup multiplexing constraint: If $I_{(i,\tilde{p}),(j,\tilde{r})}$ is one, then only one of the restoration paths can use a wavelength λ on a link l as backup, since the primary paths share link(s) on their route

$$(\nu^{i,p} \epsilon_l^{i,p} v_\lambda^{i,p} + \nu^{j,r} \epsilon_l^{j,r} v_\lambda^{j,r}) I_{(i,p),(j,r)} \le 1 \tag{4.9}$$

$$1 \le i, j \le N(N-1), 1 \le p, \bar{p}, r, \bar{r} \le KW$$

Constraint for topological diversity of primary and backup paths: Primary and restoration paths of a given demand should be node and link disjoint

$$\sum_{p=1}^{W} \delta^{i,p} = \sum_{r=W+1}^{KW} \nu^{i,r} \tag{4.10}$$

$$\sum_{p=W+1}^{KW} \delta^{i,p} = \sum_{r=1}^{W} \nu^{i,r} \tag{4.11}$$

The ILP can be used in different phases of network operation by appropriately setting the C_w value. For example, in the initial call setup phase, all $\chi^{i,p}$s are zero as there are no working connections. Hence the third term in Equation (4.1) is zero. The higher the value of C_w, more the guarantee that primary paths of the working connections will remain unaffected. In the short/medium reconfiguration phase, the cost of C_w is typically set very high for the primary paths of the working connections. It is to be noted here that a high value of C_w does not guarantee that the primary path will not be re-routed in the final solution. Hence to avoid disruption to primary paths of working connections, the capacity consumed by them should be removed and the backup capacity consumption can be optimized. In the long term reconfiguration phase, an intermediate value of C_w is chosen to capture the tradeoff between possibly disrupting all connections and avoid disrupting any connection.

4.3.1.2 Revenue Maximization

Objective: The objective is to maximize the revenue. Each demand translates into a primary path and a backup path for full protection class, or only primary path for no protection class, and either only primary or both primary and backup path for best-effort class depending on the capacity available. The first term in Equation (4.12), denotes the revenue generated from primary paths, and the second term denotes the revenue from backup paths. The last term indicates that if a currently working connection ($\chi^{i,p} = 1$) is re-assigned in the final solution ($\delta^{i,p} = 0$), then the objective value is penalized by subtracting a cost C_w from it.

Maximize

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} C_{ND} + \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \nu^{i,p} C_D - \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \chi^{i,p}(1 - \delta^{i,p}) C_w \tag{4.12}$$

Restoration path wavelength usage indicator constraint:

$$X_{l,\lambda} = \sum_{i=1}^{N(N-1)} \sum_{r=1}^{KW} \nu^{i,r} \epsilon_l^{i,r} \psi_\lambda^{i,r} \tag{4.13}$$

$$g_{l,\lambda} \leq X_{l,\lambda} \tag{4.14}$$

$$N(N-1)WKg_{l,\lambda} \geq X_{l,\lambda} \tag{4.15}$$

$$1 \leq l \leq L, 1 \leq \lambda \leq W, X_{l,\lambda} \geq 0$$

Link capacity constraint:

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \epsilon_l^{i,p} + \sum_{\lambda=1}^{W} g_{l,\lambda} \leq W \qquad 1 \leq l \leq L \tag{4.16}$$

Primary path wavelength usage constraint:

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \epsilon_l^{i,p} \psi_\lambda^{i,p} + g_{l,\lambda} \leq 1 \tag{4.17}$$

$$1 \leq l \leq L, 1 \leq \lambda \leq W$$

Backup multiplexing constraint:

$$(\nu^{i,p} \epsilon_l^{i,p} \psi_\lambda^{i,p} + \nu^{j,r} \epsilon_l^{j,r} \psi_\lambda^{j,r}) I_{(i,p),(j,r)} \leq 1 \tag{4.18}$$

$$1 \leq i, j \leq N(N-1), 1 \leq p, \bar{p}, r, \bar{r} \leq KW$$

Constraint for topological diversity of primary and backup paths:

$$\sum_{p=1}^{W} \delta^{i,p} = \sum_{r=W+1}^{KW} \nu^{i,r} \qquad 1 \leq i \leq N(N-1) \tag{4.19}$$

$$\sum_{p=W+1}^{KW} \delta^{i,p} = \sum_{r=1}^{W} \nu^{i,r} \qquad 1 \leq i \leq N(N-1) \tag{4.20}$$

Demand constraints for each node pair: Only one of the service classes described below is active in the formulation. For solving the combined problem for all classes, we adopt a different procedure as explained in Section 4.5.

- Full protection: Every demand is assigned a primary and a backup path. The number of full protection demands for node pair i is denoted by d_{i1}.

$$\sum_{p=1}^{KW} \delta^{i,p} = d_{i1} \qquad 1 \leq i \leq N(N-1) \tag{4.21}$$

$$\sum_{r=1}^{KW} \nu^{i,r} = d_{i1} \qquad 1 \leq i \leq N(N-1) \tag{4.22}$$

- No protection: Every demand is assigned only a primary path. The number of no protection demands for node pair i is denoted by d_{i2}.

$$\sum_{p=1}^{KW} \delta^{i,p} = d_{i2} \qquad 1 \leq i \leq N(N-1) \tag{4.23}$$

$$\sum_{r=1}^{KW} \nu^{i,r} = 0 \qquad 1 \leq i \leq N(N-1) \tag{4.24}$$

- Best-effort protection: Only one variation of the best-effort service class can be used in the formulation. This assumption holds when the problem is solved for all classes. (i) Every demand is assigned a primary path. A backup path is assigned, if resources are available. The number of best-effort demands for node pair i is denoted by d_{i3}.

$$\sum_{p=1}^{KW} \delta^{i,p} = d_{i3} \qquad 1 \leq i \leq N(N-1) \tag{4.25}$$

$$\sum_{r=1}^{KW} \nu^{i,r} \leq d_{i3} \qquad 1 \leq i \leq N(N-1) \tag{4.26}$$

- Best-effort protection: (ii) Accept as many demands as possible with or without backup. The number of best-effort demands for node pair i is denoted by d_{i3}.

$$\sum_{p=1}^{KW} \delta^{i,p} \leq d_{i3} \qquad 1 \leq i \leq N(N-1) \tag{4.27}$$

$$\sum_{r=1}^{KW} \nu^{i,r} \leq d_{i3} \qquad 1 \leq i \leq N(N-1) \tag{4.28}$$

Best-effort class constraints: These constraints are used only when the best-effort class demands are being solved. For best-effort variation 2 class demands (Equations (4.27) and (4.28)), no backups are admitted without a primary, i.e., for every node pair, the number of primaries accepted is equal to or greater than the backups. This constraint is required to ensure that when best-effort variation 2 class demands are admitted, the ILP does not admit more backups than primaries. The topological diversity constraint has to be modified while solving for best effort class demands. This is because all primaries need not be accepted with backups. Both these constraints can be stated together as follows.

$$\sum_{p=1}^{W} \delta^{i,p} \geq \sum_{r=W+1}^{KW} \nu^{i,r} \qquad 1 \leq i \leq N(N-1) \tag{4.29}$$

$$\sum_{p=W+1}^{KW} \delta^{i,p} \geq \sum_{r=1}^{W} \nu^{i,r} \qquad 1 \leq i \leq N(N-1) \tag{4.30}$$

In Equation (4.12), the last term indicates that if a currently working connection ($\chi^{i,p} = 1$) is reassigned in the final solution ($\delta^{i,p} = 0$), then the cost C_w is subtracted from the objective and since the objective is to maximize, it ensures that service is not disrupted unless otherwise to increase revenue. The choice of C_w offers flexibility to the network provider. Although the network would like to avoid service disruption to all connections, there may be some customers who are willing to pay more and do not wish to be disturbed. This can be accommodated by modifying C_w to be path specific ($c_w^{i,p}$) and setting a higher cost for disrupting such connections.

The number of variables $\delta^{i,p}$ and $\nu^{i,p}$ grow rapidly with network size. This effect is more pronounced with an increase in the number of wavelengths. For a network of size $N = 14$, $W = 32$ and $K = 2$, there are $K * W = 2 * 32$ instances of each variable for every node pair. Since there are $N * (N - 1) = 182$ node pairs, we have 11,648 $\delta^{i,p}$ variables and 11,648 $\nu^{i,p}$ variables. The number of equations will be roughly 125 million ($11,648^2$). Thus the problem is complex even for small networks.

In the next section, we discuss techniques for ILP problem size reduction.

4.4 ILP Problem Size Reduction

In this section, we discuss techniques for ILP problem size reduction.

4.4.1 Pruning the Variables

As explained in the previous section, the number of variables $\delta^{t,p}$ and $\nu^{t,p}$ grow rapidly with network size. A smarter solution would be to consider only variables that are relevant to the problem at hand. This implies that variables which are zero are removed. If a node pair does not have any demands to be routed between them, then all the variables relating to that node pair are removed.

For a network of size $N = 14$, $W = 32$ and $K = 2$, there are $K * W = 2 * 32$ instances of each variable for every node pair and there are $N * (N - 1) = 182$ such node pairs. For every node pair that does not have demands to be routed between them, we get a reduction of $K * W = 2 * 32$ instances of each variable. We also get a reduction of $K * W = 2 * 32$ equations for each of the constraints and so if only 10 node pairs have demands to be routed between them, we have to deal with 1320^2 instead of $11,648^2$ equations.

Further reductions are possible by considering only links that affect the specific instance of demands to be provisioned. For each link not considered, we get a reduction of 248^2 equations. The above discussions suggest that it is necessary to carefully enumerate the constraints.

4.4.2 Demand Normalization Technique

Another procedure, which results in significant problem size reductions, is the demand normalization technique. Since we deal with wavelength continuous request chunks between node pairs and since all demands between every node pair source and sink at the same nodes, we do not distinguish between each of those requests.

In order to reduce the solution space, we treat each chunk of requests between every demand pair as one entity. Since the whole network should have a consistent view of each entity, we normalize the demand sets by finding the greatest common divisor for all the demand requests, and dividing each demand set by that factor. The capacity on all links are also normalized. This results in a scaled down version of the original problem which is less difficult to solve.

Since the capacity on each link is normalized, the number of wavelengths W reduces by a factor of m, where m is the greatest common divisor of the demand sets. Considering the network with $N = 14$, $W = 32$ and $K = 2$, and if m is say 2, the number of variables reduces by a factor of 2 and we are left with 660^2 equations which is a $1/m^2$ reduction. This technique can yield considerable reduction if m were to be comparable to W. An appropriate procedure that can be adopted here is to adjust demand requests to obtain a m comparable to W and solution be adjusted accordingly.

4.5 Solution Methodology

In this section, we describe the solution methodology for solving the revenue maximization problem for all classes of demands.

Multistage Approach: As explained earlier, the number of variables grows rapidly with the network size. We present a multistage solution methodology to solve the combined problem for all classes of demands. At each stage, the problem is solved for one of the classes, and the result is used in successive stages.

Stage 1: In the first stage, we solve for the primary paths of full protection and no protection classes. The following modified maximization problem is solved at this stage.

Maximize

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} C_{ND} \tag{4.31}$$

Demand constraint:

$$\sum_{p=1}^{KW} \delta^{i,p} = d_{i1} + d_{i2} \qquad 1 \leq i \leq N(N-1) \tag{4.32}$$

Link capacity constraint:

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \epsilon_l^{i,p} \leq W \qquad 1 \leq l \leq L \tag{4.33}$$

The solution to the above ILP is a set of primary paths (chosen paths will have $\delta^{i,p} = 1$). For the next stage, for every $\delta^{i,p} = 1$, in the Stage 1 solution, the corresponding $\chi^{i,p}$ variables is set to 1 in Stage 2. Thus, the solution from Stage 1 is fed to Stage 2 as working primary paths.

Stage 2: In this stage, we solve the original problem presented in Section 4.3.1.2. The demand constraints for full protection class (Equations (4.21) and (4.22)), no protection class (Equations (4.23) and (4.24)) and best-effort variation 2 class (Equations (4.27) and (4.28)) are modified as follows.

$$\sum_{p=1}^{KW} \delta^{i,p} \geq d_{i1} + d_{i2} \qquad 1 \leq i \leq N(N-1) \tag{4.34}$$

$$\sum_{p=1}^{KW} \delta^{i,p} \leq d_{i1} + d_{i2} + d_{i3} \qquad 1 \leq i \leq N(N-1) \tag{4.35}$$

$$\sum_{r=1}^{KW} \nu^{i,r} \geq d_{i1} \qquad 1 \leq i \leq N(N-1) \tag{4.36}$$

$$\sum_{r=1}^{KW} \nu^{i,r} \leq d_{i1} + d_{i3} \qquad 1 \leq i \leq N(N-1) \tag{4.37}$$

It is to be noted here that we do not distinguish between demands from different service classes for a given node pair i. When the ILP solves, the result is interpreted as follows. The first $d_{i1} + d_{i2}$, $\delta^{i,p}$ variables which are set to 1, are considered to be the primary paths for the full protection and no protection class. Any feasible solution to the ILP has to satisfy this constraint. Similarly, the first d_{i1}, $\nu^{i,r}$ variables which are set to 1, are considered to be the backup paths for the full protection class. Equation (4.36) ensures that the backup paths for full protection class demands are chosen in this stage. Any excess primary and backup variables, which are chosen, are considered to belong to the best-effort class.

Effect of C_w: The effect of the solution depends on the value of C_w, the higher the value, more the guarantee that the path will remain unaffected. It is to be noted here that a high value of C_w does not guarantee that the primary path will not be re-routed. Typically, this value is set to be some $\beta = 3, 4$ times the cost of primary paths. This implies that the increase in the objective value for choosing β primary paths is lost for disrupting one existing path.

Complexity: We provide some insights into a possible reduction in complexity at each stage of the multistage solution methodology. To understand the reduction in complexity at each stage, let us first examine the stage 1 of the solution. Since we are interested only in the primary paths for the full protection and no protection class in the stage 1 (backups will be chosen in the stage 2 of the solution). This is a direct reduction in complexity because, we do not consider the $\nu^{i,p}$ variables in the formulation. The stage 2 complexity depends on the value of C_w. The higher the value of C_w, more the guarantee that the path will remain unaffected in the final solution. Since this stage starts with a initial solution, there may be a decrease in the number of combinations that need to be explored, hence a faster solution can be obtained. However, it should be clearly noted that, a higher value of C_w does not guarantee that the solution will be faster. This is because, the ILP can choose to re-route any or all of the existing connections, in an attempt to maximize the objective. Although, the worst case complexity of stage 2 is same as that of solving the combined problem for all classes of demands, typically the solution is obtained much faster.

4.6 Results

We use CPLEX Linear Optimizer 5.0.1 [47] to solve the ILPs. The combined routing and wavelength assignment problem is known to be NP-Complete [52] and the problems addressed in this chapter are expected to be NP-Complete as well. As a result, these formulations are not easily adaptable for real-time reconfiguration in larger and more practical networks. We use the techniques discussed in Section 4.4 for problem size reduction. Several heuristics and decomposition techniques [25, 33, 49, 50, 51] are being explored to significantly reduce the computational complexity of the original problem.

