DESIGN OF TRANSLUCENT OPTICAL NETWORKS

A THESIS
SUBMITTED TO THE DEPARTMENT OF ELECTRICAL AND
ELECTRONICS ENGINEERING
AND THE INSTITUTE OF ENGINEERING AND SCIENCES
OF BILKENT UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

By
Mustafa Arısoylu
July 2001

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Assist. Prof. Dr. Ezhan Karaşan(Supervisor)

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Assist. Prof. Dr. Murat Alanyalı

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Assist. Prof. Dr. Nail Akar

Approved for the Institute of Engineering and Sciences:

Prof. Dr. Mehmet Baray
Director of Institute of Engineering and Sciences

ABSTRACT

DESIGN OF TRANSLUCENT OPTICAL NETWORKS

Mustafa Arısoylu
M.S. in Electrical and Electronics Engineering
Supervisor: Assist. Prof. Dr. Ezhan Karaşan
July 2001

We discuss the problem of building optical networks composed of restorable, transparent subnetworks interconnected via transponders. We call the resulting network architecture as the *translucent network architecture,* also named “islands of transparency” in the literature. Translucent optical networks provide a compromise between all-optical and opaque networks and present several advantages: easier interoperability, reduced transponder costs, simpler network management, scalable network architecture and faster restoration times. We formulate the problem of designing restorable subnetworks for an arbitrary network as an Integer Linear Programming (ILP) problem, where the subnetworks are determined subject to the constraints that each subnetwork satisfies some size constraints and it is 2-connected. A greedy heuristic algorithm for the same problem is also proposed for planar networks. Numerical results are presented for both methods.

For translucent networks, failures in each subnetwork are managed by the Restoration Manager (RM) of that subnetwork, which results in quasi-distributed restoration. Quasi-distributed restoration provides smaller restoration times compared to centralized restoration. The network design problem of determining working and restoration capacities with quasi-distributed restoration is formulated as an ILP problem for two different cases: joint design, where link capacities are optimized for all subnetworks concurrently, and separate design, where each subnetwork is designed independent from other subnetworks. Furthermore, path restoration problem is also formulated in joint and separate designs, in order to compare the performance of quasi-distributed restoration with respect to path restoration. Numerical results comparing both design methods are presented. The quasi- distributed restoration method which is called section restoration, with both joint and separate designs, generate network costs which are very close to the costs of the centralized path restoration. Consequently, having low costs and fast restoration times the section restoration technique is promising for the next generation translucent optical architectures.

Keywords: optical networks restoration, translucent optical networks, network design.

ÖZET

YARI SAYDAM OPTİK AĞLARI TASARIMI

Mustafa Arısoylu
Elektrik ve Elektronik Mühendisliği Bölümü Yüksek Lisans
Tez Yöneticisi: Yrd. Doç. Dr. Ezhan Karaşan
Temmuz 2001

Bu tezde birbirlerine alıcı-vericilerle bağlanmış onarılabilir altağlardan oluşan optik ağların tasarlanma problemi ele alınmıştır. Ortaya çıkan bu ağ mimarisini yarı-saydam ağ mimarisi olarak adlandırdık. Literatürde bu tip mimarilere saydam adalar adı verilmiştir. Yarı-saydam optik ağları, saydam ve donuk optik ağlar arasında bir geçiş ağ mimarisidir. Bu yeni mimarinin bir çok avantajları vardır. Bunlar kısaca, daha kolay birlikte çalışabilirlik, alıcı-verici maliyetlerinde azalma, daha basit ağ işletimi, ölçeklenebilir ağ mimarisi ve daha hızlı onarım zamanlarıdır. Herhangi bir ağ topolojisi için onarılabilir altağların tasarım problemini, tamsayılı doğrusal programlama ile formüle ettik. Bu formülasyonda altağlar bazı sınırlamalara göre belirlenmiştir. Bu sınırlamalara göre, her bir altağ bazı büyüklük sınırlamalarına uymalıdır ve de her bir altağ iki bağlı olmalıdır. Aynı problem için bir de buluşsal algoritma öngörülmüştür. Her iki yöntem için de sayısal sonuçlar sunulmuştur.

Yarı-saydam ağlarda her bir altağdaki arıza o altağın onarım yöneticisi tarafından ele alınır. Bu onarım şekli kısmen dağıtılmış bir onarım şeklidir. Kısmen dağıtılmış onarım tekniği, merkezi onarım yöntemine göre daha kısa onarım zamanları sağlar. Ana ve onarım kapasitelerini kısmen dağıtılmış onarım ile belirleyen ağ tasarım problemi iki farklı durum için tam sayılı doğrusal programlama ile formüle edilmiştir. Bu durumlar birleşik tasarım ve de ayrık tasarımlardır. Birleşik tasarım tekniğinde bütün altağların bağ kapasiteleri aynı zamanda eniyilenmektedir. Diğer taraftan, ayrık tasarım tekniğinde her altağ diğer altağlardan bağımsız olarak tasarlanır. Bundan başka, yol onarım problemi de, birleşik ve ayrık tasarım teknikleri kullanılarak formüle edilmiştir. Bunun amacı, kısmen dağıtılmış onarım tekniğinin başarımının yol onarım tekniğininkiyle karşılaştırılmasıdır. Her iki yöntemi de karşılaştıran sayısal sonuçlar sunulmuştur. Kısmen dağıtılmış onarım yöntemi aynı zamanda parça onarım tekniği olarak da adlandırılmıştır. Parça onarımı hem birleşik hem de ayrık tasarımlarla, merkezi yol onarımının ağ maliyetlerine çok yakın ağ maliyetleri vermektedir. Sonuç olarak, düşük maliyetlere ve hızlı onarım zamanlarına sahip olan parça onarım tekniği gelecek nesil yarı-saydam optik mimarileri için umut vericidir.

Anahtar Kelimeler: optik ağların onarımı, yarı-saydam optik ağlar, ağ tasarımı

ACKNOWLEDGMENTS

I would like to express my deep gratitude to my supervisor Dr. Ezhan Karaşan for his guidance not only in my undergraduate and graduate education but also throughout the development of this thesis. I would like to thank him also for initiating this interesting subject, drawing my attention to many gratifying aspects of the topic and encouraging me to work with dedication on the problems that we have come across.

I would like to thank Dr. Murat Alanyalı for his distinctive teaching in many courses on communications.

I would like to thank Dr. Murat Alanyalı and Dr. Nail Akar for their invaluable comments and suggestions for my thesis.

Finally, I would like to thank my family for their relentless support throughout my life.

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To My Family . . .

Chapter 1

INTRODUCTION

Working on various kinds of fields, electrical and electronics engineers serve the society by creating wealth, safety and happiness. Especially, communication engineers play a great role in this task. The technology that they introduce has a big hand in the advancement of the society. Advanced communication technologies are some of the essential components of the Information Society. The products of these technologies provide people with various kinds of facilities in all parts of their lives. From business life to entertainment world, communication technologies are widely used and are getting more and more attention. One of the most widely used communication technology is the optical communication technology. It seems to maintain its popularity for decades due to decreasing costs and increasing capacities of optical fiber.

From the first series of experiments on sending high-speed data through a narrow filament of glass to the latest optical networking technology, optical communications has evolved enormously. In the *"First Generation Optical Networks"*, fiber was used only as the transmission medium. There were various kinds of advantages of using fiber over previous transmission mediums, e.g., huge bandwidth, low loss, low cost, light weight, compactness, strength, flexibility, immunity to

network Type	Traffic in 1997 (TB/month)	Traffic in 2000 (TB/month)
US Voice	40000	53000
Internet	2500-4000	20000-35000

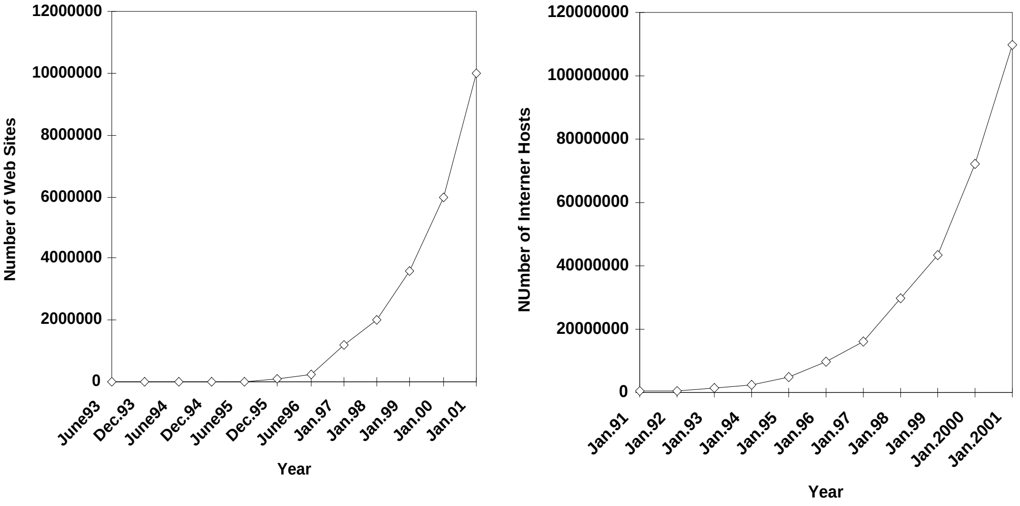
Table 1.1: Traffic on US long distance Networks

Year (December)	Traffic (TB/month)
1990	1.0
1991	2.0
1992	4.4
1993	8.3
1994	16.3
1996	1500
1997	2500-4000
1998	5000-8000
1999	10000-16000
2000	20000-35000

Table 1.2: Traffic on US long distance Networks in 2000

noise and electromagnetic interference, security, and corrosion resistance. The electronic signals in a twisted pair copper cable operate in the frequency range of up to 5MHz. On the other hand, optical fiber has a bandwidth of approximately 900THz. Due to some limitations in optical fibers, some of this bandwidth cannot be used in practice, however usable bandwidth is in the order of several hundreds of THz. Clearly, optics offers substantially more bandwidth than the twisted pair. Thus first generation optical networks are widely deployed all over the world. Synchronous Optical Network (SONET) and Synchronous Digital Hierarchy (SDH) are two examples of such networks which have been deployed in USA and Europe, respectively, since 1980s.

On the other hand, Internet traffic is doubling each year. A doubling of traffic each year represents extremely fast growth, much faster than the increases in other communication services. There are various results verifying that data traffic has already exceeded voice traffic at about 2000. One of the estimations of increase in data traffic in USA can be seen in Table 1.1 [9]. According to the table for 1997, voice traffic seems to be much more than the Internet traffic, however after 3 years, in 2000, Internet traffic was comparable to the voice traffic. Furthermore, Table 1.2 is a clear indication of the aggressive growth of traffic on Internet backbones in USA. In addition to this, there are other measures that indicate the growth of data rate in the Internet such as the number of internet hosts and the number of world wide webs. As can be seen from the Figure 1.1, they almost double each year.



(a)

(b)

Figure 1.1: (a) Number of Web Sites (b) Number of Internet Hosts

The examples shown above strongly support the notion that there is a “Moore’s Law” for data traffic where the traffic volume is doubling each year. New applications such as video on demand, voice over IP, e-commerce use significant amount of bandwidth on the Internet. To provide the necessary capacity, network operators are deploying new technologies with higher capacities and lower unit bandwidth costs. This reduction in costs stimulates the creativity of people designing new applications requiring more and more bandwidth. Such a system with a positive feedback may generate a growth in demand which will continue for at least many years.