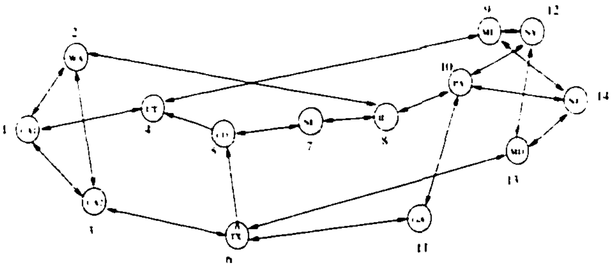


Figure 4.1 The 14 node 21 link NSFNET

We demonstrate the effectiveness of our formulation on the 14 node 21 link NSFNET topology (shown in Figure 4.1) with one fiber per link and 10 wavelengths per fiber. For comparing the increase in revenue got by two variations of the best-effort class, we show results for various demand sets on the NSFNET topology and the 20 node 32 link ARPANET topology (shown in Figure 4.2).

4.6.1 Capacity Minimization

Initial call setup: Consider a set of 25 demands distributed uniformly across 5 node pairs as shown in Table 4.1. In the static optimization stage, there are no current working connections and hence the demand matrix is to be provisioned by providing a primary and backup path for each demand. The resulting routing and wavelength assignment is shown in Table 4.1. The objective value for the ILP is 95.

Long term reconfiguration: To understand the working of the ILP for long term reconfiguration, consider the node pairs, their alternate routes, and an instance of the primary paths of the currently

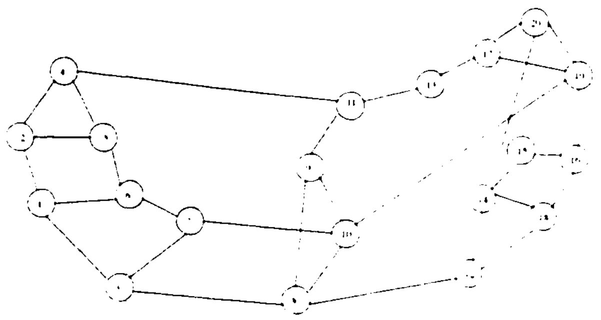


Figure 4.2 The 20 node 32 link ARPANET

Table 4.1 Static optimization stage

Node pair	Alternate routes	Primary paths	Backup paths
1	1 2	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$	-
	1 3 2	-	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$
27	3 1	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$	-
	3 2 1	-	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$
110	9 4 5 6	$\lambda_1, \lambda_2, \lambda_4, \lambda_8, \lambda_9$	-
	9 12 13 6	-	$\lambda_1, \lambda_2, \lambda_4, \lambda_8, \lambda_9$
142	11 6 13	$\lambda_1, \lambda_2, \lambda_4, \lambda_8, \lambda_9$	-
	11 10 12 13	-	$\lambda_1, \lambda_2, \lambda_4, \lambda_8, \lambda_9$
167	13 6 11	-	$\lambda_1, \lambda_2, \lambda_4, \lambda_8, \lambda_9$
	13 12 10 11	$\lambda_1, \lambda_2, \lambda_4, \lambda_8, \lambda_9$	-

working connections on their routes, as shown in Table 4.2. The ILP will try to avoid service disruption to the primary paths of the working connections. These paths are input to the formulation through the $\chi_{i,p}$ variable. The ILP was solved for node pairs shown in Table 4.2 with $C_l = 1$ and $C_w = 4$. The effect of the solution depends on the value of C_w, the higher the value, more the guarantee that the working path will remain unaffected. This value (C_w) is set to be some β times the cost of primary paths (C_{ND}). Typically the value of β is set to 3 or 4. For every connection that is disturbed, the objective value is penalized by a factor C_w.

Let node pairs 1,32,110,167 request 5 connections each and node pair 27 require 6 connections. The total number of connections requested between each node pair include those which are currently working. The resulting route and wavelength assignments for the demands are shown in Table 4.3. The objective value for the ILP is 53. The connections which were disturbed are denoted in Table 4.2 by an asterisk(*). The currently working connections were deliberately chosen

Table 4.2 Long term reconfiguration stage

Node pair	Alternate routes	Primary paths of working connections (wavelengths)
1	1 2	λ_1, λ_2
	1 3 2	λ_5 *
27	3 1	$\lambda_1, \lambda_2, \lambda_3$
	3 2 1	$*\lambda_1, \lambda_2*$
110	9 4 5 6	λ_7, λ_8
	9 12 13 6	λ_5
167	13 6 11	$\lambda_5*, \lambda_8*, \lambda_{10}*$
	13 12 10 11	λ_3
32	3 6 5 7	λ_1, λ_2
	3 2 8 7	$*\lambda_3, \lambda_4$

Table 4.3 Route and wavelength assignment

Node pair	Alternate routes	Primaries	Backups
1	1 2	$\lambda_1, \lambda_2, \lambda_3, \lambda_6, \lambda_{10}$	-
	1 3 2	-	$\lambda_1, \lambda_2, \lambda_3, \lambda_6, \lambda_{10}$
27	3 1	$\lambda_1, \lambda_2, \lambda_3, \lambda_6, \lambda_{10}$	λ_9
	3 2 1	λ_9	$\lambda_1, \lambda_2, \lambda_3, \lambda_6, \lambda_{10}$
110	9 4 5 6	$\lambda_3, \lambda_6, \lambda_7, \lambda_8$	λ_5
	9 12 13 6	λ_5	$\lambda_3, \lambda_6, \lambda_7, \lambda_8$
167	13 6 11	-	$\lambda_3, \lambda_6, \lambda_7, \lambda_8, \lambda_{10}$
	13 12 10 11	$\lambda_1 \lambda_3, \lambda_6, \lambda_7, \lambda_8$	-
32	3 6 5 7	$\lambda_1, \lambda_2, \lambda_3, \lambda_{10}$	λ_4
	3 2 8 7	λ_4	$\lambda_1, \lambda_2, \lambda_3, \lambda_{10}$

to demonstrate the working of the ILP. The connections that are disturbed are the ones which use links where backups can be multiplexed. To understand this better, take the case of node pairs 1 and 27. They share a link $(3-2)$ on one of their routes. Since both the node pairs have atleast one disjoint route, the routes corresponding to link $3-2$ could be used for multiplexing the backup paths. Thus the primary paths of connections using wavelength λ_5 on route $1-3-2$, and λ_1, λ_2 on route $3-2-1$, were re-assigned to routes $1-2$ and $3-1$ respectively.

In short/medium reconfiguration stage, the goal is to optimize resource consumption for backup paths. The higher the value of C_w, more the guarantee that primary paths of the working connections will remain unaffected. In the short/medium reconfiguration phase, the cost of C'_w is typically set very high for the primary paths of the working connections. It is to be noted here that a high value of C'_w does not guarantee that the primary path will not be re-routed in the final solution, hence to avoid disruption to primary paths of working connections, the capacity consumed by

Table 4.4 Increase in revenue for the two variations of best-effort class (NSFNET)

Demand	$\alpha = 1$					$\alpha = 0.5$				
	Best-effort 1		Best-effort 2			Best-effort 1		Best-effort 2		
	Primary	Backups	Primary	Backups	Rejected	Primary	Backups	Primary	Backups	Rejected
12	12	8	12	8	0	12	8	12	8	0
20	20	16	20	16	0	20	16	20	16	0
24	24	12	21	18	3	24	12	21	18	3
32	32	20	28	27	4	32	20	29	26	3
36	36	22	33	28	3	36	22	33	28	3
44	44	30	41	36	3	44	30	41	36	3
48	48	32	44	39	4	48	32	46	36	2

them be removed and the backup capacity consumption can be optimized.

4.6.2 Revenue Maximization

Consider the following cost relationship between the primary and backup paths. $C_D = \alpha * C_{ND}$, where $0 \leq \alpha \leq 1$. The total revenue is calculated as $(\#totalprimaries * C_{ND} + \#totalbackups * \alpha * C_D)$ costunits (cu). The network relies on the best-effort class to increase revenue. We compare the increase in revenue got by the two variations of the best-effort class with a base case of accepting all connections without any protection. We show results for $C_{ND} = 500$cu and for two values of $\alpha = \{1, 0.5\}$. The results for various demand sets on NSFNET and ARPANET topologies are shown in Table 4.4 and Table 4.5 respectively. For particular instances of demands, we see that the best-effort variation 1 results in a 67% gain in revenue and variation 2 achieves an additional 6% gain, for $\alpha = 1$. The cases are compared to the revenue generated by accepting all demands without protection $(\#primaries * C_{ND})$. For example, consider the case of 48 demands for $\alpha = 1$ in Table 4.4. The base case accepting all demands without any protection results in $48 * C_{ND} = 24,000$cu. The total revenue for variation 1 is $48 * C_{ND} + 32 * C_D = 40,000$cu, which is a 66.7% gain. The revenue for variation 2 is $44 * C_{ND} + 39 * C_D = 41,500$cu, which is a 72.9% gain. Although, both schemes employ backup multiplexing, the first variation has no choice but to choose all the primary paths and then tries to accommodate backups and so is restricted. The second variation better exploits the backup resource consumption by effectively multiplexing more connections on the same wavelength, thus accepting more connections and generating a slight increase in revenue.

We now demonstrate our multistage solution methodology on the NSFNET topology. We consider a demand set comprising of 48 demands with 12 demands in full protection class, 12 demands in no protection class, and 24 demands in best-effort class, distributed uniformly across four node pairs. The cost values used are $C_{ND} = 500$, $C_D = 500(\alpha = 1)$, $C_w = 500(\beta = 1)$.

In the first stage, the problem is solved for full protection demands. We assume that there are

Table 4.5 Increase in revenue for the two variations of best-effort class (ARPANET)

Demand	$\alpha = 1$					$\alpha = 0.5$				
	Best-effort 1		Best-effort 2			Best-effort 1		Best-effort 2		
	Primary	Backups	Primary	Backups	Rejected	Primary	Backups	Primary	Backups	Rejected
12	12	8	12	8	0	12	8	12	8	0
20	20	16	18	18	2	20	16	20	16	0
24	24	12	20	20	4	24	12	20	20	4
32	32	20	28	28	4	32	20	28	28	4
36	36	20	32	28	4	36	20	32	28	4
44	44	28	40	37	4	44	28	41	34	3
48	48	24	40	40	8	48	24	41	38	7

no currently working connections. Thus, the value of $x^{i,p}$ for all the node pairs is zero. The ILP determined a feasible solution, which is a set of paths, with a route and wavelength associated with each of them, for all the 12 demands in the full protection class. This set of paths, is fed into the second stage by setting the associated $x^{i,p}$ variables to 1. The problem is then solved for full protection and no protection classes. The 12 paths chosen for full protection class are assumed to be working paths in this stage. The ILP assigned primary paths for all full protection and no protection demands with an objective value of 11,500.

Although, the objective value is of no relevance as long as we know the number of primary and backups selected, it is interesting to see how the ILP handles service disruption. Since the ILP determined a feasible solution for all the full protection and no protection demands, the objective value is expected to be 12,000, but the value got is 11,500 (24*C_{ND} $- 1 * C_{w}$). This was due to the fact that one of the full protection demand's primary path was re-assigned . The objective value incurred a penalty for disturbing the connection. Thus, by appropriately choosing C_{w}, as explained in Section 4.5, this aspect of the formulation can be used to try and avoid service disruptions to existing connections in the network.

This set of primary paths is then fed to the third stage. The third stage solves the problem for all classes. The value of C_{w} is set to 1500 ($\beta = 3$). As explained in Section 4.5, Equation (4.30) ensures that backups for all demands of the full protection class are chosen. The final solution at the end of the third stage is shown in Table 4.6. The demands rejected are those belonging to the best-effort class. The total revenue generated for provisioning the complete demand set for all classes is $45 * C_{ND} + 36 * C_D = 58,500$cu.

4.7 Discussions

In this chapter, we considered two important objectives of network operation: (i) capacity minimization and (ii) revenue maximization. We formulated three phases in survivable WDM network

Table 4.6 Solution at the end of the third stage

Node pair	Class 1	Class 2	Class 3	Primary paths	Backup paths
1	3	3	6	10	10
2	3	3	6	11	10
3	3	3	6	12	8
4	3	3	6	12	8
				45	36

operation viz., initial call set up, short/medium-term reconfiguration, and long-term reconfiguration. All three phases are derived from a single integer linear programming formulation. This common framework includes service disruption.

We modified the framework for revenue maximization, which includes a service differentiation model based on lightpath protection. The combined problem for solving demands from various service classes can be quite complex. We proposed a multistage solution methodology to solve individual service classes sequentially and combine them to obtain a feasible solution. We provided cost comparisons in terms of increase in revenue got by various service classes with the base case of accepting demands without any protection. For particular instances of demands, we see that the best-effort variation 1 results in a 67% gain in revenue and variation 2 achieves an additional 6% gain, for $\alpha = 1$.

CHAPTER 5 Online Algorithms: Extension to Large Networks

5.1 Objective

Several methods have been developed for joint working and spare capacity planning in survivable WDM networks. These methods have considered a static traffic demand and optimized the network cost assuming various cost models and survivability paradigms. In this chapter, our focus primarily lies in network operation under dynamic traffic. We formulated various operational phases in survivable WDM networks as a single ILP optimization problem, as discussed in Section 4.3.1.1, Chapter 4. This common framework avoids service disruption to the existing connections. However, the complexity of the optimization problem makes the formulation applicable only for network provisioning and offline reconfiguration. The direct use of this method for online reconfiguration remains limited to small networks with few tens of wavelengths.

Our goal is to develop an algorithm for fast online reconfiguration. We propose a heuristic algorithm based on LP relaxation technique to solve this problem. Since the ILP variables are relaxed, we provide a way to derive a feasible solution from the relaxed problem. The algorithm consists of two steps. In the first step, the network topology is processed based on the demand set to be provisioned. This pre-processing step is done to ensure that the LP yields a feasible solution. The pre-processing step in our algorithm is based on a) the assumption that in a network, two routes between any given node pair are sufficient to provide effective fault tolerance, and b) an observation on the working of the ILP for such networks. In the second step, using the processed topology as input, we formulate and solve the LP problem. Interestingly, the LP relaxation heuristic yielded a feasible solution to the ILP in all our experiments. We provide insights into why the LP formulation yields a feasible solution to the ILP. We demonstrate the use of our algorithm on practical size backbone networks with hundreds of wavelengths per link. The results indicate that the run time of our heuristic algorithm is fast enough (in order of seconds) to be used for online reconfiguration.

Outline of the Chapter:

This chapter is organized as follows. In Section 5.2, we discuss some approaches that have been used for solving large instances of problems in optical networks, and outline our proposed work. The ILP formulation for various operational phases in survivable WDM networks is already discussed in Section 4.3.1.1, Chapter 4. In Section 5.3, we present a heuristic algorithm based on the LP relaxation technique. Section 5.4 compares the ILP and the LP solution for small problem instances, and demonstrates the heuristic algorithm applied to large problem instances. Section 5.5 presents our conclusions and observations on the heuristic algorithm.

5.2 Outline of the Proposed Work

The complexity of the optimization problem makes the formulation applicable only for provisioning and offline reconfiguration. The use of these methods for online reconfiguration is limited to small networks with few tens of wavelengths. To reduce the complexity of such problems, and to make it more tractable, various decomposition techniques based on lagrangean relaxation [49] and linear programming (LP) relaxation [51] exist in literature. We discuss some approaches that have been used for solving large instances of problems in optical networks.

In [25], the lagrangean relaxation method was used to simplify the integer problem into subproblems for each demand. Since a solution to the relaxed problem may not necessarily be a feasible solution to the original problem, heuristics were employed to extract a feasible solution. The LP relaxation of the ILP model is one of the widely used relaxation techniques. In this technique, the integrality constraints of the ILP variables are relaxed. In [43], LP relaxation technique was used to derive an upper bound on the carried traffic of connections for any routing and wavelength assignment algorithm. In [50], randomized rounding technique was used to convert fractional flows provided by the LP solution to integer flows, and graph coloring algorithms were used to assign wavelengths to the lightpaths. The problem of minimizing the total wavelength mileage, in a network with arbitrary topology, to provide shared line protection was studied in [53]. In [54], the authors proposed an efficient approach for solving the wavelength mileage problem. The algorithm provides a feasible solution, with minimal violation of the design constraints, and a pruning technique of the search space to reduce the problem complexity.

Our goal is to develop an algorithm for fast online reconfiguration. We propose a heuristic algorithm based on LP relaxation technique to solve this problem. Since the ILP variables are relaxed, we provide a way to derive a feasible solution from the relaxed problem. The algorithm consists of two steps. In the first step, the network topology is processed based on the demand set to be provisioned. This pre-processing step is done to ensure that the LP yields a feasible solution.

The pre-processing step in our algorithm is based on a) the assumption that in a network, two routes between any given node pair are sufficient to provide effective fault tolerance, and b) an observation on the working of the ILP for such networks. In the second step, using the processed topology as input, we formulate and solve the LP problem. Interestingly, the LP relaxation heuristic yielded a feasible solution to the ILP in all our experiments. We provide insights into why the LP formulation yields a feasible solution to the ILP. We demonstrate the use of our algorithm on practical size backbone networks with hundreds of wavelengths per link. The results indicate that the run time of our heuristic algorithm is fast enough (in order of seconds) to be used for online reconfiguration.

5.3 Heuristic based on LP Relaxation

In this section, we present a heuristic algorithm based on the LP relaxation. The LP relaxation of the ILP model is one of the widely used decomposition techniques. Since the integrality constraints of the ILP variables are relaxed, we may violate some constraints when the fractional flows of the LP solution are rounded off to integer flows. There is no guarantee of extracting a feasible solution once the LP provides a solution with fractional flows. Hence, we need a way of forcing the fractional flows to integer flows so that the LP formulation yields a feasible solution.

We address this problem using a two-step algorithm. In the first step, the network topology is processed based on the demand set to be provisioned. The pre-processing step is done to ensure that the LP formulation yields a feasible solution. The pre-processing step identifies possible routes for backup multiplexing demands belonging to different node pairs. Each node pair is assigned a set of wavelengths based on a set of rules as explained in Section 5.3.1.

In the second step, using the processed topology as input, we formulate and solve the LP problem (developed in Section 5.3.2). It is to be noted that the pre-processing step merely assigns a set of wavelengths to each node pair and the actual routing and wavelength assignment is performed by the LP formulation.

5.3.1 Pre-processing Step

The pre-processing is done to ensure that the LP yields a feasible solution, as will be demonstrated later. The pre-processing step in our algorithm is based on a) the assumption that in a network, two routes between any given node pair are sufficient to provide effective fault tolerance, and b) an observation on the working of the ILP for such networks. The ILP in our formulation decides for each node pair, which route, of the two available, is to be used for primary and which one for backup. We then classify demands into one of the two categories: a) if two node pairs have common links on both their routes, their backups cannot be multiplexed on the same wavelengths (as they violate the criteria for backup multiplexing), and b) if we have two node pairs and at least one route for each of them is node and link disjoint with the other, then backup paths of demands belonging to these node pairs may or may not be multiplexed depending on the specific instance of traffic that is contending for resources. The pre-processing step is formally presented below.

1. Identify the bottleneck link for each node pair as follows
   - (a) Bottleneck link for a node pair i ($Bl[i]$) is defined as that link on either of its two routes, which is part of the routes of most other node pairs
   - (b) If multiple links have the same value, the tie is arbitrarily broken
2. Pre-wavelength set assignment
   - (a) Arbitrarily choose a node pair i
   - (b) Assign d_i wavelengths on both its routes. (For satisfying d_i demands, a node pair needs d_i wavelengths on each of its routes for its primary and backup paths. A node pair i is of $Type1$ on a particular route if it has been assigned exactly the same number of wavelengths as the number of demands on its route). In this case, i is of $Type1$ on both its routes.
   - (c) For every node pair j using $Bl[i]$
     - i. One route of i and j already share a common link $Bl[i]$. Without loss of generality, let this be route 1 for both node pairs. Now, if route 2 of node pair j is link and node disjoint with route 2 of i, then assign $d_i + d_j$ wavelengths for j on route 1, out of which d_i wavelengths are shared with i. (A node pair is of $Type2$ if it has been assigned more wavelengths than its demand requirements). j is of $Type2$ in its route 1. On j's other route it is exactly assigned d_j wavelengths (j is of $Type1$ on its route 2).
     - ii. If node pairs j and i share link(s) on their other route (route 2), then j is assigned d_j wavelengths, disjoint to those assigned to i, on both its routes. In this case, j is $Type1$ on both its routes.
     - iii. Repeat the procedure for all j using $Bl[i]$, comparing with every $Type1$ node pair available on the link. The following rules apply. (Note: These rules are enforced

to handle problems arising as a result of the relaxation. This will be explained in detail in Section 5.3.2)

   A. A *Type*2 node pair can share wavelengths with only one *Type*1 node pair on a link

   B. Every *Type*1 node pair can have exactly one *Type*2 pair sharing wavelengths with it. If more than one such *Type*2 pair exists on the link, for every *Type*1, then the demands belonging to those node pairs are removed. The problem is solved for only one set of interacting demands at a time

iv. Once step 2.c is completed, node pairs which have been assigned wavelengths are marked

v. Arbitrarily choose one of the node pairs which has been marked, and repeat step 2.c on its bottleneck link

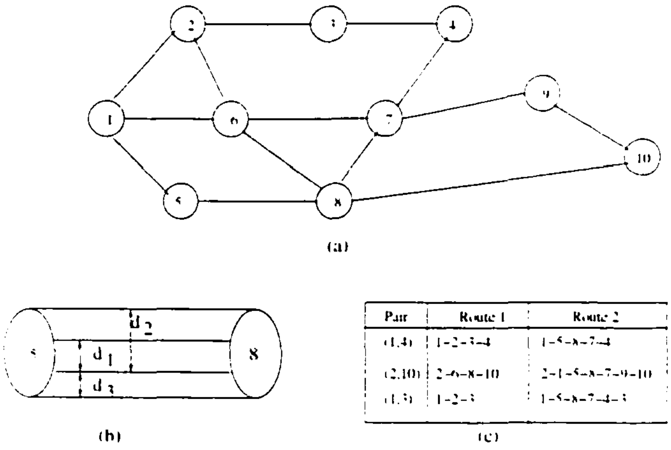
vi. Repeat step 2.c.v for all marked pairs on link $Bl[i]$

vii. Repeat step 2 and terminate when all node pairs that have non-zero demands are marked

The pre-processing step identifies possible routes for backup multiplexing demands belonging to different node pairs. Each node pair is assigned a set of wavelengths based on a set of rules (2.iii.A and 2.iii.B. above). It is to be noted that the pre-processing step merely assigns a set of wavelengths to each node pair and the actual routing and wavelength assignment is performed by the LP formulation (developed in Section 5.3.2). We provide insights into the working of the pre-processing step through an illustrative example.

Consider an example network shown in Figure 5.1(a). The node pairs of interest to us and the alternate routes between them are shown in Figure 5.1(c). Let d_1, d_2, d_3 be the demand request for each pair 1, 2, 3 respectively. The links that are of interest to us are ones where more demands belonging to different node pairs interact. In this example, links $5 \rightarrow 8$, $8 \rightarrow 7$ fall into that category. We arbitrarily choose link $5 \rightarrow 8$ for demonstration. Each node pair is assigned a set of wavelengths. This allocation does not affect the actual routing and wavelength assignment to be performed by the LP formulation. For a node pair, as long as enough wavelengths (capacity) are allocated to meet the demands, it does not matter what range of wavelengths was assigned to it.

Examining link $5 \rightarrow 8$, we arbitrarily choose node pair 3 and assign d_3 wavelengths on both its routes. Node pair 3 is of *Type*1 on both of its routes. Next we arbitrarily choose node pair 1, and since node pairs 1 and 3 have common links on both their routes, they cannot be backup multiplexed with each other. This implies that disjoint wavelength sets are needed for these two



Pair	Route 1	Route 2
(1,4)	1-2-3-4	1-5-8-7-4
(2,10)	2-6-8-10	2-1-5-8-7-9-10
(1,3)	1-2-3	1-5-8-7-4-3

Figure 5.1 An illustrative example to demonstrate the pre-processing step

link sharing pairs. Node pair 1 is assigned d_1 wavelengths ($d_3 + 1$ to $\min(d_3 + d_1, W)$ on its route 2) on both of its routes. Hence node pair 1 is also of *Type*1 on both of its routes. Since node pair 2 has at least one route (its route 1) that is disjoint from the possible routes of both the other node pairs, there is potential to do backup multiplexing, so the wavelengths may be shared with either of *Type*1 pairs available. We arbitrarily choose to share with node pair 1, since a contiguous set of wavelengths can be assigned. The order of wavelengths can be easily rearranged such that contiguous sets of wavelengths can be allocated to *Type*2 and *Type*1 node pairs which need to share the same set of wavelengths. Node pair 2 is assigned $d_3 + 1$ to $\min(d_3 + d_1 + d2, W)$ on its route 2 and d_2 wavelengths on its route 1. Hence, node pair 2 is of *Type*2 in its route 2, as it shares wavelengths with a *Type*1 node pair 1, and is of *Type*1 on its route 1. We will assume that, the LP solves a demand matrix that is feasible for the ILP.

We develop the LP formulation in the next subsection.

5.3.2 LP Formulation

The LP relaxation of the ILP formulation is developed in this section. The ILP formulation was presented earlier in Section 4.3.1.1, Chapter 4. In the formulation $lmin[i, r]$ and $lmax[i, r]$ denote the range of wavelengths assigned for node pair i on routes $r = 1, 2$.

Minimize

$$\sum_{i=1}^{N(N-1)} \sum_{p=lmin[i,1]}^{lmax[i,1]} \delta^{i,p} \sum_{l=1}^{L} \epsilon_l^{i,p} C_l$$

$$+ \sum_{i=1}^{N(N-1)} \sum_{p=lmin[i,2]}^{lmax[i,2]} \delta^{i,p} \sum_{l=1}^{L} \epsilon_l^{i,p} C_l + \sum_{l=1}^{L} \sum_{\lambda=1}^{W} (-1 * g_{l,\lambda}) C_l$$

$$+ \sum_{i=1}^{N(N-1)} \sum_{p=lmin[i,1]}^{lmax[i,1]} \chi^{i,p}(1 - \delta^{i,p}) C_w$$

$$+ \sum_{i=1}^{N(N-1)} \sum_{p=lmin[i,2]}^{lmax[i,2]} \chi^{i,p}(1 - \delta^{i,p}) C_w \qquad (5.1)$$

Demand constraints for each node pair

$$\sum_{p=lmin[i,1]}^{lmax[i,1]} \delta^{i,p} + \sum_{q=lmin[i,2]}^{lmax[i,2]} \delta^{i,q} = d_i \qquad (5.2)$$

$$1 \leq i \leq N(N-1)$$

$$\sum_{p=lmin[i,1]}^{lmax[i,1]} \nu^{i,p} + \sum_{q=lmin[i,2]}^{lmax[i,2]} \nu^{i,q} = d_i \qquad (5.3)$$

$$1 \leq i \leq N(N-1)$$

Restoration path wavelength usage indicator constraint:

$$X_{l,\lambda} = \sum_{i=1}^{N(N-1)} \sum_{r=1}^{KW} \nu^{i,r} \epsilon_l^{i,r} w_\lambda^{i,r} \qquad (5.4)$$

$$2g_{l,\lambda} = X_{l,\lambda} \qquad (5.5)$$

$$1 \leq l \leq L, 1 \leq \lambda \leq W$$

$$0 \leq g_{l,\lambda} \leq 1, X_{l,\lambda} \geq 0, 0 \leq \delta^{i,p}, \nu^{i,p} \leq 1$$

Primary path wavelength usage constraints:

$$\sum_{i=1}^{N(N-1)} \sum_{p=lmin[i,1]}^{lmax[i,1]} \delta^{i,p} \epsilon_l^{i,p} w_\lambda^{i,p}$$

$$+ \sum_{i=1}^{N(N-1)} \sum_{q=lmin[i,2]}^{lmax[i,2]} \delta^{i,q} \epsilon_l^{i,q} w_\lambda^{i,q} + g_{l,\lambda} \leq 1 \qquad (5.6)$$

$$1 \leq l \leq L, 1 \leq \lambda \leq W$$

Constraint to ensure that $Type2$ primary never clashes with $Type1$ backups: For $Type2$ demands on a link l, the following constraint applies. Node pair j belongs to $Type1$. Node pair i belongs to

$Type2$, which shares wavelengths with node pair j. p, r are those paths on the node pairs routes which uses $Bl[i]$

$$\nu^{j,r} + \delta^{i,p} \leq 1 \tag{5.7}$$

We demonstrate that the LP yields a feasible solution based on the following observation. This observation is assumed as the basis for further argument. For a given node pair, the LP formulation has a different cost associated with the primary and backup variables. Also the cost incurred depends only on the route on which the variable's path is present. For a given node pair, if all the LP constraints are being met, the LP will prefer to route the primary variable of a demand on the route which incurs a lesser cost and as long as the constraints are being met, will allocate all primaries on the same route. The same reasoning holds for the backup variables. Thus it can be expected that the primary variables $\delta^{i,p}$ for a particular node pair i take nonzero values only on one route. The same is expected of the backup variables. We state the observation more formally as follows.

Observation 1: The LP has a tendency to group the weights of the variables $\delta^{i,p}$ and $\nu^{i,p}$ for any given i. As a result, for any i,r and $lmin[i,r] \leq p \leq lmax[i,r]$, either all $\delta^{i,p}$ variables have non-zero assignments or all $\nu^{i,p}$ variables have non-zero assignments.

Based on Observation 1, we make claims, which provide insights into why LP formulation yields a feasible solution for the ILP. These claims elucidate the operation of heuristic based on LP relaxation. We now state the claims and provide arguments to support the claims.

Claim 1: The LP solution guarantees integer (binary) assignments for all $Type1$ variables.

Indeed, consider Equations (5.2) and (5.3). They are of the form $A + B = d_i$ and $C + D = d_i$. Terms A, C represent variables on one route and B, D represent variables on the other route. Based on Observation 1, either A or C is zero. Without loss of generality, let the term $C = 0$. This would force $D = d_i$ and hence $B = 0$. We now have $A = d_i$ and $D = d_i$. Recall that for $Type1$ variables, $lmax[i,r] - lmin[i,r] = d_i$. Since $0 \leq \delta^{i,p}, \nu^{i,p} \leq 1$, all the variables in terms A (primary variables) and D (backup variables) are forced to be assigned 1 and all the variables in the other terms are zero.

Claim 2: The LP solution guarantees integer (binary) assignments for all $Type2$ δ variables.

The above claim follows from the following argument. Let node pair i be of $Type1$ and j be of $Type2$. All variables, primary and backup of node pair i, are guaranteed to be binary (Claim 1). Equations (5.2) and (5.3) are of the form $A + B = d_j$ and $C + D = d_j$. Terms A, C represent variables on one route and B, D represent variables on the other route. Without loss of generality, let the term $A = 0$. This would force $B = d_j$, $D = 0$ and $C = d_j$. Recall that for $Type2$

variables. $lmax[i,r] - lmin[i,r] = d_j$ on one of its route and $lmax[i,r] - lmin[i,r] = d_i + d_j$ on its other route. Let B represent variables on route where $d_i + d_j$ has been assigned. d_i out of $d_i + d_j$ belong to $Type1$ variables and are guaranteed to be 1. Equations (5.6) and (5.7) ensure that d_i out of the $d_i + d_j$ variables cannot be used and hence forces the remaining δ variables in term B to be 1. Similar argument can be applied by letting $B = 0$. In this case $A = d_i$ and $lmax[i,1] - lmin[i,1] = d_j$ for A and hence the δ variables are forced to be 1.