There are several types of communication technologies which are designed in order to keep up with the doubling of traffic each year. The performance of each technique throughout the years can be seen in Figure 1.2. As can be seen from the figure, two main types of multiplexing techniques are deployed both in electronics and optics. These multiplexing techniques are Wavelength Division Multiplexing (WDM) where several wavelengths are transmitted simultaneously over the same fiber and Time Division Multiplexing (TDM) where many lower-speed data streams are multiplexed into higher speed stream in time domain. The details of these multiplexing techniques will be presented in the next chapter.

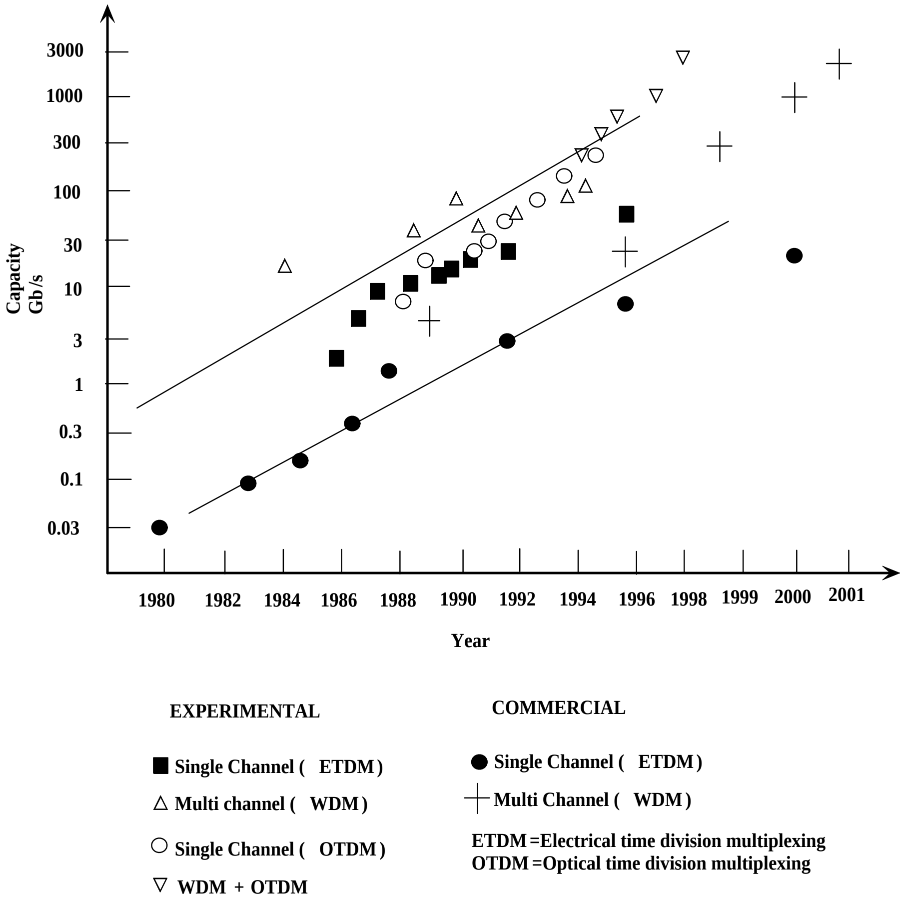


Figure 1.2: Evolution of optical fiber transmission capacity in both electronics and optics

As indicated in Figure 1.2, Electronic Time Division Multiplexing (ETDM) has been used since 1980s. The highest transmission rate using ETDM is 10Gb/s, and 40Gb/s ETDM technology is currently being developed. To push the TDM technology beyond these rates, researchers are working on methods to perform the multiplexing optically. This approach is called Optical Time Division Multiplexing (OTDM). Laboratory experiments have demonstrated the transmission rates of 250Gb/s by using OTDM. Moreover, by combining WDM and OTDM techniques, as can be seen in Figure 1.2, the transmission capacity has reached to the orders of several terabits per second in laboratories.

Although OTDM is not commercially available today, WDM has been deployed commercially since 1996. The first deployed systems had 16 channels (wavelengths) each of 2.5Gb/s capacity resulting in a total capacity of 40 Gb/s. By the end of 1999, WDM equipments with 96 channels each carrying 2.5Gb/s were available, for a total of bandwidth 240Gb/s. Commercially available systems were handling 49 channels at 10 Gb/s each in the first half of 2000, and 96 channels at 10Gb/s each by late 2000. In early 2001, a well known optical communication company in USA called “Sycamore Networks” announced WDM systems with 160 channels at 10 Gb/s each.

Figure 1.2 indicates that throughout the years electronic transmission speed has already reached tens of Gb/s which was just a starting point for optical transmission techniques in the first design stages. As also can be seen from the figure, optical techniques have reached rates in the order of several of Tb/s experimentally, which are not commercially far away. Electronic data processing technologies have rates much lower than optical transmission rates. Consequently, electronics forms a bottleneck for optics in terms of the transmission speed.

As the data traffic and transmission rates increase more than 100% each year, it becomes more and more difficult to process data electronically, and researchers discovered that optical domain has great potential other than providing point-to-point transmission. *Second generation optical networks* are introduced in order to avoid this electronic bottleneck to some extent. In second generation optical networks, optical domain includes not only the transmission medium, but also the switching and routing tasks at the nodes.

Second generation optical networks with WDM technology have optical cross-connects as the nodes of the network. The function of these nodes is to route different wavelengths at an input port to different output ports. By this way, wavelengths can be utilized in a balanced fashion throughout the network such that the spatial efficiency is increased. As will be discussed in the next chapter, there are various kinds of node architectures in second generation optical networks regarding switching and conversion capabilities.

Multiwavelength optical networks are currently deployed widely in long distance core networks. There are several architectures suitable for optical networks each involving complex combinations of optical and electronic devices. All these architectures have the optical fiber as the transmission medium and contain some form of Optical Cross-Connects (OXC) interconnecting these fibers. However, they have significant differences necessitating separate network design, control and management tools to be developed.

The first type of a multiwavelength optical network is *"All Optical"* or *"Transparent Networks"*. A connection is carried entirely over the optical domain in a transparent network. On the other hand, the *"Opaque Network"* architecture is another optical network type in which there are optical-to-electronics-to-optical (O/E/O) converters, called transponders, at both sides of all optical links. These transponders terminate each incoming optical signal, regenerate the signal electronically and remodulate the signal in optical domain possibly at a different wavelength. There exist many advantages and disadvantages of both type of network architectures. For instance, transparency (with respect to bit rate, modulation format, analog/digital data independence), cost effectiveness are some of the advantages of all-optical networks whereas fast fault management, multi-vendor interoperability are those of opaque networks.

Optical networks that are deployed today are opaque, and transparent networks seem to be the future architecture. However, due to some limitations in optical transmission and switching systems, optical networks will evolve through some intermediary stages starting from opaque networks ending eventually with a transparent architecture.

The limitations in optical transmission includes attenuation, dispersion (modal, chromatic, polarization mode) and certain non-linear effects in optical fiber. The first limitation for optical communications is the attenuation of light traveling along the fiber. Since the fibers are not ideal, they have some losses due to various kinds of mechanisms, such as material absorption and scattering which are caused by some impurities in the fiber. The next important type of impairment in fiber is dispersion. Dispersion refers to the phenomena that different components of a signal propagates with different velocities in the fiber. Because of dispersion the signal gets smeared at the receiver where it becomes very hard to detect the original form of the signal. Finally, transmission nonlinearities in fibers also contribute to transmission impairments. We will discuss these impairments in more detail in Chapter 2.

There are several efforts to eliminate these limitations both in electronics and optics. In opaque networks transponders may be used for compensating the attenuation and dispersion of light through fiber, since they regenerate a fresh and cleaned copy of the signal in electronics domain. However transponders are not only expensive but also bit rate dependent. On the other hand, optical amplifiers are the dual of regenerators in optics. They perform the amplification process entirely in optical domain. The most widely used optical amplifier is Erbium Doped Fiber Amplifier (EDFA). The principles of operation of this optical amplifier will be explained in the next chapter.

Optical amplifiers are superior to transponders in many aspects. First of all, they are transparent to bit rate, protocol format and they can easily be deployed to WDM systems, since they can amplify signals in a wide range of frequencies. If a WDM signal is to be regenerated in electronics, each wavelength should be demultiplexed and regenerated individually via a transponder and remultiplexed. On the other hand, only one optical amplifier is sufficient to amplify all the signals at different wavelengths.

Although optical amplifiers are very promising, they also have some disadvantages. The first such drawback is that they amplify not only the signal itself but also the noise within the signal. Moreover, due to internal emission, some internal noise is also added to the amplified signal. Finally, they have a non-flat gain spectrum which results in non-uniform power levels at different wavelengths.

Today many researchers are working on building optical amplifiers with larger bandwidth and gain while achieving a uniform gain spectrum. Consequently, optical amplifiers are deployed with larger spacings that can jointly amplify an increasing number of wavelengths. However, there is a limit on the number of consecutive optical amplifications without an electronical regeneration since noise is introduced by each optical amplifier and it is further amplified by subsequent amplifiers.

Because of the aforementioned limitations of building national-scale, all-optical networks and the high cost of opaque networks because of transponders, a new type of optical network architecture is recently considered in the literature. In this formation there are *islands of transparency*, i.e. all-optical subnetworks, each having a limited geographic size [16, 25, 30]. These subnetworks are interconnected to each other via transponders. In this thesis we call this type of network as the *translucent optical network*, since it provides a compromise between transparent and opaque networks. Translucent networks have several advantages over previously known architectures: easier vendor interoperability, reduced transponder costs, simpler network management, scalable network architecture and faster restoration times. We will investigate these issues in more detail in the next chapter.

Although translucent networks have been introduced in the literature, the design of such networks have not been investigated. In this thesis we discuss two interrelated problems in the design of translucent networks. First, we analyze how a given topology can be best partitioned into transparent, restorable subnetworks. In the partitioning problem, for a given network topology, we partition the network into subnetworks regarding some criteria. The objective of the partitioning problem is to minimize not only the number of generated subnetworks but also the total number of shared links between subnetworks. By this way we try to form more independent subnetworks in terms of management. The subnetworks are generated subject to the following constraints. First, each subnetwork should have a certain maximum size, that is if two nodes are in the same subnetwork, there should exist at least two link disjoint paths between these nodes both having lengths not exceeding a maximum distance. The presence of these link disjoint paths between nodes of the same subnetwork also ensures the 2-connectivity of each subnetwork. In other words, when a link fails in one of the subnetworks the subnetwork remains still connected. The next important constraint is that each subnetwork can have at most a certain number of links and nodes. Finally, each link and node should belong to at least one of the subnetworks.

We formulate the network partitioning problem as an Integer Linear Programming (ILP) problem in Chapter 3. We also propose a greedy heuristic algorithm for solving the network partitioning problem.

Once the partitioning problem is solved, the network design problem of determining working and restoration capacities in translucent networks is studied. We solve the network design problem for a given partitioned network topology, and a traffic demand set where there is one unit wavelength of traffic for each demand. However, for the same demand pair, it is possible to have more than one demands and each demand is considered separately. In the network design problem for translucent networks, a working path is chosen for each demand. Each working path comprises sections which are parts of the path each residing in a different subnetwork. These sections are connected to each other via transponders located at the boundaries of subnetworks. A wavelength is assigned for each section of the working path. Since transponders may perform wavelength conversion, wavelength continuity constraint is enforced for each section, not for the entire working path. Once working paths are determined, restoration paths are selected such that all connections can be fully restored against all single link failures. Similar to working paths, a wavelength is assigned for each section of a restoration path. After working and restoration paths and corresponding wavelengths are assigned, the number of working and restoration fibers for each link are determined such that all traffic passing through the link can be carried. The objective of the network design problem is to minimize the total length of fiber used for both working and restoration purposes.

We formulate the network design problem as an ILP problem in Chapter 4. This problem is formulated for two different cases: *joint design*, where link capacities are optimized for all subnetworks concurrently, and *separate design*, where each subnetwork is designed independent from other subnetworks. Although network partitioning and capacity design problems are coupled to each other, we consider them separately because of the large complexity of the composite problem.

In order to provide high quality services, the network should be immune to failures. When a failure occurs in the network, e.g. when a fiber link is cut, all the connections affected by the failure should be restored within a small period of time. In this thesis we consider restoration against single link failures. When a working path fails due to a link failure, the connection is rerouted between the endpoints of the section of the working path where the failed link is located. We call this rerouting method as *section restoration*.

There are various kinds of restoration techniques proposed in the literature. One of the most widely used rerouting technique is the *path restoration*. When a link fails, path restoration mechanism reroutes the affected connections between their source and destination nodes. Since path restoration allows the affected connections to be rerouted within the entire network, it is known to be the most efficient restoration technique in terms of reducing the network cost.

In order to compare performances of the proposed section restoration in translucent optical networks and path restoration, the path restoration problem is also formulated with joint and separate designs. Path restoration is implemented for two different cases considering the locations of the transponders. First, in order to have a fair comparison, path restoration is implemented such that the transponders are placed at exactly the same locations of the transponders in the translucent network architecture. This scheme corresponds to an all optical network with wavelength conversion at selected nodes. Secondly, path restoration is implemented with the transponders at every port of the nodes in the network. This case is the same as an all optical network with all nodes capable of wavelength conversion or an opaque network.

Our numerical studies demonstrate that section restoration generates fiber costs that are comparable with the fiber costs obtained by using path restoration with wavelength conversion at all nodes. Considering the more scalable and manageable features of quasi-distributed section restoration, and high cost of wavelength conversion, section restoration is a viable alternative to centralized path restoration.

After presenting the evolution of optical network architectures and general framework of the translucent network architecture in Chapter 2, we discuss the network partitioning problem in Chapter 3. In Chapter 4, the network design problem of computing working and restoration capacities is considered. Chapter 5 presents the conclusions and points out future research directions.

Chapter 2

ARCHITECTURES FOR OPTICAL NETWORKS

In this chapter, we first discuss the evolution of optical transmission technologies and next we discuss the evolution of optical networks. We also present the significance of translucent optical network architecture in this evolution process. Finally, we discuss the restoration problem, first in a general setting and then for translucent networks.

2.1 Evolution of Optical Transmission Technologies

Advances in the optical technologies directly affect the architectures of optical networks. In the light of the developments in optics, optical networks move from opaque to transparent architecture. While going through stages from opaque to transparent architecture, optical networking has to overcome many impairments present in optical transmission. These impairments put some limitations on the development of optical networking technology.

Before discussing the evolution of optical transmission systems, we briefly explain some basics in optical transmission. An optical fiber consists of a cylindrical core which is surrounded by a cladding. A simple cross section of a fiber can be seen in Figure 2.1. Both cladding and core are made of SiO_2 which is called Silica. The refractive index of a medium is the ratio of the speed of light in free space to that in the medium. Refractive index of core is slightly higher than that of cladding due to some processes introduced in the core and cladding.

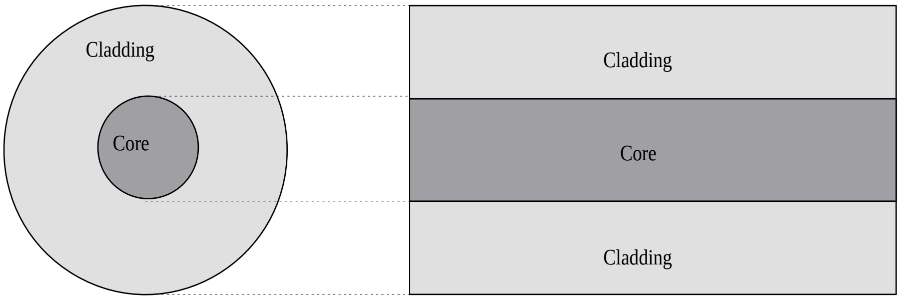


Figure 2.1: Cross section and longitudinal section of an optical fiber indicating the core and the cladding parts)

In 1960s some experiments indicated the transmission of encoded light in waveguides. In 1970s the introduction of low loss fiber made of Silica spurred the developments in optical transmission. The lowest loss was around 0.25dB/km in 1.55μm wavelength band. The attenuation versus wavelength is plotted for the period 1979-1988 in Figure 2.2. These fibers were able to carry signals over distances of several tens of kilometers before they were regenerated by transponders. As stated before, a transponder converts the light into electrical signal and regenerate a fresh copy of the signal and retransmit it as light signal.

There are various kinds of sources of loss or attenuation in fiber. Three main sources of loss in fiber are the material absorption, Rayleigh scattering and waveguide imperfections. Material absorption results from absorption by silica and some impurities in the fiber, whereas Rayleigh scattering occurs because the medium is not absolutely uniform which causes slight fluctuations in the refractive index throughout the fiber. The last source of attenuation is waveguide

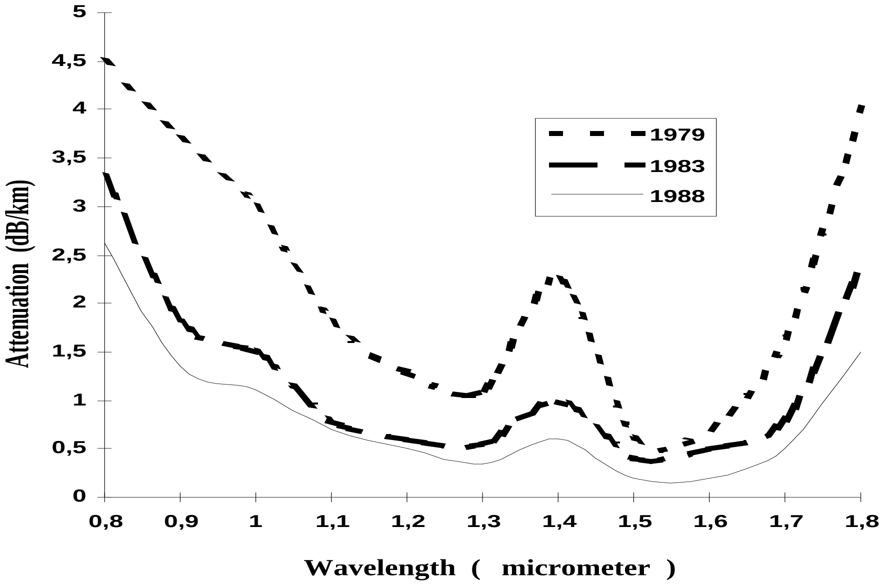


Figure 2.2: Attenuation vs. wavelength for silica based optical fiber

imperfections which are caused by non ideal fiber geometries which occur due to manufacturing imperfections and some other distortions in the fiber.

As can be seen in Figure 2.3(a), the first deployed fiber was the multi-mode fiber whose core radius is much larger than the wavelength of the transmitted light. The core radius is about 50 to 85 μm. In these fibers, light travels in multi-modes and each mode has a different reflection angle which is always greater than the critical angle. Since each mode travels different paths whose lengths are also different, it takes different amount of time for each mode to travel from transmitter to the receiver. This phenomena is called "Modal Dispersion". In the early communication systems multi-mode fibers were used with the Light Emitting Diodes (LEDs) and Multilongitudinal Mode (MLM) Fabry-Perot laser transmitters which were low cost devices. However, optical signal should have been regenerated every few kms with these equipments due to the modal dispersion.

In the optical systems of early 1980s single-mode fibers were used eliminating the modal dispersion. MLM Fabry-Perot laser were used at 1.3μm window (see Figure 2.3(b).) Unlike the multi-mode fibers, single mode fibers has a core radius

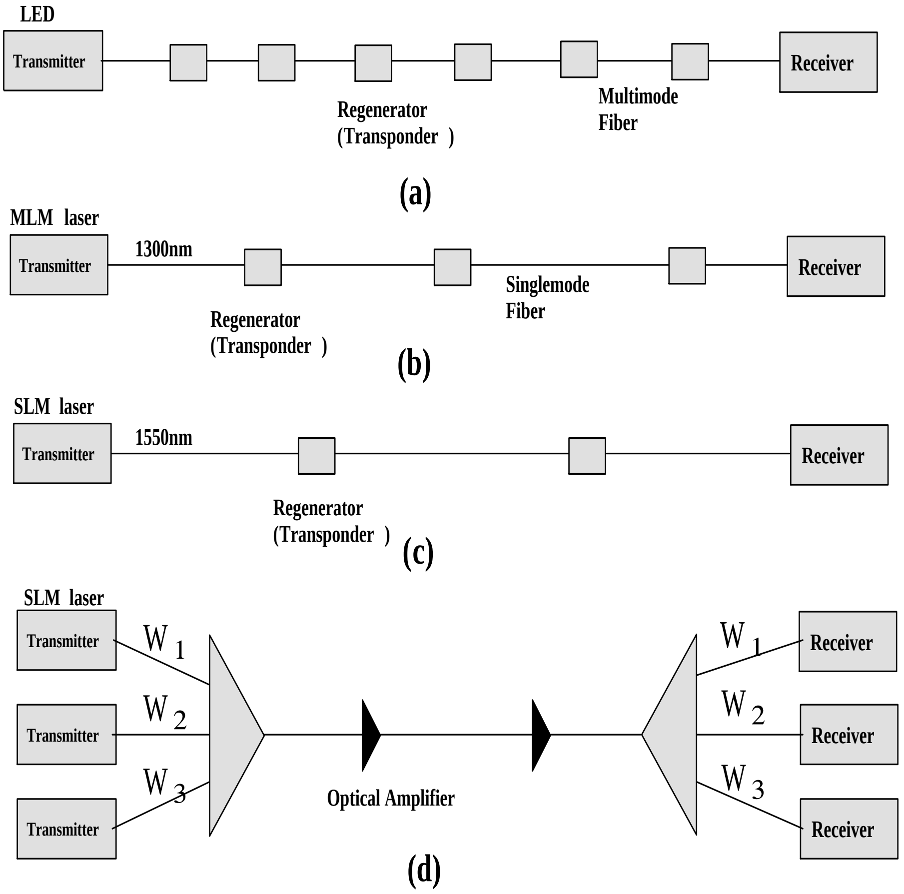


Figure 2.3: Evolution of optical transmission technologies (a) A system using LEDs over multi mode fiber (b) a system using MLMs in the 1300nm band to avoid multimode dispersion (c) A system using SLMs in the 1550nm band to reduce chromatic dispersion (d)A WDM system with multiple wavelengths in the 1550nm band with optical amplifiers replacing regenerators

comparable to the wavelength of the transmitted optical signal. This structure forces the light to travel only in a single mode. This new technology had a big hand in increasing the bit rates and the spacings between the regenerators (transponders). The bandwidth spacing product of different technologies can be seen in Figure 2.4.