Similar argument can be applied for ν variables of $Type2$. When $C = d_j$ and $lmax[i,1] - lmin[i,1] = d_j$ for that route and ν variables in C are forced to be 1. Suppose if $D = d_j$ and $lmax[i,2] - lmin[i,2] = d_i + d_j$, then there are two cases. If d_i were primaries, then Equation (5.7) forces the variables in D to be 1. However, if d_i were backups, then we have $d_i + d_j$ variables and d_j capacity to fill. In this one case the assignments may be fractional. This case is still acceptable because these violations occur only when $Type1$ backups and $Type2$ backups share the link on the route and since we allow this case for backup multiplexing, we might be able to reclaim resources by adjusting the fractional flows of $Type2$ to be 1 and make it coincide with the backups of $Type1$.

We now proceed with the LP formulation. In the ILP formulation, $g_{l,\lambda}$ takes a value one or zero. We should find a way to identify that a wavelength λ is being used as a backup or else Equation (5.6) will be violated and primary and backup path may end up using the same wavelength on a link.

We have to appropriately modify $g_{l,\lambda}$ for the LP and make it choose a higher value whenever a wavelength on a link is used for backup. Recall rules 2.iii.A,2.iii.B in the heuristic algorithm, which state that every $Type1$ node pair can have exactly one $Type2$ pair sharing wavelengths with it. If more than one such $Type2$ pair exists on the link, for every $Type1$, then the demands belonging to those node pairs are removed. The problem is solved for only one set of interacting demands at a time and the multi-step procedure for such a solution and its implications are discussed in Section 5.3.3. Since only one $Type2$ demand is allowed to share wavelengths with a $Type1$ demands, the value of $X_{l,\lambda}$, which counts the number of backup paths that share a wavelength λ on link l, can be either zero (if the path is not used for backup), 1 (one backup path), or 2 (if two paths share this link l and wavelength λ, as backup). Equation (4.3) of the ILP is modified as shown in Equation (5.5).

Since $X_{l,\lambda}$ can take values 0,1, or 2 (enforced by rules 2.iii.A,2.iii.B), $g_{l,\lambda}$ in Equation (5.5), can take values 0, 0.5, or 1 respectively. In the ILP formulation, $g_{l,\lambda}$ is guaranteed to be 1 or 0. In the LP formulation, this cannot be captured exactly. Since $g_{l,\lambda} = 0.5$ implies that only one backup path uses link l and wavelength λ, $g_{l,\lambda} = 1$ implies that two backup paths share link l and wavelength

λ, we can modify the objective to make it favor cases when $g_{l,\lambda} = 1$. This formulation is not exact, since the cost of two backup paths sharing link l and wavelength λ ($g_{l,\lambda} = 1$), is the same as using 2 different wavelengths for backup ($2 * g_{l,\lambda} = 1$). The modified objective is shown Equation (5.1). Equations (4.5) and (4.9), representing link capacity constraint and backup multiplexing constraint of the ILP, are no longer constraints in the LP formulation, as these constraints are ensured in the pre-processing step.

5.3.3 Solving for Excess Demands

As explained in the previous subsection, every $Type1$ node pair can have exactly one $Type2$ pair sharing wavelengths with it. If more than one such $Type2$ pair exists on the link, for every $Type1$, then the demands belonging to those node pairs are removed. In such cases, the problem is solved for one set of interacting demands at a time. We propose a multistage approach to solving this problem. We used a similar approach as already discussed in Section 4.5, Chapter 4. At each stage, one instance of the problem is solved, for one set of interacting demands, and the result is used in successive stages. If the problems are solved independently, the resulting solution may be infeasible, as the same path might be used by multiple primaries or backups. In order to avoid infeasibility, we feed the information about one stage to the next through the X^{cp} variable. Typically, this variable is used to feed information about existing paths to avoid service disruption. We exploit this aspect of our formulation by feeding the solution of one stage to the next. The objective function is modified to include backups chosen during one stage to be fed to the next. This feature is exploited only to make sure that assignments are binary. However, there may be a penalty for this type of solution, first because the problem is solved sequentially and is not shown the full solution space, the result may be sub optimal. Secondly, depending on the solution from one stage, some demands may be blocked.

5.4 Results

5.4.1 Experimental Design

We use CPLEX Linear Optimizer 7.0 [47] to solve the ILP and the LP formulations. The experiments were run on a Pentium III 500 MHz processor with 256MB RAM (note that the solution to the optimization problem is both cpu and memory intensive). This data is provided for the results on run times of our algorithm presented later in this section. We ran our experiments on

Table 5.1 Illustrative example

Node pair	Alternate routes
1	1 2
	1 3 2
27	3 1
	3 2 1
110	9 4 5 6
	9 12 13 6
167	13 6 11
	13 12 10 11
32	3 6 5 7
	3 2 8 7

the 14 node 21 link NSFNET topology (shown in Figure 4.1) and the 20 node 32 link ARPANET topology (shown in Figure 4.2).

The following experiments are presented in the remainder of this section. We present sample results, which provide insight into the working and quality of our LP formulation is presented in Section 5.4.2. The complexity of the optimization problem makes the ILP solution intractable for large problem instances. This effect is sometimes seen for small problem instances. In Section 5.4.3, we compare run times for the ILP and LP solutions for small problem instances. Finally, for large problem instances, we demonstrate the run time of our LP heuristic algorithm in Section 5.4.4. The LP heuristic algorithm yielded a feasible solution in all the experiments presented in this section.

5.4.2 Insights into the Working and Quality of the LP heuristic Algorithm

Consider the node pairs and their two alternate routes shown in Table 5.1. Let the number of wavelengths per link be 10. Let the node pairs, in this example, require 5 primaries and 5 backups. Since we have restriction in our model that only one $Type2$ node pair can share wavelengths with a $Type1$ node pair on a link, demand requests for node pair 32 are removed in the first stage. The results of the ILP and the LP are shown in Table 5.2 and Table 5.3, respectively.

The ILP solution assigns backups for demands belonging to node pairs 1 and 27 in the route which has the common link $3 \rightarrow 2$ and similarly assigns backups for demands belonging to node pairs 110 and 167 on the route that has the common link $13 \rightarrow 6$. The primary paths were assigned as shown in the table 5.2. Now, let us compare the LP solution in Table 5.3. Since the cost of two backup paths sharing a link and wavelength is the same as using two different wavelengths for

Table 5.2 ILP Solution (5 demand requests/node pair, 10W/Link)

Node pair	Alternate routes	Primary	Backup
1	1 2	$\lambda_1 - \lambda_5$	-
	1 3 2	-	$\lambda_1 - \lambda_5$
27	3 1	$\lambda_1 - \lambda_5$	-
	3 2 1	-	$\lambda_1 - \lambda_5$
110	9 4 5 6	$\lambda_1 - \lambda_5$	-
	9 12 13 6	-	$\lambda_1 - \lambda_5$
167	13 6 11	-	$\lambda_1 - \lambda_5$
	13 12 10 11	$\lambda_1 - \lambda_5$	-
32	3 6 5 7	$\lambda_1 - \lambda_5$	-
	3 2 8 7	-	$\lambda_1 - \lambda_5$

Table 5.3 LP Solution (5 demand requests/node pair, 10W/Link)

Node pair	Alternate routes	Primary	Backup
1	1 2	$\lambda_1 - \lambda_5$	-
	1 3 2	-	$\lambda_1 - \lambda_5$
27	3 1	$\lambda_1 - \lambda_5$	-
	3 2 1	-	$\lambda_5 - \lambda_9$
110	9 4 5 6	$\lambda_1 - \lambda_5$	-
	9 12 13 6	-	$\lambda_1 - \lambda_5$
167	13 6 11	$\lambda_1 - \lambda_5$	-
	13 12 10 11	-	$\lambda_1 - \lambda_5$
32	3 6 5 7	$\lambda_1 - \lambda_5$	-
	3 2 8 7	-	$\lambda_1 - \lambda_5$

Table 5.4 LP/ILP Solution (10 demand requests/node pair, 10W/Link)

Node pair	Alternate routes	Primary	Backup
1	1 2	$\lambda_1 - \lambda_{10}$	-
	1 3 2	-	$\lambda_1 - \lambda_{10}$
27	3 1	$\lambda_1 - \lambda_{10}$	-
	3 2 1	-	$\lambda_1 - \lambda_{10}$
110	9 4 5 6	$\lambda_1 - \lambda_{10}$	-
	9 12 13 6	-	$\lambda_1 - \lambda_{10}$
167	13 6 11	-	$\lambda_1 - \lambda_{10}$
	13 12 10 11	$\lambda_1 - \lambda_{10}$	-

backup (refer to discussion on $g_{l,\lambda}$ in Section 5.3.2), the backup wavelength assignment is different from the ILP assignment. As in the case of the ILP solution, the backups for demands belonging to node pairs 1 and 27 are assigned on the route which has the common link $3 \rightarrow 2$. But the wavelength assignment for backups is different. The backup paths for node pair 1 were assigned on route $1 \rightarrow 3 \rightarrow 2$ on wavelengths $\lambda_1 - \lambda_5$, and backups for node pair 27 were assigned on route $3 \rightarrow 2 \rightarrow 1$ on wavelengths $\lambda_5 - \lambda_9$. Only one wavelength (λ_5) was used for backup multiplexing, as against all five ($\lambda_1 - \lambda_5$) in the ILP solution. However, once the LP provides this feasible solution, we may, in such cases, merge the backup routes to coincide with backup paths of node pair 1 and reclaim the wavelengths (refer to the discussion in Section 5.3.2 on adjusting $Type2$ backups to coincide with backup paths of its corresponding $Type1$. In this case demands of node pair 1 belong to $Type1$ and those of node pair 27 belong to $Type2$).

For the next set of node pairs, 110 and 167, primary paths for demands belonging to both pairs were chosen on their first route and backup paths on their second route as shown in Table 5.3. Hence, no backup multiplexing was done. This is in contrast with the ILP solution that used the route containing the common link $13 \rightarrow 6$ for routing backups and as a result could backup multiplex the demand requests of node pairs 110 and 167.

In the above example, node pair 32 has to be solved in the next stage. In such cases, the solution from the first stage is fed to the second stage as currently working primary and backup paths. In this example we considered, since the LP chose the backup routes for node pairs 1 and 27 on the route which uses link $3 \rightarrow 2$, all the requests for node pair 32 were accommodated with the primary and backup route and wavelength assignments as shown in Table 5.3. Although, the demands for node pair 32 were accommodated in this example, there is no guarantee that all the demands will be accepted for node pairs that are solved in successive stages. Thus, there may be a penalty for solving the problem sequentially as discussed in Section 5.3.3.

Table 5.5 Sample results demonstrating the quality of the LP solution

Demands	ILP Objective	LP Objective
10	38	43
20	76	90
30	114	120
40	152	156
50	190	190

Now suppose the node pairs required 10 demands each instead of 5 demands as in the previous case. The solution for the LP and ILP for this case is same and is shown in Table 5.4. The LP in this situation, to accommodate all demand requests, is forced to backup multiplex all possible demands, and thus yields an optimal solution. It is well known that if the LP relaxation to the ILP provides a solution that is an integer vector, then the solution is feasible and hence optimal to the ILP [51]. This is the reason for the LP providing an optimal and a feasible solution to the ILP in this case, as the LP solution vector is forced to be integer in such cases. This behavior is demonstrated in Table 5.5. The results are run on the NSFNET topology with 10 wavelengths per link, for the example in Table 5.1, with demand requests distributed uniformly across 5 node pairs. As explained earlier, the reason why the LP yields an optimal and a feasible solution to the ILP as the number of demand requests per node pair increase (comparable to the capacity on the link), is due to the fact that the LP solution vector is forced to be integer in such cases.

5.4.3 Comparing ILP and LP Solution Run times

The complexity of the optimization problem makes the ILP solution intractable for large problem instances. This effect is sometimes seen for small problem instances. The ILP and LP solution run time comparison is shown in Table 5.6. In the table PT and FT denotes partial and full terminations. CPLEX terminates mixed integer optimizations under a variety of circumstances [47]. CPLEX will find an integer optimal solution and terminates when all nodes have been processed. Optimality in this case is relative to the tolerances and other optimality criteria set by the user. The default relative optimality tolerance is 0.0001 in which case the final integer solution is guaranteed to be within 0.01% (default mipgap in CPLEX) of the optimal value. Many formulations do not require such tight tolerances. Requiring CPLEX to seek integer solutions that meet 0.01% tolerance in such cases is wasted computation time. In our case, to make the comparison fair, we report results when the mipgap is around 3-5%. The problem could be terminated when the mipgap reaches within a desired value. As the results show, the LP solution time is considerably less for

Table 5.6 Comparing ILP and LP solution run times

Demands	ILP Time (in secs) (PT)	ILP Time in secs (FT)	LP Time (in secs)
22	601 (3.35% mipgap)	>9000	0.12
32	3973 (4.40% mipgap)	>9000	0.11
42	852.31 (4.03% mipgap)	>9000	0.13
52	104.87	104.87	0.14
72	84.00	84.00	0.17
92	20.84 (0.29% mipgap)	8289.76	0.23

Table 5.7 Numerical results for 14 node NSFNET topology with 100 wavelengths per link

Demands	LP Constraints	LP Variables	LP Time (in secs)
100	14029	4280	0.52
150	22029	4520	1.10
200	33229	4760	2.18
250	47629	5000	3.89
300	56429	5160	5.25
400	78829	5480	21.87
500	107629	5800	15.75

this example. In the ILP solution result, the fast run times for the 52, 72 demands as against the slower run times for smaller demand requests is not surprising. The solver performs a lot of preprocessing and depending on how close the initial solution is to the final integer optimal solution, the problem can run that much faster.

5.4.4 Run times for the LP Heuristic Algorithm

We demonstrate the use of our algorithm on practical size backbone networks with hundreds of wavelengths per link. Numerical results for NSFNET and ARPANET topologies, with 100 wavelengths per link are shown in Table 5.7 and Table 5.8, respectively. All the techniques discussed for problem size reduction were applied before the LP was solved. The complexity of the problem is determined by the number of variables and constraints in the formulation. We can see from the results that for large demand sets, the run time of our heuristic algorithm is considerably fast (in order of seconds). This has a great impact on the applicability of our solution for online decision making at various phases in survivable WDM network operation.

Table 5.8 Numerical results for 20 node ARPANET topology with 100 wavelengths per link

Demands	LP Constraints	LP Variables	LP Time (in secs)
100	22117	9880	0.70
200	31767	10360	1.16
300	47817	10840	3.06
400	70267	11320	4.94
500	99117	11800	8.34
600	116767	12120	29.04
700	137617	12440	27.26
800	161667	12760	35.64
900	188917	13080	44.24
1000	219367	13400	30.91

5.5 Discussions

Considerable literature exists in design of survivable WDM networks. In this chapter, our focus is on network operation under dynamic traffic. Once the network is provisioned, the critical issue is how to operate the network in such a way that the network performance is optimized under dynamic traffic. The various operational phases in survivable WDM networks as a single Integer Linear Programming (ILP) optimization problem. This common framework incorporates service disruption. However, the complexity of the optimization problem makes the formulation applicable only for network provisioning and offline reconfiguration. The direct use of this method for online reconfiguration remains limited to small networks with few tens of wavelengths.