Introduction of single mode fibers increased the regenerator spacings to around 40km and operated at orders of Mb/s. At those times the distance between regenerators or transponders were determined primarily by the fiber loss (attenuation). Another step in the evolution of optical transmission in the

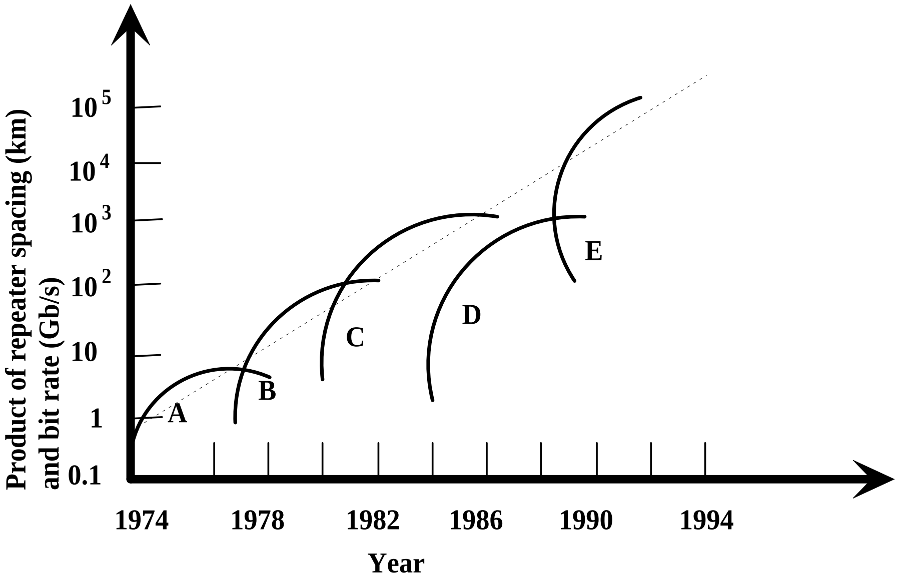


Figure 2.4: Growth history of single link fiber optic transmission capability as the product of inter-repeater spacing and bit rate. (A) Multimode fiber at 0.8us wavelength (B) Single Mode fiber at 1.3us (C) single mode fiber single frequency laser 1.5us (D) Coherent detection substituted for direct detection and (E) Erbium doped fiber amplifiers substituted.

late 1980s was to implement systems with 1.55μm wavelength band which had a lower loss feature than that of 1.3μm window as shown in Figure 2.3(c).

At that time another impairment started to become a limiting factor for the bit rate and spacing between regenerators. This impairment is called "Chromatic Dispersion". In chromatic dispersion, each frequency content of the signal forms the components that travel with different velocity. One of the main reasons for this is that the refractive index of fiber depends on the frequency of the propagating light, so each frequency component has a different velocity.

It was observed that, SiO_2 based optical fiber has no chromatic dispersion in the 1.3μm band but a significant dispersion in 1.55μm band. Unfortunately, 1.55μm window was the lowest loss window. In order to eliminate the significant chromatic dispersion at 1.55μm band, "Dispersion Shifted Fibers" were invented such that these fibers has zero dispersion in the 1.55μm window. However at those times due to some standardization efforts, these dispersion shifted fibers could not be deployed widely. Fortunately, there was another way of eliminating chromatic dispersion by reducing the bandwidth of the transmitted signal. This idea has spurred the development of single-longitudinal mode (SLM) distributed feedback (DFB) laser, which lead further increases in the bit rate to the orders of Gb/s.

Polarization related effects are also contributing the limitations to the optical transmission. One of these impairments is called “Polarization Mode Dispersion” (PMD). Here dispersion is used to define the same general concept as in the case of both modal and chromatic dispersion. Different polarization components of light travels with different velocities in the fiber due to the elliptical structure of fiber core, which makes the signal smeared before it is detected by the receiver.

The next and the most important development in the optical fiber transmission is the introduction of Erbium Doped Fiber Amplifiers (EDFAs) in the late 1980s and early 1990s. These optical amplifiers are a major milestone in the evolution of optical networking from opaque architecture to all-optical architecture. EDFAs perform amplification without any electronic processing. Moreover, transmission costs are substantially reduced by replacing transponders with EDFAs.

Since EDFAs perform the amplification in optical domain, they are transparent to bit rate and modulation formats. So they are open to new technologies, i.e., if the bit rate increases, there will be no change in the EDFAs, whereas all the transponders should be altered for the same bit rate increase.

Another important advantage of EDFAs is that they are compatible with WDM systems, that is they are capable of amplifying many wavelengths at the same time as shown in Figure 2.3(d). If transponders are used for regeneration, it will cost substantially more since a different transponder should be used for each wavelength as given in Figure 2.5,. The cost of optical amplifiers are in the same order as multiplexer and demultiplexer, however transponders add a significant cost. As can be seen from Figure 2.4, EDFAs make it possible to increase the product of amplifier spacing and bit rate for optical transmission.

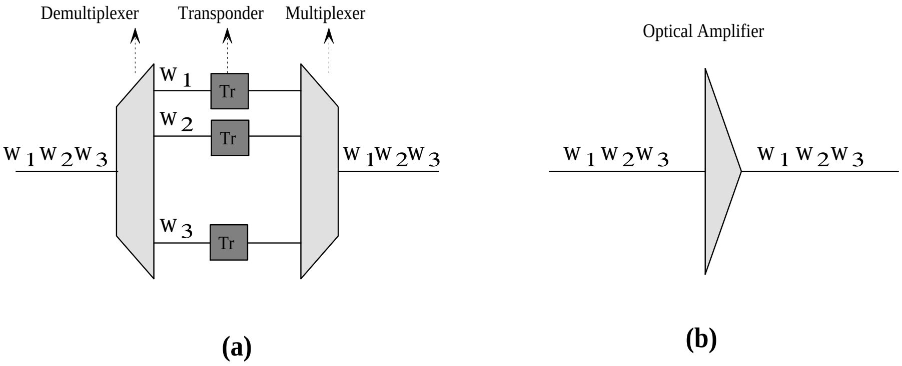


Figure 2.5: Schematic structures of (a) an opaque transponder and (b) a transparent optical amplifier

In addition to the impairments described, non-flat gain spectrum of EDFAs and non-linear effects in fiber optic transmission also put limitations on optical fiber transmission systems.

After discussing the evolution of optical transmission technologies, next we discuss the evolution of optical networks.

2.2 Evolution of Optical Networks

The data traffic continues to increase exponentially for the last 25 years . It is estimated that the volume of data traffic has already exceeded the voice traffic. As can be seen in Figure 2.6, with respect to one of the estimations, data traffic in USA increases each year more than 100 percent since 1996 and has exceeded voice traffic in 1999, whereas the crossover point in Japan is expected to be in 2002. Due to this tremendous increase in traffic over the Internet, there is an increasing demand for high bandwidth transmission and switching systems. In order to satisfy this huge capacity demand, various kinds of technologies have been used so far.

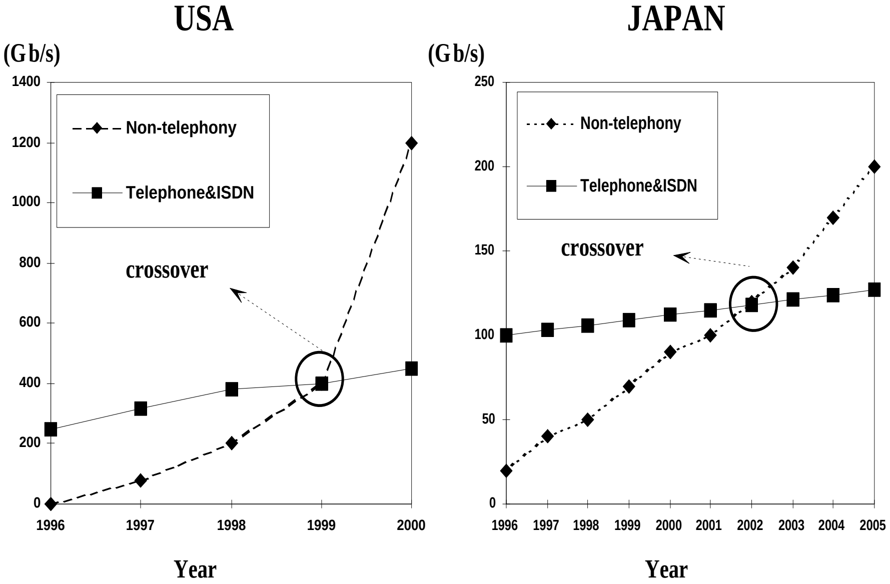


Figure 2.6: Voice Traffic vs. Data Traffic

Among these technologies, optics has a distinctive place which has played a great role in the advancement of telecommunications. The *"First Generation Optical Networks"* have been introduced with the first use of optical fiber as the transmission medium. In first generation networks, optical fiber is used only as a transmission medium, and other tasks such as switching, routing, processing are all handled by electronics. Furthermore, all of these networks are single-wavelength networks. To put it another way, WDM technology was not used in the first generation optical networks.

Currently, first generation optical networks are widely used in core transport networks. The most widely deployed first generation optical technology is Synchronous Optical Networks (SONET) or Synchronous Digital Hierarchy (SDH) which are used in USA and Europe, respectively. Actually, both SONET and SDH are the same protocols except for a few differences in the standards. SONET and SDH are used for transmission of high-speed signals by using Time Division Multiplexing (TDM) technology. TDM is used in order to multiplex lower bit rate streams into a higher bit rate traffic stream. As can be seen in the Figure 2.7, N connections each of which has a rate of R bits per second are multiplexed in time domain, and the resulting stream at the output of the multiplexer has a data rate equal to the summation of all multiplexed signals.

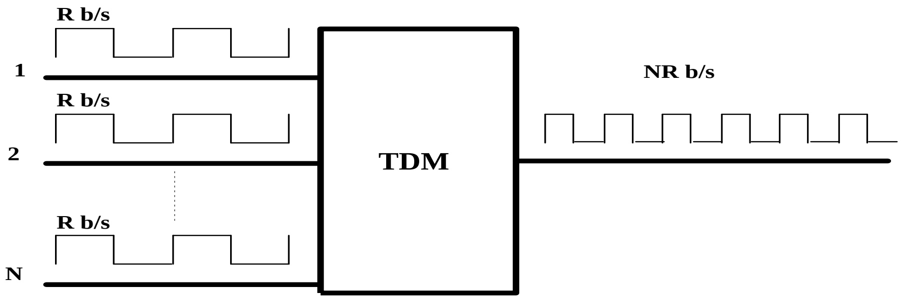


Figure 2.7: Time division multiplexing of $N\ Rb/s$ data streams into a single fiber with a total bit rate of NRb/s

SONET is implemented on many topologies such as point-to-point, linear and ring architectures. Among these, the ring architecture is the most popular one. SONET is implemented on a ring based architecture with various kinds of network elements such as Add/Drop Multiplexer (ADM) and Digital Cross Connect (DCS).

Figure 2.8 illustrates a SONET architecture composed of three rings (each with four ADMs) interconnected by a DCS. ADMs are used to drop a lower speed stream from a higher speed stream or to inject a lower speed traffic into a higher speed traffic. The standard bit rates for SONET can be seen in Table 2.1. For example, a SONET ADM can drop an OC-3 stream from an OC-48 stream or add an OC-12 and OC-3 streams to an OC-192 stream. The function of a DCS is to multiplex, switch and remultiplex the signals with which it interfaces. A DCS is capable of cross connecting the streams that are passing through, and it is mainly used for ring interconnection.

Ring networks are widely used by many network service providers basically because of their simple 2-connected structure. In a ring topology there exist two link and node disjoint paths between any node pair on the ring. This structure

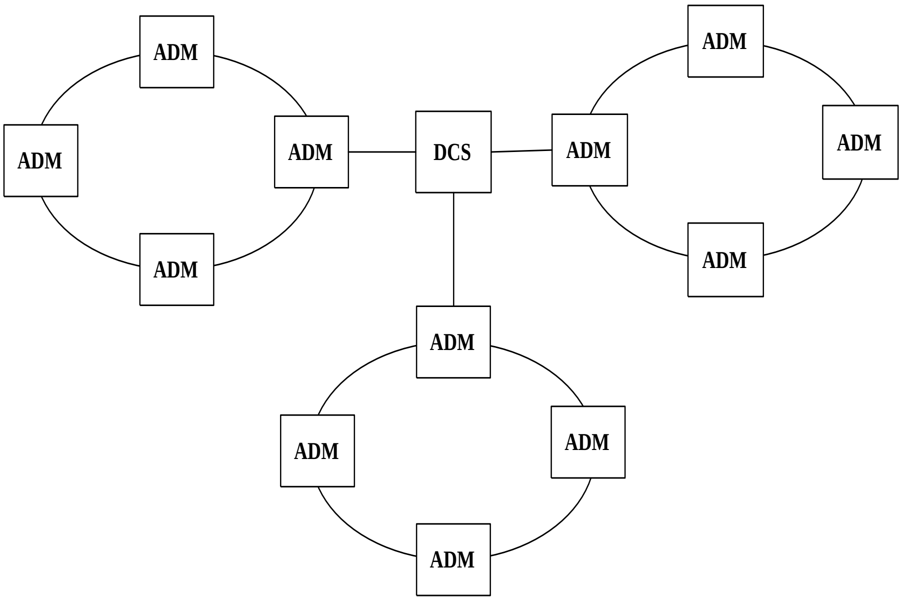


Figure 2.8: Elements of a SONET infrastructure

SONET Signal	Bit Rate (Mb/s)
OC-1	51.84
OC-3	155.52
OC-12	622.8
OC-24	1244.16
OC-48	2488.32
OC-192	9953.28

Table 2.1: Traffic on US long distance Networks

allows rings to be resilient against failures. Hence SONET rings have attracted intense attention for this resilience capability. Although, there exist different SONET ring implementations in terms of protection mechanism, the restoration time in SONET rings does not exceed 50 milliseconds. SONET is deployed both in the access and core networks. In the access part, the typical data rates are OC-3/OC-12 and for the backbone part the rates are generally OC-12, OC-48 and OC-192.

Although, carriers rely on SONET's ring structure for restoration within 50 milliseconds, this protection technique requires 100 percent extra capacity for restoration. Furthermore, the economics of SONET rings are not as attractive as desired. To increase capacity, rings are stacked up on top of each other, and DCSs are required to interconnect these rings and to manage the traffic in the core network. The cost and complexity of this structure grows very rapidly. In addition to this, the required time to provision high-speed (OC-48 and higher) services between two cities can reach a few months, and there have to be some manual configurations of network elements throughout the path.

Furthermore, as a general drawback of first generation of optical networks, electronic switching forms a speed bottleneck for optical domain. Therefore, *"Second Generation Optical Networks"* which use optical domain not only in transmission but also in switching and routing are considered.

With the introduction of Wavelength Division Multiplexing (WDM), the capacity of the fiber is substantially increased. WDM provides substantial increase in the transmission capacity by deploying multiple channels (wavelengths) over a single fiber. The idea of WDM is the same as that of Frequency Division Multiplexing (FDM) , where data is transmitted over multiple frequencies which are sufficiently apart from each other in order to avoid aliasing. On the other hand, in WDM the data is transmitted over multiple wavelengths where the frequency of each wavelength is far from each other such that the wavelength spacing is significantly larger than the bandwidths of the individual signals (see Figure 2.9.)

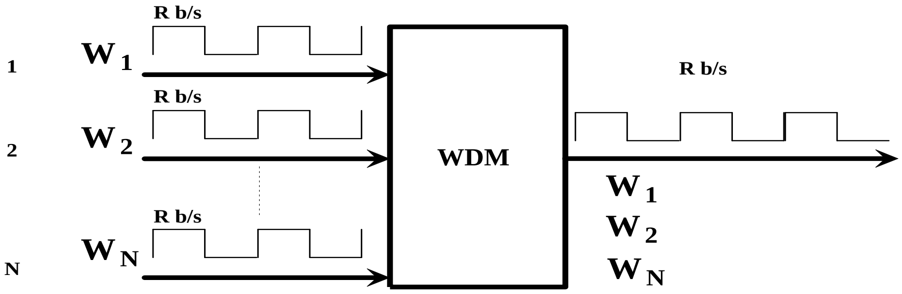


Figure 2.9: Wavelength division multiplexing of N Rb/s data streams into a single fiber

With the advent of WDM technology, second generation optical networks have been considered with mesh structures. The main reason for this is the efficient usage of capacity. Although the number of wavelengths on a fiber is limited, the wavelengths can be more efficiently deployed and reused all over the network. A wavelength routing network can be seen in Figure 2.10. As can be seen in the figure, the same wavelength can be reused spatially all over the network, which leads to an efficient usage of capacity.

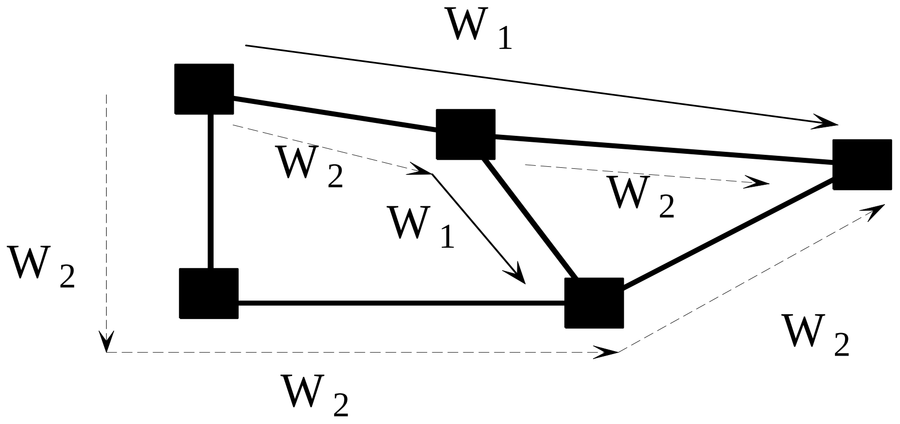


Figure 2.10: A WDM wavelength routing network

As the second generation optical networks extend the tasks of optical domain from transmission to switching, transparency becomes a very crucial concept to be examined. Transparency of optical networks implies that the lightpaths can carry the data over a range of bit rates, protocols, modulation formats. The size of this range depends on the degree of transparency that the optical network provides.

Second generation optical networks can be divided into two main groups considering transparency. On one hand, a full implementation of optics may result in independence to digital/analog data, bit rate, modulation format, and this implementation generates a high level of transparency. Network that possess such a full optical deployment are called *All-Optical or Transparent Networks.* On the other hand, there exist other networks where at each node the optical signal is converted to electrical signal as in the first generation optical networks.

This type of networks are called *Opaque Networks.* Opaque networks may not support any transparency at all, i.e. they may not allow any change in bit rate or modulation format without replacement or reconfiguration of some network elements.

All-optical networks have been considered extensively in the literature [3, 7, 18, 31]. In this architecture, a connection goes through the network over a completely optical path. This path consists of point-to-point optical links interconnected by all-optical nodes. These nodes typically contain two types of OXCs. Wavelength Selective Cross-Connects (WSXC) can switch an incoming connection on some wavelength onto the same wavelength in any of its outgoing fibers (see Figure 2.11.) In networks utilizing WSXCs connections must satisfy the wavelength continuity constraint, i.e., a connection must remain on the same wavelength on all links along its path. On the other hand, Wavelength Interchanging Cross-Connects (WIXC) employ optical wavelength conversion in order to switch an incoming connection onto any wavelength in any outgoing fiber (see Figure 2.11.) As such, they enable more efficient packing of wavelengths onto the fibers by eliminating wavelength conflicts. Optical wavelength converter technologies have been studied for many years, but their performances so far have been unsatisfactory [13]. Furthermore, they have high costs. Performance of all-optical networks with and without wavelength converters have been studied extensively in the literature [19, 27–29, 32].

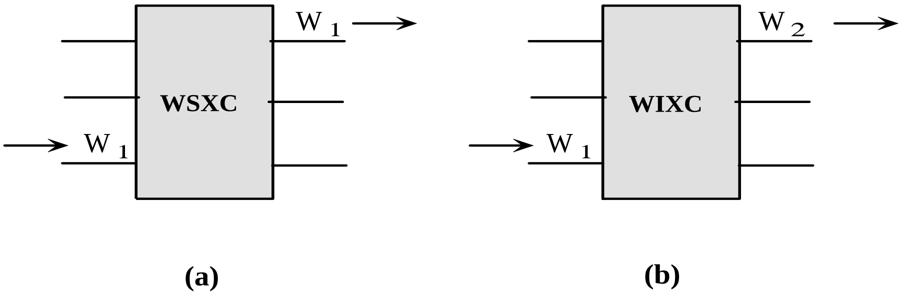


Figure 2.11: Cross connects in all-optical networks (a) Wavelength Selective Cross Connect (WSXC) (b) Wavelength Interchanging Cross Connect (WIXC)

In opaque networks a connection passes through optical/electronic/optical converters, called transponders, at each node [4]. Opaque networks may utilize optical or electronic form of switching at intermediate nodes (see Figure 2.12.) Optical networks that are deployed today are typically opaque, and they use Electronic Cross-Connects (EXC) which perform switching electronically [16]. Although EXCs currently have cost advantages over OXCs they are not very scalable. As the number of wavelengths per fiber is increasing continuously, developing large-size EXCs will become a major obstacle on the evolution path of currently deployed networks. Therefore promising technologies such as micro-electromechanical systems (MEMS) are being considered for developing large-size low-cost OXCs [20, 23]. Performance analysis of opaque networks is quite similar with WIXC-based all-optical networks, hence the literature therein is applicable. The main reason for this is that transponders are devices that can perform wavelength conversion electronically.

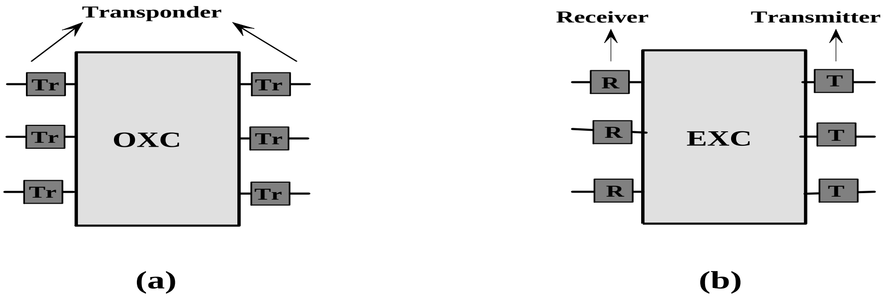


Figure 2.12: Cross connects in opaque networks (a) Optical Cross Connect (OXC) with transponders (b) Electronic Cross Connect (EXC) with receivers and transmitters

One of the main advantages of all-optical networks is transparency. There are various levels of transparency delivered by all-optical networks such as bit rate, protocol, modulation format and analog/digital transparencies. Transparency has important practical evolutionary effects since it enables easier deployment of new technologies. However, transparency also brings a cost due to accumulated impairments in optical transmission and switching systems requiring regeneration of optical signals. Currently, there is no optical regeneration technique with a satisfactory performance. As such, geographic extent of all-optical networks is limited, which prohibit them from deployment on a national scale for large countries such as USA.

Since they do not contain either transponders or optical optical wavelength converters, WSXC-based all-optical networks provide cost advantages. Another advantage of all-optical networks is functional simplicity which provides initial and maintenance cost benefits [16].