We propose a heuristic algorithm based on LP relaxation technique to solve this problem. Since the ILP variables are relaxed, we provide a way to derive a feasible solution from the relaxed problem. The algorithm consists of two steps. In the first step, the network topology is processed based on the demand set to be provisioned. This pre-processing step is done to ensure that the LP yields a feasible solution. The pre-processing step in our algorithm is based on a) the assumption that in a network, two routes between any given node pair are sufficient to provide effective fault tolerance, and b) an observation on the working of the ILP for such networks. In the second step, using the processed topology as input, we formulate and solve the LP problem.

Interestingly, the LP relaxation heuristic yielded a feasible solution to the ILP in all our experiments. We provide insights into why the LP formulation yields a feasible solution to the ILP. The claims we make in the thesis are argued based on the following observation. For demands belonging to a given node pair, the optimization formulation has a tendency to group the primary paths of all demands on one route and the backup paths on the alternate route. We provide arguments to support the observation. Currently, we are working on proving the observation, or alternatively provide conditions under which the observation holds true. We are extending our formulation to accommodate pairs of alternate routes for each node pair, and the optimization problem can be made to choose from such candidate pairs. Our relaxation heuristic can directly be used with optimization formulations that provide such sets of candidate pairs for every node pair.

We presented sample results that provide insight into the working and quality of our LP formulation. We showed that as the number of demand requests per node pair increase (comparable to the capacity on the link), the LP yields an optimal and a feasible solution to the ILP, as the LP solution vector is forced to be integer in such cases. We also provided comparison on the run times of the ILP and the LP solution and the LP solution run time is considerably fast. We demonstrated the use of our algorithm on practical size backbone networks with hundreds of wavelengths per link. We can see from the results that for large demand sets, the run time of our heuristic algorithm is considerably fast (in order of seconds). This has a great impact on the applicability of our solution for online decision making at various phases in survivable WDM network operation.

CHAPTER 6 Dynamic Routing with Partial Information

6.1 Objective

Changing trends in backbone transport networks towards dynamic path provisioning and evolving optical technologies have motivated the study of dynamic routing algorithms in the context of Multi Protocol Label Switching (MPLS) based networks. The main motivation behind such interest is the functional similarity between setting up wavelength switched paths and MPLS label-switched paths (LSP). Recent proposals have tried to define a single control-plane for MPLS and optical channel routing [28]. Several methods have been proposed for joint optimization of working and spare capacity in survivable optical networks. These techniques are centralized and do not scale well as they rely on per-flow information. This motivates the need for developing a) distributed algorithms with complete information, b) source based algorithms with partial information. This information can be easily obtained from traffic engineering extensions to routing protocols. Since our algorithms use partial aggregate information, instead of complete information, the algorithms are already restricted in the amount of knowledge available for routing. Hence we employ a link state based approach for network state collection. Recently, proposals have been made to use OSPF-like link state discovery and MPLS signaling, in optical networks, to dynamically setup wavelength paths[28, 55].

In this chapter, we develop dynamic algorithms for source based routing with partial information. The algorithms are classified based on the path selection approach used for the primary path. We compare the performance of various routing algorithms through simulation studies, based on metrics such as the call blocking probability, average path length of an accepted connections, capacity redundancy, and effective network utilization. Our studies show that dynamic routing algorithms perform better than static routing algorithms using pre-computed paths even when the path selection in static algorithms is based on optimizing a global network metric. The other interesting observation we make is that the performance improvement of dynamic routing algorithms using K pre-computed paths is significant even for small values of K.

Outline of the Chapter:

This chapter is organized as follows. Section 6.1.1 reviews related work on dynamic algorithms in wavelength-routed networks. We introduce various heuristic algorithms for dynamic routing, which work with partial information, and discuss performance metrics in Section 6.2. The performances of the different approaches are evaluated and compared in Section 6.3. Section 6.4 presents our conclusions and discusses further improvements based on our observations.

6.1.1 Related Work

Dynamic routing in wavelength-routed WDM networks has been studied extensively in the literature[26, 56]. The following studies are most relevant to the algorithms developed in this chapter.

The study in [57], investigates the influence of end-to-end protection on the wavelength conversion gain under dynamic traffic conditions. Dedicated and shared protection approaches are compared and three routing algorithms are analyzed. Fixed alternate path routing (FAPR) has been studied in [58] and [59]. Fixed-path least-congestion routing (FPLCR) has been analyzed in [60]. In these approaches, a path from a source to destination is selected from a set of pre-computed paths. While FAPR attempts the paths in a specified order, FPLCR uses some knowledge of the network state and selects the least loaded path. In [61], alternate link routing (ALR) is proposed. In this approach, a pre-computed set of preferred links to reach a destination is available at every node. A request is forwarded on any one of the preferred outgoing links to the destination. A methodology for dynamic routing in WDM grooming networks is developed in [62]. The effect of dispersity routing, where higher capacity requests are broken into multiple unit capacity requests, is also studied.

Routing dependable connections under dynamic traffic was studied extensively in [63]. They introduced a primary-backup multiplexing technique to significantly improve network blocking performance at the cost of an acceptable reduction in restoration guarantee. The work in [55], describes an architecture and analyzes the performance of dynamic provisioning of lightpaths. Performance studies indicate significant gains as a result of wavelength sharing even in sparse meshed networks, and even at moderate loads. The study in [64], addresses the problem of dynamically establishing dependable low-rate traffic stream connections in WDM mesh networks with traffic grooming capabilities. A dynamic algorithm is also presented to obtain the optimal spare capacity on a wavelength on a link when a number of backup traffic streams are multiplexed onto it. Dynamic routing of restorable bandwidth guaranteed tunnels is studied in [65]. They study dynamic routing under three information scenarios: none, complete and partial information routing. Our algorithm uses the partial information model used in [65]. An online network-control mechanism to manage connections in a network employing path protection schemes is presented in [56]. A discussion on RWA algorithms, network state updates, protection schemes, and signaling for path setup and fault recovery is also presented.

6.2 Dynamic Routing with Partial Information

In this section, we present a framework for dynamic routing of primary and backup connections and propose various routing algorithms. We modified the framework presented in [62] for partial information routing.

6.2.1 Framework for dynamic routing

Every link in the network is denoted by a *link-state vector*. The vector consists of a set of properties associated with a link, eg. available bandwidth, primary capacity, backup capacity, hop-length, fiber length etc. Each entity in the vector is referred to as a *metric*. Every path from a source to destination has a *path-vector* that is obtained by combining the link-state vectors of the links in the path. Note that the link vector is a special case of a path vector when the path has only one link.

In WDM networks, the metrics can be classified either as path-specific or wavelength-specific. Path-specific metrics are those metrics that depend only on the route from a source to destination and are independent of the wavelength used. One example of path metric is the hop-length. The usage of a wavelength as a primary or backup on a link is an example of a wavelength-specific metric. A metric is said to be *concave* if its value in a path vector is the minimum among the corresponding metrics on the individual links of the path, *additive* if its value in a path vector is the sum of the corresponding metrics of the individual links in the path, *multiplicative* if its value in a path vector is the product of the corresponding metrics on individual links. Various dynamic path selection algorithms can be developed based on the above specified metrics.

Every node in the network is assumed to maintain the global state information through a link-state protocol. The information available for each link (i, j) is the status of each wavelength, set to 1 if used as a primary, 0 if used as backup, and -1 if available. For a wavelength-routed network, this translates to aggregate bandwidth usage on each link by primary paths denoted by

α_{ij}, backup paths denoted by β_{ij}, and available residual capacity denoted by r_{ij}. We also assume that there is a count per wavelength when used as a backup, indicating the number of flows using the wavelength for backup. This partial information scenario is depicted in Figure 6.1. Note that, although we know if a wavelength is used as a primary or backup, we still do not know which node pair's flow is using the wavelength as a primary, or which flows are sharing the wavelength for backup. This information is usually available for any routing algorithm working with complete information. Such algorithms can efficiently backup multiplex wavelengths while ensuring 100% protection guarantee. Since we are working with partial information, we need to optimally route requests while ensuring 100% protection guarantee.

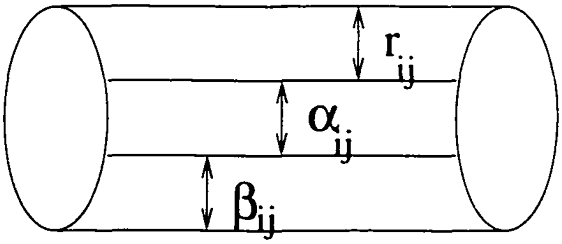
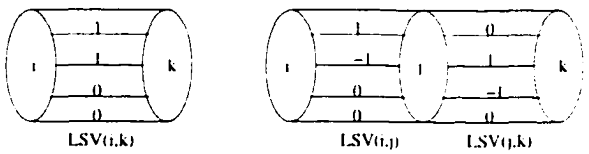


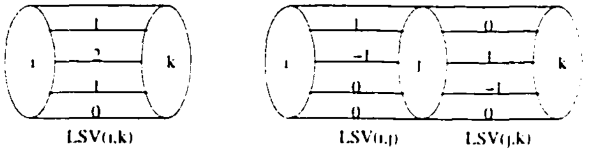
Figure 6.1 Partial information: aggregate bandwidth usage

Dijkstra's shortest path algorithm is extended to the above link-state vector, referred to as extended Dijkstra's shortest path (EDSP) algorithm, and is employed at every node in the network. The EDSP algorithm uses the link-state vector as defined above instead of a single metric that is traditionally used. The EDSP algorithm has two important operations: (1) combining two path vectors and (2) selecting the best path vector. A path vector is a combination of link state vectors. The various combine functions are described later in the section. We will illustrate the path vector combine function using an example shown in Figure 6.2.

As defined earlier, associated with each wavelength in a link-state vector lsvij is a status variable which is set to 1 if used as a primary, 0 if used as backup, and -1 if available. By examining each lsv, we can determine the total primary wavelengths by adding all the wavelengths whose status value is 1, the total backup wavelengths by adding wavelengths whose status value is 0, and total available wavelengths by adding wavelengths whose status value is -1. Although a status variable is indexed and maintained for each wavelength in a link, in the discussions to follow, we use a generic status variable to represent all wavelengths. If the combine function is the maximum



a) lsvik = max(lsvij.Status,lsvjk.Status)



b) lsvik = abs(lsvij.Status)+abs(lsvjk.Status)

Figure 6.2 Combine function for two path vectors

of the status variables, i.e., $lsv_{ik}.Status = max(lsv_{ij}.Status, lsv_{jk}.Status)$. By examining the combined $lsv_{ik}.Status$ as shown in Figure 6.2a, the following information can be obtained. Since we are interested in wavelength continuous paths, any wavelength λ whose status in the combined lsv is 1 cannot be used as there is atleast one link in the corresponding wavelength continuous path where λ is being used as a primary wavelength. Any λ whose status in the combined lsv is -1 means the wavelength continuous path corresponding to λ is available on all links on the path. Similarly, any λ whose status in the combined lsv is 0 means the wavelength continuous path has λ either being used as a backup or is available. Therefore, to check if a wavelength continuous path can be established or not, it is sufficient to check the status of the wavelengths in the combined path vector.

The second operation of selecting the best path vector from a given set of path vectors is defined by a specific path selection policy. For example, the traditional shortest path algorithm selects a path with minimum hop length. To understand how different combine functions have different effects on the path selection, and hence the routing algorithm, refer to Figure 6.2. Let us assume that we would like to choose a path which has maximum number of backups (already reserved) available. If we use the combine function in Figure 6.2a, we will get paths where, in the worst case only one link along the path has the corresponding wavelength being used as backup and on all other links the wavelength is available. In such a scenario, once the path is selected we need to reserve capacity on all links where the wavelength was available. On the other hand, if we assume that the combine function as shown in Figure 6.2b is used, i.e., $lsv_{ik}.Status = abs(lsv_{ij}.Status) + abs(lsv_{jk}.Status)$. Now in this case, as can be seen in the figure, any λ whose status in the combined lsv is 0, means that λ is being used as backup on all links on the path. In such a scenario, once the path is selected, we do not need to make any excess reservations. It is to be noted here that, we merely use the above illustration to explain the process of combine and selection, actual decision on whether we can multiplex a given connection's backup on to an already reserved backup wavelength will depend on whether such an assignment will violate the 100% protection guarantee. We will explain how the algorithms ensure 100% protection guarantee later in the section.

6.2.2 Routing algorithms

We first discuss the basis upon which the routing algorithms are developed. The key is to use the aggregate information in the partial information scenario to obtain significant gains in network performance. Let us assume that the primary path for an arriving request has been selected. The maximum number of primary connections on a link along the path is referred to as the *conflict* created upon routing the current primary connection, inclusive of the primary. Let δ_{ij} be a binary variable which is set to 1 if link ij is being used by the primary path, 0 otherwise. δ_{ij} will be 1 for all links on the primary path. Now find the link on which the primary creates maximum conflict, i.e. $C = \max_{ij} \ \alpha_{ij}\delta_{ij}$. Let ν_{ij} be a binary variable which is set to 1 if link ij is being used by the backup path, 0 otherwise. ν_{ij} will be 1 for all links on the backup path. For any potential backup path which is disjoint from the primary, no additional bandwidth needs to be reserved as long as $\nu_{ij}.\beta_{ij} \geq C$. For any potential backup path which is disjoint from the primary, it is required that the path has atleast C wavelengths that are either available or used as backup. Note that, as explained earlier in the section, this depends on the kind of combine function used. Now suppose if we cannot find C backup wavelengths, then assign one wavelength continuous path without any sharing. It is a fairly simple exercise to see that in both the above cases, 100% protection guarantee is maintained.

We will illustrate this with an example. Figure 6.3 shows the snapshot of a part of the network. Assume that there are two wavelengths λ_1, λ_2 on each link. There are two primary paths P1 and P2 which use, as part of its route, links 2-3 and 2-1 respectively. Assume that a primary path for the new request between (3,1) has been selected to be 3-2-1 (Pnew) on λ_2. Note that the primary wavelengths cannot be shared. The maximum conflict created by Pnew is $C = 2$. Now the claim is that as long as there are C wavelength-continuous backups assigned on the selected backup path for this new request, 100% protection guarantee can be ensured. The other case is to assign one wavelength continuous path on 3-4-1 without any sharing. It is trivial to see that in the

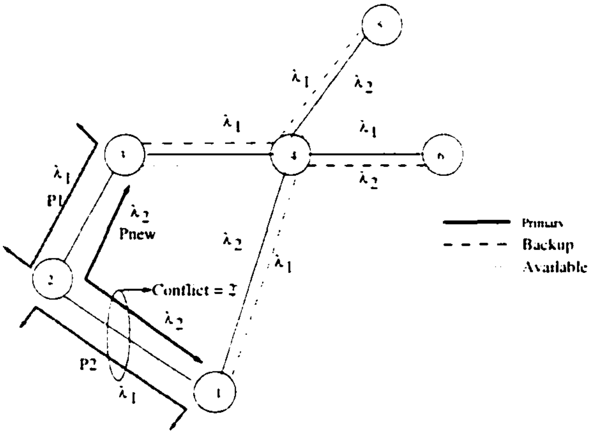


Figure 6.3 Snapshot of a part of the network to illustrate protection guarantee

latter case, since one dedicated wavelength continuous path has been assigned for the new request, 100% guarantee is ensured.