Opaque networks are superior to transparent networks in fault management. Although there are some proposals for monitoring optical channel continuity and quality using transmitted/received power and cross-talk measurements, these techniques are currently far away from maturity [15]. It will take some time before these methods have performances comparable to electronic fault monitoring techniques such as those in SONET which achieve restoration times under 50 ms. Since electronic monitoring schemes do not satisfy bit-rate transparency, the only currently available method for detecting faults in all-optical networks is to discover the failure at the edges of the network. When a fiber cut occurs in the network, the endpoints of each failed connection detect the failure, but not the location of the link that has failed. Without knowing where the failure has occurred the endpoints may reroute a failed connection over a restoration path which is link-disjoint from the working path. This method requires communication between two end systems at two different sides of the network before switching to the restoration path. Furthermore, all OXCs on the restoration path must be reconfigured for rerouting. Such a technique limits the geographic extent of all-optical networks so that they have restoration times comparable with their electronic counterparts. For example, a national scale network in US may have round-trip propagation delays in close to 40 ms. With opaque networks, on the other hand, a link failure can be detected almost immediately by the two transponders at either sides of the link which results in shorter restoration times.

Another point of comparison between all-optical and opaque networks is the vendor interoperability issue. There are several companies that are developing optical transmission and switching systems. These companies are manufacturing products utilizing different sets of wavelengths with different wavelength spacings. Therefore, it is extremely difficult to have two products from different vendors interoperating with each other, and it will probably remain so in the short term despite ongoing standardization efforts. Since transponders may define standard interfaces between transmission and switching systems, interoperability issue in opaque networks is much simpler compared to all-optical networks.

Finally, as stated before, transponders may also perform wavelength conversion like WIXC based all optical cross connects, that also improves the performance of opaque networks.

In this section we discussed the evolution of optical networks, and presented two architectures for optical networking: all-optical and opaque networks. We examined advantages and disadvantages of these architectures. In the next section we discuss a new architecture for optical networking which is a compromise between all-optical and opaque networks.

2.3 Translucent Optical Networks

As we have stated previously, optical networks evolve from an opaque to a transparent architecture. Due to the limitations defined in the previous sections, currently it is not feasible to deploy an all-optical networking architecture on a national or global scale. As optical networking becomes more commonplace in core transport networks, optical switching technologies are introduced in more network nodes. When the number of nodes in the optical network is large the design and management of the network becomes much complicated. For example, computing the optimum solution of typical network design problems is known to be NP-hard which implies that there is no currently available algorithm for solving these problems in polynomial time [14].

A new type of architecture is being discussed recently in the literature which is called *"islands of transparency"*, where there are all-optical subnetworks each with a certain limited size, and these islands are connected to each other via opaque transponders. A general structure of islands of transparent networks can be seen in Figure 2.13. This new architecture is called translucent optical networks in this thesis. We believe that islands of transparent optical network architecture will be the main stage through the evolution from opaque to transparent optical networks.

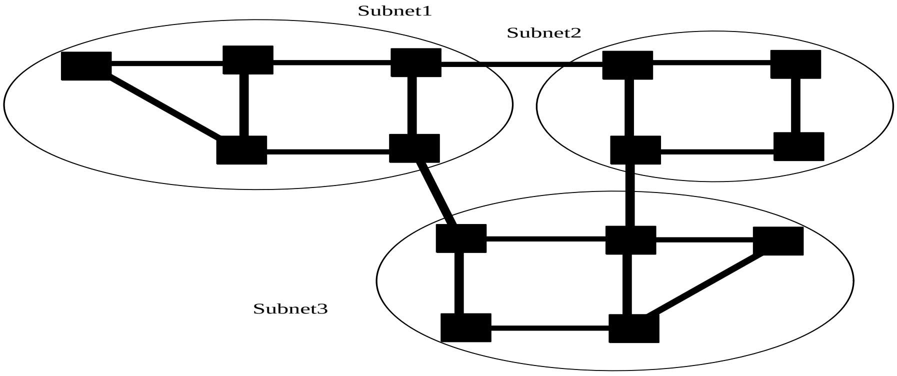


Figure 2.13: Translucent Optical Networks with NNI links

Translucent networks partition a network topology into multiple subnetworks. Each of these subnetworks can be designed and managed separately simplifying these problems substantially. This results in a scalable network architecture: as the number of nodes in the network increases the number of subnetworks will increase, but not the sizes of these subnetworks.

One of the main advantages of translucent optical networks is easier vendor interoperability compared to all-optical networks. On the other hand, translucent networks do not have interoperability flexibility as much as opaque networks where it is possible to have each transmission and switching system bought from different vendors. A simple example of multivendor interoperability in translucent optical networks can be seen in Figure 2.14. Translucent networks require that all transmission and switching systems within a subnetwork should be able to interoperate in the optical layer. However, systems in different subnetworks can be supplied from different vendors which do not necessarily share a common all-optical interface. Those systems are interconnected via transponders using standard O/E/O interfaces. Transponders in translucent networks introduce extra network equipment cost, however their number is substantially reduced compared to opaque networks where each transmission-switching interface contains a transponder.

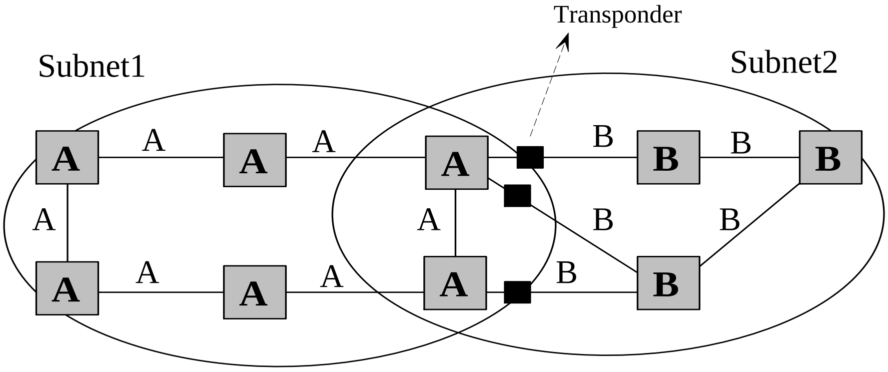


Figure 2.14: Multivendor interoperability in translucent optical networks. The network elements (links and nodes) with label A are from vendor A or compatible, and the network elements with label B are from vendor B or compatible. The interoperability between these network elements are provided by the transponders located at the boundaries of the subnetworks.

Translucent networks also provide simplified operation, administration and management (OAM). The OAM functions of each subnetwork can be performed independent of other subnetworks. This results in a quasi-distributed OAM architecture where there are multiple OAM agents in the network, each responsible for a single subnetwork. The quasi-distributed nature of OAM allows enhanced scalability compared to centralized OAM.

One example of an OAM functionality is restoration. Before discussing the restoration in translucent optical networks, we first describe the restoration problem in a general setting.

2.4 Restoration Problem

Providing resilience against failures is getting intense attention for many high-speed networks as the amount of traffic through these networks is getting larger and larger. Especially with the introduction of the WDM technology, huge amount of data can be carried on a single fiber. Hence, in a single link failure thousands or more connections, each with a bit rate in the order of several Gb/s, may be affected. Therefore, an automatic rerouting scheme is necessary so that when a failure occurs in the network, the end users of the affected connections should not have a disruption of service due to the failure.

There are various kinds of restoration types regarding different criteria. These criteria include type of rerouting, computation timing, location of route computation and execution. Each of these restoration types has some advantages and disadvantages over each other.

When we consider the type of rerouting, there are two main classes: *link restoration* and *path restoration*. When a link fails, link restoration technique reroutes the affected traffic around the failed link, regardless of the sources and destinations of the affected connections. On the other hand, path restoration handles the failure by rerouting each affected connection between its source and destination (see Figure 2.15.)

Link restoration handles the failure faster than the path restoration, since only the end nodes of the failed link will be in charge of the restoration. Meanwhile in the path restoration, for each failed connection the sources and the

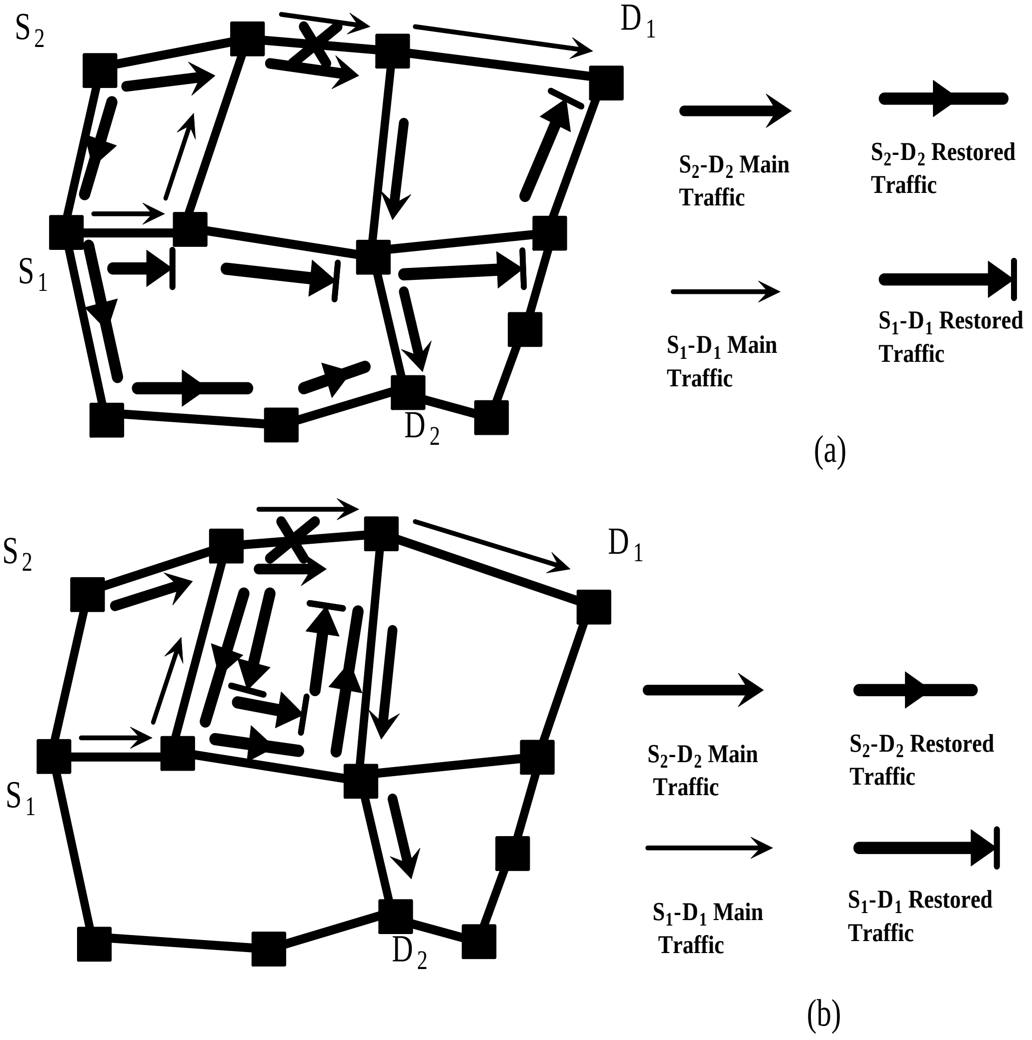


Figure 2.15: (a)A path restoration scenario (b) A link restoration scenario both with two demand pairs

destinations should be informed about the failure, and related sources and destinations compute new routes for affected connections. For national scale networks even the propagation delay from the failed link to the source and destination pair takes a significant amount of time. This task requires much more time than that of link restoration where only neighboring nodes perform the restoration.

On the other hand, path restoration is more efficient than link restoration in terms of network cost. The main reason for this is that path restoration has a much larger choice of restoration paths than link restoration. In other words, path restoration may use spare capacity all over the network, while link restoration has a more limited number of choices for restoration paths since the affected traffic is just bypassed around the failed link.

Restoration types can be divided into two other main groups when we consider the computation timing: *precomputed* and *real-time*. In the precomputed restoration technique, the restoration paths are computed beforehand, and before a failure occurs all restoration paths are ready to carry rerouted traffic in case of any failure in the network. Unlike the precomputed approach, in the real-time approach, the restoration paths are determined just after the detection of the failure. This technique may need Ethernet type discovery mechanisms to allocate the spare capacity for the restoration purposes. Precomputed method is faster than the real-time technique since there is no restoration path discovery.

Restoration techniques can also be classified regarding the route computation and execution phase. There are two basic types which are *centralized* and *distributed* restorations. As the name implies, centralized restoration has a single restoration manager (RM) which is in charge of all restoration in case of any failure. This manager or controller has all the topology and demand information of the network and performs all necessary computation and communication with the nodes. For large networks, it is not easy to store all the information about the whole network at a single point and to respond quickly once the failure occurs. Therefore the centralized method is not a scalable technique. Furthermore, having a single RM creates a singe point of failure in case the RM goes out of service. On the other hand, distributed approaches do not have a RM which deals with all the restoration process for the entire network. Instead, the network elements themselves are in charge of the rerouting process in a distributed manner. However, like the centralized method, distributed technique has the scalability problem, since the network elements will have difficulty in storing, processing and managing all the path and capacity information for a very large network.

After presenting a background information about restoration problem, we next discuss the restoration in translucent optical networks.

2.5 Restoration in Translucent Optical Networks

In translucent networks the restoration function can be managed by multiple RMs, one for each subnetwork. Each RM is held accountable for restoring failures within its own subnetwork. This results in a quasi-distributed restoration technique. In this thesis, we consider restoration in the optical layer in response to only single link failures. With that assumption, the restoration technique presented in this thesis guarantees that only one RM is rerouting failed connections at any given time without communicating with other RMs. Below we describe the proposed restoration architecture in translucent networks in more detail.

In this thesis, we consider precomputed restoration where working and restoration link capacities are computed for a static traffic demand such that all connections can be restored in the case of any single link failure. Network design algorithms for preplanned restoration in all-optical networks have been studied extensively in the literature [2, 8, 10–12, 22, 33].

Translucent optical networks introduced in the literature possess a network architecture shown in Figure 2.13 [25]. The optical subnetworks are interconnected via links which are implementing a network-network interface (NNI). These NNI links do not belong to any subnetwork. Whereas a failure within a subnetwork is restored internally, failure of an NNI link results in path restoration between source and destination nodes which may reside in different subnetworks [25]. Such a rerouting requires actions executed in multiple subnetworks simultaneously that significantly complicate the execution of restoration. Furthermore, path restoration in a national-scale network results in longer restoration times.

In the translucent network architecture presented in this thesis each link belongs to a subnetwork. When a link within subnetwork S_i fails the transponders located at the boundaries of S_i will detect the failure of each affected connection without requiring any optical monitoring. This information will be forwarded to the RM for S_i which will handle the restoration of all failed connections. Each failed connection will be rerouted between its entry and exit points of subnetwork S_i. We call this type of rerouting as *section restoration,* since the section of the failed path that resides within S_i is rerouted. If a failed connection has its source and/or destination nodes in S_i, then the tunable laser/receivers at the add/drop ports of the OXCs will detect the failure. Examples of section restoration for two possible failure scenarios are illustrated in Figure 2.16.

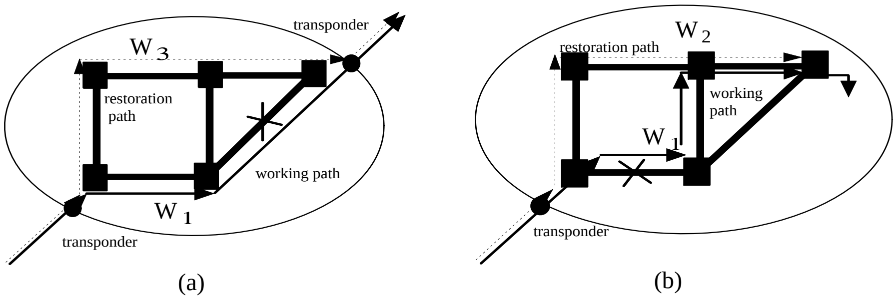


Figure 2.16: Examples of section restoration: (a) restoration path for a connection expressing through a subnetwork, (b) restoration path for a connection terminating in a subnetwork

Since the size of each subnetwork is relatively small, propagation of failure information and reconfiguration of OXCs can be accomplished in shorter time with section restoration compared to path restoration. Estimated restoration times of section restoration are illustrated in Table 2.2. These restoration times are composed of the time for propagation of failure information from the location of failure to the related RM, detection time of failure in RM, cross connection time which is the time for reconfiguring the network elements for rerouting.

Distance Between Failure and RM (km)	Detection Time (ms)	Cross Connection Time (ms)	Propagation Time (ms)	Total Restoration Time (ms)
5000	10	20	16.7	46.7
4000	10	20	13.3	43.3
3000	10	20	10.0	40.0
2500	10	20	8.0	38.0
2000	10	20	6.7	36.7
1000	10	20	3.3	33.3
500	10	20	1.7	31.7

Table 2.2: Estimated restoration times for section restoration

Table 2.2 illustrates the estimated restoration times of section restoration for several distance values between the failure location and the RM. The maximum restoration time with the distance 5000km is estimated to be 46.7ms. This value is comparable with the restoration time of SONET achieving restoration times under 50ms (See Section 2.5.)

Transponders also allow that the restoration path may use a different wavelength than the working path, since they perform electro-optical wavelength conversion.

The quasi-distributed restoration architecture is a compromise between centralized and distributed restoration techniques. Distributed control protocols have been proposed for all-optical networks [21], and distributed control algorithms for link and path restoration are studied [26]. Distributed control protocols are scalable, but they are not easily manageable which may result in undesired modes of operation. Quasi-distributed restoration is more robust compared to centralized restoration, and it is easier to manage compared to distributed restoration.

In the next chapter, we discuss the problem of partitioning the network into subnetworks subject to size and connectivity constraints in order to form a translucent network architecture.

Chapter 3

NETWORK PARTITIONING PROBLEM

In this chapter we present the problem of partitioning a network topology into subnetworks for translucent optical networks. The subnetworks must satisfy several properties. First, each subnetwork should be 2-connected, i.e., there should exist at least two link disjoint paths between any two nodes in the same subnetwork. This is a crucial constraint for guaranteeing 100% restoration against any single link failure within a subnetwork.

Next, the size of the subnetworks should not exceed some certain measures. With subnetworks having small number of links and nodes, RMs deal with smaller databases, and this leads to a more scalable architecture. We restrict the number of nodes in a subnetwork to N_{max} and the number of links to L_{max}. When the size of the entire network increases, the number of the subnetworks, but not their sizes, will increase. Subnetwork size constraints have also impacts on the quality of the signal. Transmission and switching impairments limit the span of all-optical domains. These impairments get worse as the bit rate increases. Although optical technology is advancing rapidly and making larger domains possible [17], a national-scale transparent network is still far away from deployment. In this thesis, we limit the lengths of the working and restoration paths, i.e., the lengths of both paths between any two nodes in the same subnetwork should not exceed R_{max}.

Although we would like to have small sized subnetworks, it is not efficient to have a large number of subnetworks each with a size much smaller than the constraints. Such a design leads to an inefficient design of restoration capacities since section restoration in a small subnetwork resembles link rerouting where the affected traffic is rerouted around the failed link. We would like to have the number of subnetworks as small as possible, leading to subnetworks with sizes close to size constraints.

For restoration purposes each link should belong to only one subnetwork, i.e., when a link fails only one RM of the related subnetwork will be responsible for restoration of failed connections. However, for partitioning purposes, a link may be shared by two or more subnetworks in order to satisfy 2-connectivity for each subnetwork.

The discussion above can be described by introducing a two-layer structure. In the *restoration layer* each link belongs to a single subnetwork, i.e., when that link fails only one RM will handle the failure. There is no need to have the 2-connectivity requirement for the subnetworks from the point of view of restoration layer. On the other hand, in *subnetwork layer* some links may be shared by two or more subnetworks so that each subnetwork is 2-connected. The links shared in the subnetwork layer may be carrying restored traffic resulting from a failure in one of the sharing subnetworks. Since we only consider single link failures, a shared link can be used by traffic directed by at most one RM at any given time.

Subnetwork and restoration layers are illustrated in Figure 3.1 for an example network. Links 1, 2 and 3 are shared by the two subnetworks in the subnetwork layer: link 1 between subnets 1 and 2, link 2 between subnets 1 and 3, and link 3 between subnets 2 and 3. In the restoration layer, links 1 and 2 are in subnet 1, and link 3 belongs to subnet 2. When link 3 fails RM2 will take care of this failure and will reroute all connections passing through link 3. For restoring failed connections, RM2 can use all links in subnet 2 including shared links, e.g. link 1, although failure of that shared link might be handled by another RM.

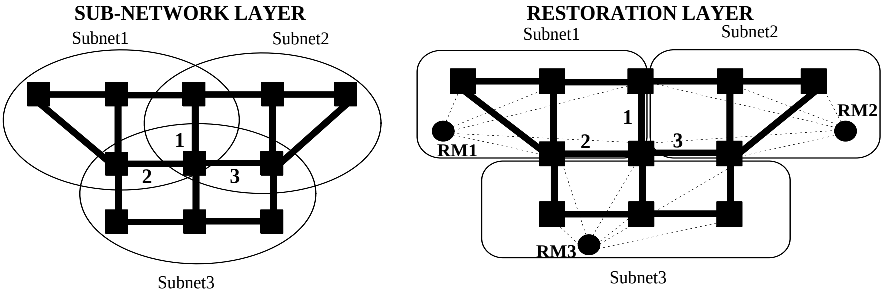


Figure 3.1: Network partitioning in subnetwork and restoration layers

As evident from the above discussion, RMs and network elements in different subnetworks should be sharing a common network control platform, i.e., their network control softwares should be able to interoperate. This is currently the trend in the industry, and there are efforts on developing a standardized optical network control plane [5].

Based on the above constraints two solutions for network partitioning problem are presented below, first based on an ILP formulation and the other based on a greedy heuristic algorithm.

3.1 ILP Formulation

An ILP formulation is developed for the network partitioning problem. This formulation is valid for arbitrary 2-connected network topologies. The entire formulation can be divided into two main parts. First, we compute the set of link disjoint paths between each node pair in the whole network, and then the network is divided into subnetworks using the outputs of the first part. Link disjoint paths are used in the second part in order to guarantee 2-connectivity within each subnetwork. The input-output relationship of these two parts is described below.

3.1.1 Finding the Link Disjoint Paths

The aim of this formulation is to find the maximum number of link disjoint paths for each node pair such that all paths have lengths not exceeding R_{max}. We compute these paths by using a method with two stages. First, the unconstrained max-flow problem is solved, i.e., for each node pair the maximum number of link-disjoint flows that can be carried between these nodes is found such that the total length of all links used by these flows is minimized. At the second stage, link disjoint paths passing through the links with positive flows in the first stage are found subject to the constraint that all paths have lengths not exceeding R_{max}. These two formulations are performed subsequently for all node pairs.

A) Finding Max-Flow with Minimum Cost:

Suppose the network topology is represented by an undirected graph $G = (V, E)$, where V is the node set and E is the set of links. The length of link $(i, j) \in E$ is given by d_{ij}. We define the following variables.

$$D^{mn} = \text{maximum flow that can be carried between nodes } m \text{ and } n$$

$$X_{ij} = \begin{cases} 1 & \text{if there exists flow from node } i \text{ to } j, (i,j) \in E \\ 0 & \text{otherwise} \end{cases}$$

The following formulation is the standard max-flow formulation for computing the maximum number of unconstrained link disjoint path between nodes m and n [1].