Let us examine the first case of the claim that there are C wavelength-continuous backup paths assigned. Suppose, if it is not the case then it would result in the violation of 100% guarantee. To understand this better consider the example shown in Figure 6.3. Suppose that we were to assign one wavelength continuous path on 3-4-1 using λ_1. Here on both 3-4 and 4-1 λ_1 has been already reserved as backup for some earlier request(s). Assume that the backup path for P2 had been assigned λ_1 on link 3-4. Suppose of link 1-2 fails, both Pnew and P2 contend for the same wavelength λ_1, thereby violating 100% protection guarantee. Note here that instead of λ_1, if we were to assign the backup path for the new request on 3-4-1 using λ_2 which is available on both links, then this becomes a dedicated backup for Pnew and as shown earlier is a trivial case.

It is clear that in some cases, due to lack of information, more backup wavelengths may be reserved than required. In the above example, if P2 were not using any of links 3-4 or 4-1 for backup, we could have assigned the backup path for the new request on 3-4-1, sharing the already reserved wavelength λ_1. The inherent assumption here is that the algorithm had ensured protection guarantee for all earlier requests before the arrival of the new request. This is the best decision that any routing algorithm can make to provide 100% protection guarantee given the partial information scenario. So we need to exploit the excess reservations that may be made in some cases to our advantage by reusing such links where backup wavelength chunks are already available.

It is to be noted that, we need to ensure C wavelength continuous paths, instead of merely checking for C wavelength capacity to be either available or reserved as backup on all links on the backup path. This is because when the backup has to be actually assigned for this request, we may not find a common wavelength that is available on all paths, although the required capacity is present. Although we provide C possible backup wavelengths for some arriving requests, we need to switch the connection onto one specific wavelength when a failure occurs. There are some issues as to the order in which the affected requests pick the backup wavelength to switch to. A wrong assignment here may result in some requests being blocked. This can be avoided by some extra processing to ensure that the switch to the backup path is done without blocking any requests.

The optimality metric for our dynamic algorithm is stated as follows: route the primary on the shortest path, and try to route backup on links where backup wavelengths are already reserved by earlier requests, at the same time ensuring 100% protection guarantee. We develop routing algorithms based on our optimality definition and all the observations discussed earlier in the chapter. All the algorithms are designed to provide 100% protection guarantee. Each of the algorithms have a metric for path selection and a wavelength assignment algorithm. The algorithms are classified based on the path selection approach used for the primary path, as listed below.

Shortest Cycle (SC): This approach uses fixed alternate path routing. For path selection, the shortest vertex disjoint cycle which minimizes the sum of path lengths is chosen. The two vertex disjoint paths are pre-computed using the algorithm in [66]. The primary is routed on the shortest path and the backup on the alternate path. Wavelength sharing is allowed on the backup path.

Shortest Path Unconstrained Primary (SPUP): In this approach, the primary is routed without any constraints on the shortest path. The metric used for routing the backup path is to maximize the minimum backup capacity (MAXMINBACKUP) available. This metric attempts to find a path for which minimum backup capacity available on the path is maximum. This can be achieved using the EDSP framework, by using a minimum metric in the link-state vector combine function for backup capacity, and choosing the maximum value when comparing path vectors to update the Dijkstra cost. The backup is constrained by the fact that the primary has been routed on the shortest path and C conflicts have been created. Now suppose it is not possible to find a backup path that can satisfy the conflict, the algorithm tries to accommodate the request using the SC approach.

Least Conflict Path Unconstrained Primary (LCPUP): The primary is routed using the least conflict path, i.e., minimize the maximum conflict created on the primary path. This is achieved in the EDSP framework, by using a maximum metric in the link-state vector combine function for primary capacity, and choosing the minimum value when comparing path vectors to update the Dijkstra cost. The backup path as in the SPUP approach is chosen using the MAXMINBACKUP metric.

K Shortest Paths (KSP): In this approach, K shortest paths are pre-computed for each node pair. The routing algorithm employs SPUP approach for each of the K paths, and chooses the one that minimizes some chosen network metric. Unlike the SPUP approach, if for any path ik on which the primary is assumed to be routed, if it cannot find C conflict backups, it merely skips and proceeds with the next shortest path. Some good network metrics include minimizing the total wavelength miles consumed, or minimizing the maximum link utilization. Since this approach tries to minimize a global network metric, and has a choice of paths to choose from, it is expected to work the best. We use this algorithm mainly to draw comparisons to other approaches.

The key aspect in all these algorithms is to exploit the excess reservations that may be made in some cases to our advantage by reusing the already reserved backup capacity. As a result, it makes sense not to fragment the primary and backup wavelengths, as it may prove difficult to find wavelength continuous paths. Random wavelength assignment policy will prove to be detrimental in this scenario. To reduce such fragmentation in the algorithms, We use FirstFit wavelength assignment policy. Primary paths use FirstFitDescending, by arranging wavelengths in descending order and picking the first wavelength that is available. Backup paths use FirstFitAscending, by arranging wavelengths in ascending order and picking the first wavelength that is available.

Each approach works on different aspects of the optimality definition. For example SC would try to assign requests on shortest cycle, but may not be able to perform efficient sharing of backup wavelengths. A metric like SPUP may gain initially by providing primary on shortest path and share a backup on some longer path. However, as requests which share wavelengths on the longer paths leave, it might end up using extra resources. Thus it is clear that each algorithm tries to arrive at a tradeoff on optimal routing. In the next section, we will evaluate and compare the performance of these different approaches.

6.3 Performance Evaluation

The performance of the algorithms described in the previous section are evaluated on the 14 node 22 link NSFNet network topology, shown in Figure 4.1. When a request arrives at a node, primary and backup paths are chosen using the above mentioned routing algorithms. FirstFit wavelength allocation policy is used for both primary and backup paths, with primary choosing from wavelengths in descending order, and backup in ascending order.

6.3.1 Experimental setup

The experimental setup for the simulation is based on the following assumptions: (1)The arrival of requests at a node follows a Poisson process with rate λ and are equally likely to be destined to any other node; (2) The holding time of the requests follow an exponential distribution with unit mean; (3) The capacity requirement of a request is restricted to a full wavelength; and (4) Every link has 32 wavelengths.

The requests are generated independently at a rate of $N\lambda$, where N denotes the number of nodes in the network. The requests are equally likely to have any of the N nodes as its source. The generated requests are fed to the different networks running in parallel and their performances are measured. A total of 5×10^5 requests were generated with performance metrics being measured in batches of 10^5 requests. The average of the performance metrics over observed five set of values are reported in the results.

6.3.2 Performance metrics

The performance metrics measured are the request blocking probability, average path length of an accepted connection(Z), redundancy, and network utilization (η). Since every request is assigned a primary and a backup path, and since the network revenue is gained as a result of accepting more primaries, and the backup capacity is idle until a failure occurs, all the measurements and performance comparisons are made specific to the primary paths.

The blocking probability is computed as the ratio of the number of blocked requests to the total number of requests generated. Z is computed as the average of the length of the primary paths assigned to the accepted requests by a specific routing algorithm. Redundancy is defined as the ratio of total spare to working capacity in the network.

The *network utilization* is computed by assigning an effective network capacity requirement for a request. A request r for capacity b from source s to destination d has an effective capacity requirement of $b \times h_s$, where h_s is the shortest path length from the source to the destination. This effective capacity requirement of a request is the minimum capacity that is required in the network to support the request, irrespective of the routing algorithm. If a routing algorithm selects a path of length h for the connection, $b(h - h_s)$ denotes the additional capacity used by the network to support the connection.

The effective network capacity utilized at an instant of time, denoted by U, is defined as the sum of the effective network primary capacity requirement of all the connections that are active at that instant. The value of U at any instant of time is bounded by $L \times C$, where L is the total number of links in the network and C is the capacity on each link. The network utilization is then computed as the ratio of the effective used capacity to the maximum capacity of the network as $\eta = \frac{U}{L \times C}$.

6.3.3 Results and discussion

The blocking performance of various routing algorithms versus the total arrival rate of requests for the NSFNet network with 32 wavelengths is shown in Figure 6.4. We observe that LCPUP performs the best. The SC algorithm performs the worst. Although the SC algorithm allocates the primary on the shortest path, it does not have much choice on the selection of the backup path. As a result it is constrained, hence performs poorly. The SPUP algorithm which fixes the primary to the shortest path but has a choice of selecting the best backup path, still performs very close to SC. The gain is small, with less than 2% improvement in blocking performance. This is because both these algorithms restrict the primary connection to the shortest path. As a result both these approaches create similar conflict values, and since SPUP has a choice of selecting the best backup path available, it performs slightly better than SC. LCPUP which routes the primary on the least conflict path and selects the backup based on the MAXMINBACKUP metric, performs the best. However, as the load increases longer calls are blocked and primary paths are restricted to being close to shortest path lengths, the performance of all the algorithms converge.

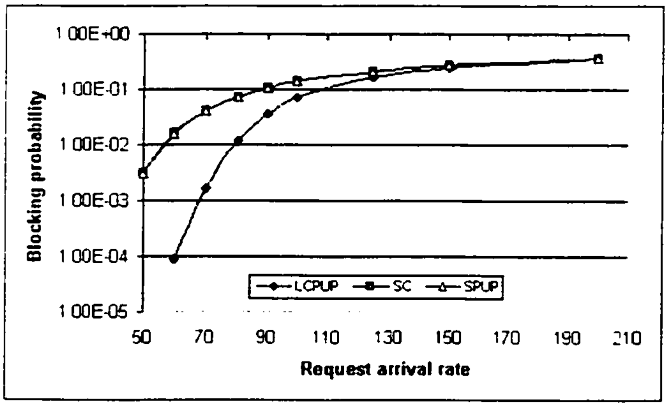


Figure 6.4 Blocking performance of various routing algorithms

Figure 6.5 shows the average primary path length of the accepted connections. The average primary path length of LCPUP algorithm is greater than those of SC and SPUP. The average primary path lengths of SC and SPUP are almost the same. The reason they are not exactly the same, although both route primary on the shortest path. This is because there is a slight difference in the number of requests admitted by both routing algorithms and the average is computed for only accepted connections. This trend confirms the fact seen in Figure 6.4. Since LCPUP is able to route primary path through least conflict longer paths, it is able to improve the overall blocking. Average primary path length of LCPUP is almost 17% greater than those of SC and SPUP.

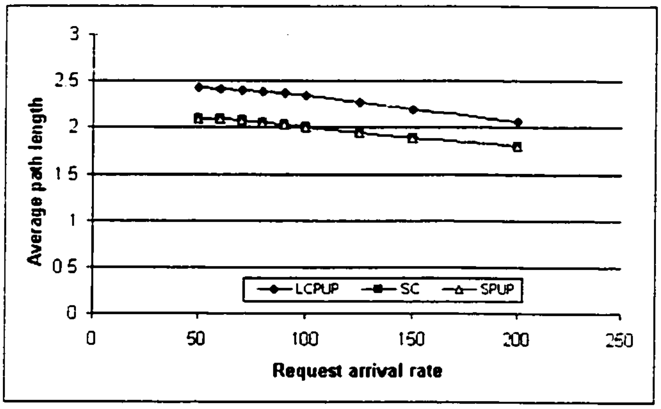


Figure 6.5 Average primary path length of accepted requests under different routing algorithms

These trends are similar under the effective network utilization performance metric as can be seen in Figure 6.6. Note that although there is significant improvement in blocking for LCPUP, the improvement in effective network utilization is only 8%. As explained earlier, the effective capacity requirement for any request is computed based on the minimum capacity that is required to support the request (based on shortest path length), irrespective of the routing algorithm. As a result LCPUP, which routes on a longer paths, consumes additional capacity than required and hence does not gain much in this metric.

The redundancy, which is a ratio of the total spare to total working capacity in the network, is plotted for various routing algorithms in Figure 6.7. The more the redundancy the worse the blocking performance, since this capacity can otherwise be used to accommodate more requests. SC is almost similar to dedicated protection. This is because although we allow backup wavelength sharing for SC, the paths are still restricted. As a result it performs the worst in redundancy and

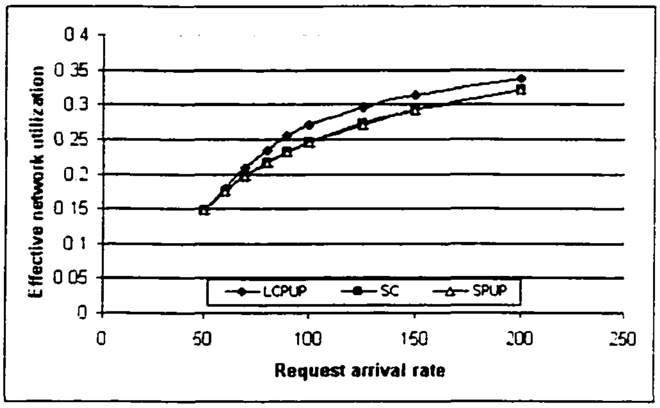


Figure 6.6 Network utilization under different routing algorithms

hence worst in blocking performance as seen earlier. SPUP which is an improvement over SC still performs poorly for the same reasons stated above. LCPUP has the best redundancy over all. One interesting aspect to note here is that even for LCPUP, redundancy is still greater than 100%. Typical path protection algorithms perform very efficiently with almost 50% redundancy. But they work with complete per-flow information. The routing algorithms developed in this chapter work under the partial information scenario, and so the performance is expected to be worse when compared to algorithms which have complete information.

To confirm the trends observed and to demonstrate the effectiveness of the LCPUP algorithm, we compare these algorithms with KSP routing algorithm. The results comparing SPUP and LCPUP with KSP routing algorithm for different values of K are shown in Figure 6.8. In the KSP approach, we minimize the total wavelength miles. Surprisingly LCPUP still performs the best in terms of blocking performance, although under heavy loads, KSP with K=10 outperforms LCPUP slightly. This is because, under heavy loads longer paths are typically blocked, and given that path selection has to be made using shorter paths, KSP, which explores over all possible K paths and chooses based on minimum wavelength usage, performs better. Thus the dynamic algorithm LCPUP performs better as compared to static algorithms using pre-computed paths, even when the path selection is based on current network state.

Note that SPUP is provided with more paths with increasing values of K. This results in better performance. This effect is seen for values of K as small as 3 or 5. Although the set of 3 or 5 pre-computed paths might look restrictive, it is interesting to note that even for such small values

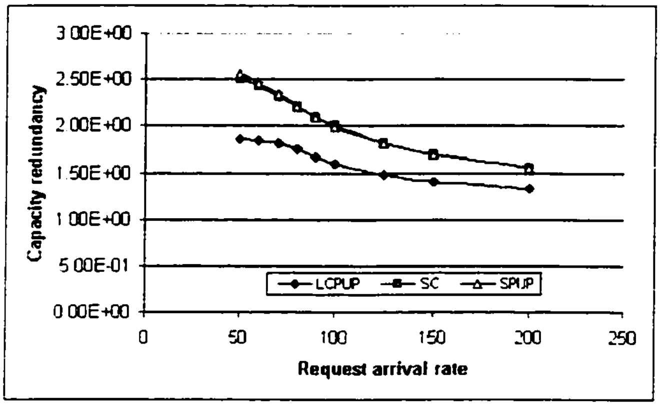


Figure 6.7 Redundancy of various routing algorithms

the performance improvements are fairly significant.

6.4 Discussions

In this chapter, we develop source based algorithms with partial information. This information can be easily obtained from traffic engineering extensions to routing protocols. The algorithms differ on the path selection approach used for the primary path. We compare the performance of various routing algorithms through simulation studies based on metrics such as the call blocking probability, average path length of an accepted connections, capacity redundancy, and effective network utilization.

Our studies show that dynamic routing algorithms perform better than static routing algorithms using pre-computed paths, even when the path selection in static algorithms is based on current network state. The other interesting observation we make is that the performance improvement of dynamic routing algorithms using K pre-computed paths is significant even for small values of K.

Currently, we are working on an integer programming based formulation for capacity optimization in the partial information scenario to provide theoretical basis for the simulation studies carried out in this chapter.

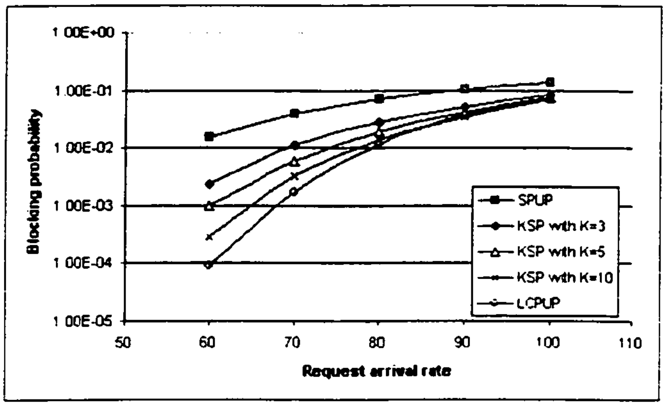


Figure 6.8 Blocking performance improvements for KSP routing algorithm

CHAPTER 7 Conclusions and Future Directions

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 becomes indispensable in such networks. The primary focus of this dissertation is the design and operation of survivable optical networks.

In long haul networks the greater distance related cost makes capacity efficiency much more important. Thus, there is continued interest in the design and operation of mesh-restorable backbone networks. In Chapter 3, we developed a integer programming based design scheme for WDM network design and provided 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. The meaning in this case is 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 and for different economy-of-scale values. In order to make the problem more tractable, we made the assumption that the shortest route between two end nodes is the most cost effective to route demands and hence the working capacity can be pre-assigned. Although this assumption greatly simplifies the problem formulation, there may arise situations when all the links in the final topology are automatically active when we pre-assign working capacity on the shortest path. To avoid such instances, we have developed a generalized formulation that can handle multiple path choices for assigning working capacity, and can dynamically compute backup multiplexing conflicts. However this formulation is fairly complex and we are working on simulated annealing heuristics to simplify the design problem. It is to be noted that the design formulation presented in this chapter can be easily extended to accommodate K= 2 or 3 shortest paths for assigning working capacity instead of pre-assigning on the shortest path. The backup conflicts can be handled by explicitly checking for the primary in one of these K paths.

In Chapter 4, we considered two important objectives of network operation: (i) capacity minimization and (ii) revenue maximization. We formulated three phases in survivable WDM network operation viz., initial call set up, short/medium-term reconfiguration, and long-term reconfiguration. All three phases are derived from a single integer linear programming formulation. This common framework includes service disruption. We modified the framework for revenue maximization, which includes a service differentiation model based on lightpath protection. The combined problem for solving demands from various service classes can be quite complex. We proposed a multistage solution methodology to solve individual service classes sequentially and combine them to obtain a feasible solution. We provided cost comparisons in terms of increase in revenue got by various service classes with the base case of accepting demands without any protection. For particular instances of demands, we see that the best-effort variation 1 results in a 67% gain in revenue and variation 2 achieves an additional 6% gain, for $\alpha = 1$.

However, the complexity of the optimization problem makes the formulation applicable only for network provisioning and offline reconfiguration. The direct use of such methods for online reconfiguration remains limited to small networks with few tens of wavelengths. We develop a heuristic algorithm based on LP relaxation technique for fast, near optimal, online reconfiguration in Chapter 5. Interestingly, the LP relaxation heuristic yielded a feasible solution to the ILP in all our experiments. We provide insights into why the LP formulation yields a feasible solution to the ILP. The claims we make in the thesis are argued based on the following observation. For demands belonging to a given node pair, the optimization formulation has a tendency to group the primary paths of all demands on one route and the backup paths on the alternate route. We provide arguments to support the observation. Currently, we are working on proving the observation, or alternatively provide conditions under which the observation holds true. It is to be noted that our formulation can be extended to accommodate pairs of alternate routes for each node pair, and the optimization problem can be made to choose from such candidate pairs. Our relaxation heuristic can directly be used with optimization formulations that provide such sets of candidate pairs for every node pair.

In Chapter 6, we develop source based algorithms with partial information. This information can be easily obtained from traffic engineering extensions to routing protocols. The algorithms differ on the path selection approach used for the primary path. We compare the performance of various routing algorithms through simulation studies based on metrics such as the call blocking probability, average path length of an accepted connections, capacity redundancy, and effective network utilization. Our studies show that dynamic routing algorithms perform better than static routing algorithms using pre-computed paths, even when the path selection in static algorithms is based on current network state. The other interesting observation we make is that the performance improvement of dynamic routing algorithms using K pre-computed paths is significant even for small values of K. Currently we are working on a generalized framework for partial information routing based on lagrangian relaxation.

APPENDIX A Enabling Technologies

With the widespread deployment of DWDM optical networks with huge transmission capacities, identifying and reacting to failures is an important aspect of network management. In this appendix, we will review the state-of-the-art approaches in optical monitoring technology that is commercially available today.

As the number of wavelengths carried per fiber on a WDM optical network increases, wavelength drifts and power variations are more likely to cause errors in transmission. It is therefore imperative that network management is able to dynamically monitor the performance of optical signals. Conventional optical performance monitoring devices typically measure collective power level provided by all channels. Such a measurement is not very useful, since power levels of different channels can compensate each other, with the total power remaining the same, thus providing inaccurate information about the network performance. Most network monitoring is conducted in the electronic domain, thus in order to monitor individual wavelengths in a DWDM network, optical layer measurements are required.

WDM measurement equipment that directly measure the quality of the optical signal can be divided into the following categories: Individual Testing Equipment (ITE) and Group Testing Equipment (GTE) [67]. ITE devices measure the parameters of a single wavelength or channel. One such example is the network tester ANT-20 [68], which can measure the bit-error-rate (BER). The drawback of such a measurement is the knowledge of the upper layer transmission technology (ATM, SONET/SDH etc). This compromises the transparency advantages in a WDM network.

GTE devices measure the quality of the overall optical signal, which includes the used wavelengths, maximum power of each wavelength, and Signal-to-Noise ratio (SNR) of each channel. Examples of such devices include spectrum analyzers OSP-102A [68] and MON-001 [69]. Other possible monitoring functionalities at higher layers include checksum monitoring at the IP and TCP layers, CRC-10 error detecting code in ATM layer, and forward error control (FEC) mechanisms point-to-point WDM systems [67].

A.0.1 BaySpec's $IntelliGuard^{TM}$

Optical Channel Performance Monitors (OCPM) [70] is an integrated spectrometer module that embraces the essential functions of optical channel monitor (OCM), optical performance monitor (OPM), optical wavelength meter, optical power meter, and spectral analyzer, providing rapid channel identification, and non-invasive wavelength, power and OSNR measurements. The distinction between OCM and OPM is not very well defined [71].

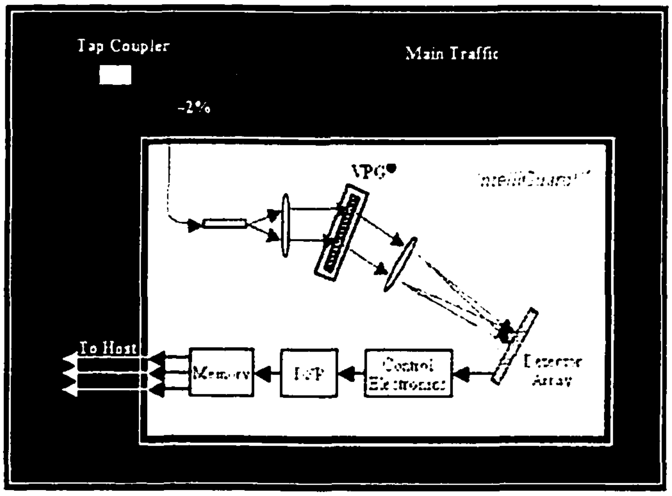


Figure A.1 Schematic operating block diagram of BaySpec's $IntelliGuard^{TM}$ OCPM

The working of BaySpec's $IntelliGuard^{TM}$ OCPM is shown in Figure A.1. From the main data transmission link, a small fraction (typically 2%) is tapped. The weak light is input to OCPM through a single-mode fiber. The control electronics reads out the signal that is then processed by a digital signal processor (DSP) to extract the information.

Functionally, an OCPM should be capable of providing real-time measurements of the wavelengths, powers, and OSNR of all DWDM channels. From these measurements, we will know: 1) channel central wavelengths, 2) central wavelength shifts with respect to the ITU grid, 3) channel powers, 4) channel power distribution, 5) presence of channels, and 6) OSNR of each channel.

A.0.2 Anritsu's Optical Measurement Solutions

Anritsu's [72] MN9320A channel drop unit, precisely extracts individual optical channels from a DWDM signal and feeds them to a data analyzer for analysis. In addition to analyzing each channels power and wavelengths, it also prevents potentially damaging 'hot' signals from being inadvertently transmitted to the analyzer. The MN9320A can scan and drop channels of 50 GHz spacing in the typical 1520nm to 1565 nm C band window at data rates upto 10Gbps.

Measuring the optical amplifier noise figure (NF) and gain in long haul optical networks is of prime importance. Anritsu's ME7890C optical amplifier test system measures the gain and noise figure using an optical pulse probe method ANRITSU-9320 which minimizes the insertion losses.

The optical time domain reflectometer (OTDR) series MW9076 series is used for measuring loss and locating faults in optical fiber cables at fiber installation and maintenance.

The MD6430A network data analyzer can measure errors for a variety of bit rates on a variety of networks. Measurements include bit errors, alarms, delay time, frequency, digital level measurements, user pattern send/trace, etc.

A.0.3 Acterna Remote Monitoring System

Acterna [68] provides for remote web-based network testing combining various digital and optical testers in a single unit. This main features include handling of line rates from 622Mbps to 10Gbps. It also uses a dual port optical spectrum analyzer (OSA 200) for switched DWDM networks. Applications include

- DWDM optical network testing
- SONET/SDH analysis
- Optical spectrum analysis
- Q-factor performance analysis

A.0.4 Optical Path and Crosstalk Monitoring

Recently a study in [75], demonstrated a simple and efficient technique to monitor the optical paths in all-optical WDM transport networks using pilot tones. This technique could also monitor the crosstalk increases caused by the partial failures of optical switches in the optical cross-connects. In addition, unlike the other monitoring techniques based on the pilot tones, their technique was insensitive to the cross-gain modulation of EDFA. The intraband crosstalk measurement within an OXC is a very useful feature to monitor. The crosstalk could be caused by a variety of reasons from a partial switch failure to a malicious user injecting high power to corrupt signals in neighboring channels. However in the experiment, the authors concentrate of crosstalk induced due to partial switch failures.

Other monitors include Yokogawa WDM monitors [73], which monitors wavelength power levels. Agilent's 11896A, a polarization-dependent loss monitor [74].

APPENDIX B Related Work in Mesh-Restorable WDM Optical Networks

B.1 Miyao et al - Joint optimization, Static traffic demand

Miyao et al [21] propose an optimal design scheme for survivable WDM transport networks. In this work, integer programming based design problems are formulated to optimally jointly determine working and their corresponding restoration paths, the number of fibers in each span, and the number of optical crossconnects (OXC) in each node. A span is same as a link when it connects two core node directly without any intermediate through nodes. A core node is one which has atleast one optical crossconnect (OXC) and through nodes are nodes where no OXC is required to reconfigure optical paths as they are in transit and are always routed from one span to another. These optimization problems minimizes the total facility cost which includes the transmission cost and also cross connection.

The restoration model assumes that each path accommodates an OAM (operation, administration, and maintenance) channel terminated by the source destination pair of that path. Some signals such as the alarm indication in case of a network failure can be inserted on this channel by the nodes on the route if necessary. The procedure when a alarm indication signal arrives depends on whether spare wavelengths to setup restoration paths are dedicated or shared with individual s-d pairs whose paths fail independently. This design formulation accounts for multiple network failures. To achieve fast restoration for the shared case, they establish the following requirements. a) A single restoration path is predetermined for each working path on an one-to-one basis. b) A single predetermined restoration path for each working path is independent of the location of failure. c) The wavelengths which have been assigned to each working path which fails will not be released in normal spans on its route. This requirement is included because of restoration paths have been selected by assuming release of these wavelengths in the design phase, the setup of some of the restoration paths might have to be postponed until enough wavelengths become available by releasing wavelengths in the normal spans along the route. One of the variations of their formulation also accounts for the wavelength release in normal spans of the working paths which fail.

The cost model includes the transmission cost, multiplexing cost and crossconnection cost into the total facility cost. The total cost is formulated as follows. Total facility cost = C_T * total fiber length + C_M * total number of fibers + C_X * total number of OXCs where C_T, C_M, C_X are cost coefficients with respect to transmission, multiplexing, and cross connection, respectively. Assuming that the C_M/C_T is approximately zero, the following relative cost is derived. Total relative facility cost = (total fiber length) + γ * (total number of OXCs), where $\gamma = C_X/C_T$.

For combinations of shared and dedicated assignment of spare wavelengths, γ and the maximum available wavelengths per fiber ω, the integer programming problems were solved. The results indicated that the dependence of total fiber length and number of OXCs on γ is very small. This suggests that the total number of OXCs may need to be reduced as the cross connection cost increases if the total facility cost has to be reduced. Total fiber length is shown to decrease with increase in ω.

B.2 Caenegem et al - Two step optimization, Static traffic demand

Caenegem et al [23] investigate routing, planning of working and spare capacity, and rerouting in WDM networks. ILP and simulated annealing are used as solution techniques. Given the number of wavelengths per fiber, the planning consists of defining paths on which the demand is routed and dimensioning the links (to define the number of fibers and channels for each link). This paper formulates the design of fiber topology and optical path layer for WDM networks, with a fixed channel plan, minimizing the total cost for a given static traffic demand.

The restoration model consists of three routing strategies a) Link restoration b) Path restoration c) Precomputed link disjoint backup route for fast restoration independent of the location of the failure. The model assumes that the capacity used by working paths can be released and reused for restoration purposes. Two types of WDM networks are considered with and without wavelength conversion. Two types of tunability of laser sources are further distinguished. The case wherein the transmitter and receivers are tunable, and a restoration route on another wavelength can be used, or the transmitter wavelength is fixed and the restoration route must be found on the same wavelength.

The planning approach described in the paper assumes the following. Location of optical crossconnects are known, a set of candidate links between these crossconnects, and the demand pair between each pair of nodes expressed in the number of wavelength channels. 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 (α cost), to the fiber (β cost), and to the channel (γ cost). The α cost stands for the required investment in a link before any capacity on this link can be used like digging and leasing costs and cable maintenance costs. The β cost typically includes the multiplexer, demultiplexer, optical amplifiers, and dispersion compensation management components. It can be subdivided into three components. a) fixed amount (β_{oi}): represents the fiber terminating equipment (eg. (de)multiplexer) b) amount of scaling with the fiber length (β_{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. γ includes all per-channel cost e.g., management and regeneration, wavelength conversion, and modular 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.

The results are shown for the first step in planning by comparing the β costs with network cost for upgrading a single channel system to multiwavelength systems. The α cost differs for every network operator. If the dark fibers are already in place, they can be used without major investment. In conclusion, since the α and β costs dominate as compared to the γ cost, optimization will try to aggregate more traffic into fewer number of fibers and fewer number of links. But no quantitative conclusions could be made as the variations in the results were quite large. The results for the space capacity are intuitive, the number of additional spare fibers compared to working fibers decreases as the wavelengths per fiber is increased. This result holds for both the wavelength converter case and tunable transmitter case. But when the working/restoration path should be on the same wavelength, the above result does not hold as the flexibility of efficiently packing the wavelengths is lost.

B.3 Crochat et al - Design protection, Static traffic demand

In WDM networks, the failure of a single component may cause simultaneous failure of many optical channels which makes impossible the rerouting directly in higher layers like ATM, IP, directly using the optical network. Crochat et al [24] introduce the concept of design protection, which aims at preventing such failure propogations to higher layers. This case arises because the virtual topology seen by the higher layers which have their own protection mechanisms, may seem to offer adequate redundancy between the higher layer switches and nodes. The higher layer rerouting strategy will be based on this topology. But when the higher layer routes share a common link in the physical layer, then the failure of one link may leave the virtual network disconnected. The purpose of design protection is to avoid such situations by finding, from a given topology, a route for each of the path such that a single optical link failure leaves the virtual network connected. This design protection is a static protection and does not consider the dynamic reconfiguration of nodes in the network following a node or link failure.

The effect of correlated failures of many virtual paths sharing a common physical link is minimized by using a disjoint alternate path (DAP) algorithm. The DAP algorithms maps virtual paths (single hop) in such a way that there exists an alternate path (multihop) with the same end nodes, but which does not share an optical link with its associated single hop path. This has to be done while respecting the link capacity constraints. The search for the best solution is shown to be extremely complex and is expected to be NP complete although it is not proved in the paper. Two heuristics are proposed for use by the DAP algorithm. Each of the heuristics employ a shortest path algorithm with and without capacity constraints. The simplified DAP algorithm starts from an arbitrary solution and randomly modifies the route for each virtual path, with higher probability to avoid critical links, and keeps the solution which has minimum broken links. (Ideally this value should be zero). It then computes the new list of critical links based on the new solution matrix and repeats the process. The DAP is shown to be more resilient to single link failures than the other two heuristics.

B.4 Bharat et al - Joint optimization, Static traffic demand

Bharat et al [25] study the fast distributed restoration for mesh-based optical networks. Two problems of importance are addressed. a) determining the best restoration route for each wavelength demand, given the topology and capacities and primary routes of all demands b) jointly determining primary and restoration routes for each wavelength demand to minimize network capacity and cost. The goal of the paper is to achieve subsecond restoration, high capacity efficiency and scalability without fault isolation and moderate processing.

The restoration model is evaluated based on restoration speed, restorability, capacity efficiency, and algorithm scalability. The restoration model employed in the paper is distributed, precomputed, path based and failure independent. Failure independence is based on the disjoint path concept, primary and restoration routes are topologically diverse. The model also employs the shared backup methodology.

The distributed precomputation of restoration route algorithm employs the following procedure. The source node of each demand executes the contention locking procedure to lock its contenders. If the locking is unsuccessful, the source waits for a random amount of time and retries. Or else is starts the procedure for searching for the restoration route using a distributed breath first search algorithm to find the route from source to the destination using the links with residual spare capacity. If a route is found, the source uses it as the restoration route for the demand. Otherwise, an optimization procedure is triggered which tries to release some link capacities critical to the current route construction by reassigning restoration routes of other demands.

For the joint optimization problem, both the centralized and the distributed versions are solved. Heuristic algorithms are presented one based on a lagrangean relaxation of the ILP formulation and the other based on local rerouting. The restoration activation architecture consists of two implementations, one is a sequential architecture where upon detecting a failure, the destination node works back determining a new incoming port number and switches its signal selector to receive signal on the new port. It determines the corresponding outgoing port of its preceding neighbor and then sends a cross connect request message to that node. This procedure is repeated until the source node is reached. The second approach is a parallel activation approach used to speed up connection setup of restoration routes. The penalty of achieving fast restoration is the extra messaging to communicate port assignments. The results are shown for small sample networks and nation wide large networks.

B.5 Alanyali et al - Joint optimization, Static traffic demand

Alanyali et al [26] consider the connection provisioning WDM networks. Two kinds of design problems are considered in the paper. Primary network design is formultated as an ILP to minimize the cost of the working fibers. This does not account for restoration. Heuristic algorithms are presented which are then extended to the connection provisioning in restorable networks. They consider a precomputed restoration model.

The algorithm for primary network design is based on greedy decisions by the connections to decrease a certain metric whose minimal value corresponds to an optimal assignment. The second method concerns the design of a restorable network. This algorithm is an extension of the primary network design heuristic. It evaluates based on a independent/ coordinated planning of several failure scenarios. The numerical study shows that coordinated planning provides more efficient solution than those obtained by considering the failures independently.

B.6 Ramamurty et al - Joint optimization, Static traffic demand

Ramamurty et al [22] study different ways to protect mesh-based WDM optical networks from single link failures. This is a joint optimization which jointly determines routing and wavelength assignment for primary and backup paths. Given a certain static traffic demand, and given a 100% restoration requirement, ILPs were formulated to minimize the total capacity used.

The restoration model examines different approaches to survive single link failures in the networks. The approached are based on two basic survivability paradigms path protection/restoration and link protection/restoration. In path protection, dedicated and shared path protection are considered. The capacity sharing approaches, dedicated and shared protection are considered under the link protection paradigm also.

Three ILPs were formulated for dedicated path protection, shared path protection and shared link protections. They have shown that dedicated link protection is not always possible in a bidirectional ring network so dedicated link case is not considered. The results are reported for small mesh networks (of the order of ten nodes) with limited number of wavelengths per fiber. The routing and wavelength assignments for both primary and backup paths are shown for two demands. Capacity utilization for path and link protection schemes for interconnected ring network with random traffic demands (upto 35 connections) are also reported. They are not able to solve larger instances of the problem as the ILP size explodes as the network size and the number of wavelengths per fiber increases. The results also indicate that shared path protection provides significant savings in capacity utilization over the other two schemes and dedicated path protection provides marginal capacity savings as compared to shared link protection.

APPENDIX C General Formulation for K Alternate Paths

In this section, we develop the generalized ILP formulation for optimizing network capacity, while trying to avoid service disruption to the current working paths.

The following information is assumed to be given: the network topology, a demand matrix consisting of the new connections to be established for each class, and the set of current working connections. We also assume that a set of K alternate routes between each node-pair is precomputed and given. Each route between every s-d pair is viewed as W wavelength continuous paths, one path corresponding to every wavelength and therefore, we do not have an explicit constraint for wavelength continuity. Each node pair can accommodate as many demands as the number of wavelength continuous paths between them. Each accepted demand corresponds to one wavelength continuous path between the corresponding node pair. Information regarding whether any two given paths are link and node disjoint (except the source and destination nodes) are also assumed to be given. The ILP solution determines the primary and backup paths for the demand set and hence the routing and wavelength assignment.

C.1 Notation

The network topology is represented as a directed graph $G(N, L)$ with N nodes and L links with W wavelengths on each link. We assume in our model that there are K alternate paths between each s-d pair. The following notations are used.

- $n = 1, 2, \ldots, N$: Number assigned to each node in the network
- $l = 1, 2, \ldots, L$: Number assigned to each link in the network
- $\lambda = 1, 2, \ldots, W$: Number assigned to each wavelength
- $i, j = 1, 2, \ldots, N(N-1)$: Number assigned to each s-d pair
- K = Number of alternate routes

- $p, r = 1, 2, \ldots, KW$: Number assigned to a path for each s-d pair. The first $1 \leq p, r \leq W$ paths belong to route 1 and $W+1 \leq p, r \leq 2W$ paths belong to route 2 and $(K-1)W+1 \leq p, r \leq KW$ paths belong to route K
- $x, y = 1, 2, \ldots, KW$: Number assigned to a demand. There can be atmost KW demands between any given node pair
- d_i^x: Demand x of node pair i
- (i, p): Refers to the pth path for s-d pair i
- (d_i^x, p): Refers to the path p assigned to xth demand of node pair i

The following cost parameters are employed.

- C_l: Cost of using a link l (data)
- C_w: Cost of disrupting a currently working path (data)

Information regarding whether two given paths are link and node disjoint

- $I_{(i,p),(j,r)}$ takes a value one if paths (i, p) and (j, r) have at least one link in common, zero otherwise. if $i = j$ then $p \neq q$ (data)

The following notations are used for path related information

- $\delta^{d_i^x, p}$: Path indicator which takes a value one if (i, p) is chosen as a primary path for d_i^x, zero otherwise (binary variable)
- $\nu^{d_i^y, r}$: Path indicator which takes a value one if (i, r) is chosen as a restoration path for d_i^y, zero otherwise (binary variable)
- $\delta_l^{i,p}$: Link indicator which takes a value one if link l is used in path (i, p), zero otherwise (data)
- $w_\lambda^{i,p}$: Wavelength indicator which takes a value one if wavelength λ is used by the path (i, p), zero otherwise (data)
- $\Gamma^{i,p}$: Cost of the path (i, p)

$$\Gamma^{i,p} = \sum_{l=1}^{L} \delta_l^{i,p} C_l$$

- $g_{l,\lambda}$ takes a value one if wavelength λ is used by some restoration route (i, r) that traverses link l (binary variable)
- $IP(d_i^x, d_j^y)$ takes a value 1 if the primary paths of d_i^x, d_j^y share a common link (binary variable)

The following notations are used for current working (primary) path related information. We are only interested in the primary route of the current working connection as the restoration paths can be re-assigned.

- $\chi^{d_i^x,p}$: Path indicator which takes a value one if (i, p) is a currently working primary path, zero otherwise (data)

The following notation is used to denote the demand in terms of lightpath requests for every node pair

- d_i: Demand for node pair i, in terms of number of lightpath request. Each request is assigned a primary and restoration route.

C.2 Problem Formulations

Objective: The objective is to minimize the network capacity. The first term in objective function denotes the capacity consumed by primary paths, and the second term denotes the capacity consumed by backup paths. The last term indicates that if a currently working connection ($\chi^{i,p} = 1$) is not picked in the final solution ($\delta^{i,p} = 0$), then the objective value is penalized by adding a cost C_w to it.

Minimize

$$\sum_{i=1}^{N(N-1)} \sum_{x=1}^{d_i} \sum_{p=1}^{KW} \delta^{d_i^x,p} \sum_{l=1}^{L} \delta_l^{i,p} C_l + \sum_{l=1}^{L} \sum_{\lambda=1}^{W} g_{l,\lambda} C_l$$
$$+ \sum_{i=1}^{N(N-1)} \sum_{x=1}^{d_i} \sum_{p=1}^{KW} \chi^{d_i^x,p} (1 - \delta^{d_i^x,p}) C_w \tag{C.1}$$

Restoration path wavelength usage indicator constraint: $g_{l,\lambda}$ takes a value one if wavelength λ is used by some restoration route (i, r) that traverses link l

$$X_{l,\lambda} = \sum_{i=1}^{N(N-1)} \sum_{y=1}^{d_i} \sum_{r=1}^{KW} \nu^{d_i^y,r} \delta_l^{i,r} w_\lambda^{i,r} \tag{C.2}$$

$$g_{l,\lambda} \leq X_{l,\lambda} \tag{C.3}$$

$$N(N-1)WKg_{l,\lambda} \geq X_{l,\lambda} \tag{C.4}$$

$$1 \leq l \leq L, 1 \leq \lambda \leq W, X_{l,\lambda} \geq 0$$

Link capacity constraint:

$$\sum_{i=1}^{N(N-1)} \sum_{x=1}^{d_i} \sum_{p=1}^{KW} \delta^{d_i^x,p} \delta_l^{i,p} + \sum_{\lambda=1}^{W} g_{l,\lambda} \leq W \tag{C.5}$$

$$1 \leq l \leq L$$

Demand constraints for each node pair

$$\sum_{p=1}^{KW} \delta^{d_i^x,p} = 1 \tag{C.6}$$

$$1 \leq i \leq N(N-1), 1 \leq x \leq KW$$

$$\sum_{r=1}^{KW} \nu^{d_i^y,r} = 1 \tag{C.7}$$

$$1 \leq i \leq N(N-1), 1 \leq y \leq KW$$

$$\sum_{x=1}^{KW} \sum_{p=1}^{KW} \delta^{d_i^x,p} = d_i \qquad 1 \leq i \leq N(N-1) \tag{C.8}$$

$$\sum_{y=1}^{KW} \sum_{r=1}^{KW} \nu^{d_i^y,r} = d_i \qquad 1 \leq i \leq N(N-1) \tag{C.9}$$

Primary path wavelength usage constraint: Only one primary path can use a wavelength λ on link l, no restoration path can use the same λ on link l.

$$\sum_{i=1}^{N(N-1)} \sum_{x=1}^{d_i} \sum_{p=1}^{KW} \delta^{d_i^x,p} \delta_l^{i,p} \psi_\lambda^{i,p} + g_{l,\lambda} \leq 1 \tag{C.10}$$

$$1 \leq l \leq L, 1 \leq \lambda \leq W, 1 \leq x \leq KW$$

Backup multiplexing constraint: If $IP(d_i^x, d_j^y)$ is one, then only one of the restoration paths can use a wavelength as backup among the primaries contending for backup. $IP(d_i^x, d_j^y)$ is set to one if the primary paths of demands d_i^x, d_j^y have any common links, zero otherwise.

$$(\nu^{d_i^x,p} \delta_l^{i,p} \psi_\lambda^{i,p} + \nu^{d_j^y,r} \delta_l^{j,r} \psi_\lambda^{j,r}) IP(d_i^x, d_j^y) \leq 1 \tag{C.11}$$

$$1 \leq i,j \leq N(N-1), 1 \leq p,r \leq KW$$

Constraint for finding interacting primaries: This constraint is used to find if primary paths of any two given demands share a common link. If $V_l = 2$ for any l, then the primary paths of the demands d_i^x, d_j^y have atleast one common link. Equations (C.13) - (C.17) are used to set $IP(d_i^x, d_j^y)$ to one whenever $V_l = 2$.

$$V_l = \delta^{d_i^x,p}\delta_l^{i,p} + \delta^{d_j^y,r}\delta_l^{j,r} \tag{C.12}$$

$$1 \leq i,j \leq N(N-1), 1 \leq l \leq L$$

$$1 \leq p,r \leq KW, 1 \leq x,y \leq KW$$

$$0 \leq V_l \leq 2$$

$$N_l \leq (2 - V_l) \tag{C.13}$$

$$N(N-1)WKN_l \geq (2 - V_l) \tag{C.14}$$

$$1 \leq l \leq L, N_l(binaryvariable)$$

$$W_l = \sum_{l=1}^{L}(1 - N_l) \tag{C.15}$$

$$IP(d_i^x, d_j^y) \leq W_l \tag{C.16}$$

$$N(N-1)WKIP(d_i^x, d_j^y) \geq W_l \tag{C.17}$$

$$1 \leq l \leq L, W_l \geq 0$$

Constraint for topological diversity of primary and backup paths: Primary and restoration paths of a given demand should be node and link disjoint

$$(\sum_{p=1}^{KW} \delta^{d_i^x,p} + \sum_{r=1}^{KW} \nu^{d_i^x,r}) I_{(i,p),(i,r)} = 1 \tag{C.18}$$

$$1 \leq i,j \leq N(N-1), 1 \leq p,r \leq KW, 1 \leq x \leq KW$$

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