Objective: Maximize $D^{mn} - \epsilon \sum_{(i,j)} d_{ij} X_{ij}$
Subject to:

$$\sum_j X_{ij} - \sum_j X_{ji} = \begin{cases} D^{mn} & \text{if } i = m \\ -D^{mn} & \text{if } i = n \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in V$$

$$D^{mn} \in Z^+$$

$$X_{ij} \in \{0,1\} \quad \forall (i,j) \in E$$

The main objective of the above formulation is to maximize the number of link disjoint paths between m and n, which is denoted by D^{mn}. The second term in the objective function ensures that the optimization not only maximizes D^{mn}, but also minimizes the total length of links used. This is needed since otherwise the optimal solution may include unnecessarily long paths as long as the number of disjoint paths is maximized. The scalar ϵ is a very small positive number to ensure that the maximization of D^{mn} takes higher priority. The only constraints in the ILP formulation are the flow conservation equations at each node.

The above problem is solved subsequently for all node pairs. After finding the links whose flow variables are positive for node pair (m, n), we compute the set of all possible paths between nodes m and n using only those links. We denote this set by $\hat{P}^{mn}$.

B) Finding Link Disjoint Paths:

In the second stage, we find the maximum number of link disjoint paths among these enumerated paths such that total lengths of all chosen paths is minimized subject to the constraint that the length of each selected path does not exceed R_{max}. This problem is formulated below for node pair (m, n). Here d_l denotes the length of link $l = (i, j)$. Let the indicator function δ_{lp} is defined as

$$\delta_{lp} = \begin{cases} 1 & \text{if link } l \text{ is on path } p \\ 0 & \text{otherwise} \end{cases}$$

for each $l \in E$ and $p \in \hat{P}^{mn}$. The decision variable X_p is defined as

$$X_p = \begin{cases} 1 & \text{if path } p \text{ is chosen as one of the link disjoint paths,} p \in P \\ 0 & \text{otherwise} \end{cases}$$

The ILP formulation is given by

Objective: Minimize $\sum_p \sum_l X_p \delta_{lp} d_l$
Subject to:

$$\sum_l X_p \delta_{lp} d_l \leq R_{max} \quad \forall p \in \hat{P}^{mn} \tag{3.1}$$

$$\sum_p X_p \delta_{lp} \leq 1 \quad \forall l \in E \tag{3.2}$$

$$\sum_p X_p = D^{mn} \tag{3.3}$$

$$X_p \in \{0, 1\} \forall p \in \hat{P}^{mn}$$

Constraint (3.1) ensures that any selected path should have a length less than or equal to R_{max}. Constraint (3.2) guarantees that selected paths are link disjoint, and (3.3) forces that maximum number of paths to be chosen.

The above formulation is solved subsequently for all node pairs. It is possible that some of the paths that constitute the maximum flow D^{mn} have lengths exceeding R_{max}. In that case, there is no feasible solution to the above problem. Since our goal is to maximize the number of link disjoint paths subject to length constraints, we decrement D^{mn}, and solve the above problem again. We continue this procedure until either there exists a feasible solution or, D^{mn} becomes 0. In the latter case, we set the number of constrained link disjoint paths between nodes m and n to zero.

At the output of the final stage, we obtain the link disjoint paths between all node pairs, and these paths will be input to the second phase of the ILP formulation which concludes the network partitioning.

3.1.2 Partitioning Process

In the above formulation maximum number of link disjoint paths are found whose lengths are all less than R_{max}, and these paths are used by the partitioning formulation given below. Let P^{mn} denote the set of link disjoint paths as found at the end of first phase. Let P_k^{mn} denote k-th shortest path in P^{mn}, and let $[P_k^{mn}]$ denote the number of links on path P_k^{mn}. Let the indicator function δ_{ln} describe the node-link adjacency as defined below

$$\delta_{ln} = \begin{cases} 1 & \text{if link } l \text{ is adjacent to node } n \\ 0 & \text{otherwise} \end{cases}$$

We define the following decision variables:

$$Y_{ns} = \begin{cases} 1 & \text{if node } n \text{ is in subnetwork } s \\ 0 & \text{otherwise} \end{cases}$$

$$U_{ls} = \begin{cases} 1 & \text{if link } l \text{ is in subnetwork } s \\ 0 & \text{otherwise} \end{cases}$$

Next, we define the following auxiliary variables:

$$Z_{mns} = \begin{cases} 1 & \text{if } Y_{ms} = Y_{ns} = 1 \text{ i.e., both nodes } m \text{ and } n \text{ are in subnetwork } s \\ 0 & \text{otherwise} \end{cases}$$

$$W_{ks}^{mn} = \begin{cases} 1 & \text{if } P_k^{mn} \text{ lies completely inside subnetwork } s \\ 0 & \text{otherwise} \end{cases}$$

$$T_s = \begin{cases} 1 & \text{if subnetwork } s \text{ exists} \\ 0 & \text{otherwise} \end{cases}$$

The ILP formulation for the network partitioning problem is given by:

Objective: Minimize $\sum_s T_s + \epsilon \sum_s \sum_l U_{ls}$

Subject to:

$$\sum_s U_{ls} \geq 1 \quad \forall l \tag{3.4}$$

$$Y_{ns} \geq U_{ls}\delta_{ln} \quad \forall n, \forall s, \forall l \tag{3.5}$$

$$Y_{ns} \leq \sum_{l \in E} U_{ls}\delta_{ln} \quad \forall n, \forall s \tag{3.6}$$

$$\sum_l U_{ls} \leq L_{max} \forall s \tag{3.7}$$

$$\sum_n Y_{ns} \leq N_{max} \forall s \tag{3.8}$$

$$Z_{mns} \leq Y_{ms} \quad \forall m, n, \forall s \tag{3.9}$$

$$Z_{mns} \leq Y_{ns} \quad \forall m, n, \forall s \tag{3.10}$$

$$Z_{mns} \geq Y_{ns} + Y_{ms} - 1 \quad \forall m, n, \forall s \tag{3.11}$$

$$W_{ks}^{mn} \leq U_{ls} \quad \forall l \in P_k^{mn}, \forall s, \forall k, \forall m, n \tag{3.12}$$

$$W_{ks}^{mn} \geq \sum_{l \in P_k^{mn}} U_{ls} - [P_k^{mn}] + 1 \quad \forall s, \forall k, \forall m, n \tag{3.13}$$

$$\sum_k W_{ks}^{mn} \geq 2Z_{mns} \quad \forall m, n, \forall s \tag{3.14}$$

$$U_{ls} \leq T_s \quad \forall l \tag{3.15}$$

$$Y_{ns}, U_{ls}, Z_{mns}, W_{ks}^{mn} \in \{0, 1\}$$

The objective of the formulation is to minimize not only the total number of subnetworks but also the total number of shared links. Both objectives are embedded into one objective function by multiplying the latter one with a small constant ϵ such that the values of the objectives will remain in different digits. By reducing the number of shared links we make the design of individual subnetworks, which will be discussed in the next section, more independent from each other.

Constraint (3.4) expresses that each link must belong to at least one subnetwork. This constraint describes the sharing of links in the subnetwork layer as discussed in the beginning of Chapter 3. The constraints (3.5-3.6) state that if one adjacent link of node n belongs to subnetwork s then node n is a part of subnetwork s. Constraints (3.7-3.8) guarantee that each subnetwork satisfies node and link size constraints. The equations (3.9-3.11) imply that if both nodes m and n are in subnetwork s then the variable $Z_{m,n,s} = 1$, otherwise $Z_{m,n,s} = 0$. Constraints (3.12-3.13) indicate that in order to have $W_{k,s}^{m,n} = 1$, all the links on path P_k^{mn} should reside in subnetwork s, otherwise $W_{k,s}^{m,n} = 0$. Equation (3.14) provides the 2-connectivity requirement for each subnetwork. If nodes m and n are in subnetwork s, i.e. $Z_{m,n,s} = 1$, then there should exist at least 2 link disjoint paths between nodes m and n lying completely inside subnetwork s. If there are no such two paths $Z_{m,n,s} = 0$. Finally equation (3.15) ensures the existence of a subnetwork if at least one link belongs to that subnetwork.

In this section, we have presented the network partitioning problem as an ILP problem. In the following section, we present a heuristic algorithm for the same partitioning problem.

3.2 Greedy Heuristic Algorithm For Partitioning

The computational complexity of the above ILP formulation is exponential in problem size. The number of variables of the above ILP formulation is $(S).\{\binom{N}{2}.(K) + (N) + (E) + \binom{N}{2} + 1\}$ and the number of constraints is $(S).\{4.\binom{N}{2} + 3.(E) + (LK) + \binom{N}{2}.(K) + (N)\} + (E)$ where (S) is the number of subnetworks, (N) is the number of nodes, (E) is the number of links, (K) is the average number of existing link disjoint paths between a node pair, and finally (LK) is the total number of links belonging to the link disjoint paths between all demand pairs. The dominating factor in the problem size is $\binom{N}{2}$ which is in the order of N^2. For instance, for a 32-node, 50-link network, the number of variables is approximately 10000 and the number of constraints is around 30000.

For large networks it may not be possible to obtain a result within a reasonable amount of time. Therefore, we propose a heuristic algorithm for planar network topologies. A *planar graph* is a graph that can be drawn in the plane such that its edges intersect only at their common end-vertices [6]. Most of the core network topologies deployed in the field are planar. When there are two links that intersect each other, typically a node is placed at that junction. Planar networks possess nice properties that simplify partitioning.

For a planar graph the regions bounded by the edges are called *faces.* The links surrounding a face constitute a simple cycle which is 2-connected. Two faces are called adjacent if they share one edge. The number of faces of a connected planar graph $G = (V, E)$ is given by the Euler formula

$$|F| = |E| - |V| + 2$$

where $|E|$ is the number of edges and $|V|$ is the number of nodes in G.

The heuristic algorithm can be examined in two parts. In the first part we find the faces of the planar graph corresponding to the network topology. There are several algorithms for finding the faces in a planar graph (see [24] for references). After faces are found we combine adjacent faces to form the subnetworks which satisfy size constraints. The 2-connectivity constraint is already met since individual faces and their combinations with other adjacent faces form 2-connected subgraphs.

3.2.1 Combining Faces

Before stating the algorithm used in the heuristic, we define a concept called dilation.

Definition 3.1: Let P_1 be the shortest path between nodes m and n and $l_1, l_2, \ldots, l_p$ be the links on the shortest path. Let G be the graph that represents the network topology. Define $dist(m, n|G)$ as the length of P_1 in G. The *dilation* of m and n in topology G is defined as

$$dil(m, n|G) = \frac{max_{i=1,2,\ldots,p} dist(m, n|(G - l_i))}{dist(m, n|G)}.$$

The face combining algorithm starts with a cluster which is initially a single face, and then begins to enlarge the cluster by combining it with adjacent faces. If the face to be added violates one of R_{max}, N_{max} or L_{max} constraints for the newly formed cluster, that cluster is no more considered and a new cluster is initiated with a previously unselected face.

Next, we describe which adjacent face is selected for joining the cluster. In a cluster $\tilde{G}$ obeying the R_{max} constraint, the shortest path between each node pair within the subnetwork should have a length less than or equal R_{max}, that is $dist(m, n|\tilde{G}) \leq R_{max} \forall m, n \in V$. Furthermore, $dist(m, n|\tilde{G} - l_i) \leq R_{max} \forall m, n \in V, \forall i$ where l_i's are the links that are on the shortest path between nodes m and n. In other words these paths are obtained by deleting each time one of the links of the shortest path and finding the new shortest path between the node pair.

Among the newly formed candidate clusters satisfying the R_{max}, N_{max} or L_{max} constraints, the one with the minimum average dilation is chosen as the face to be added to the current cluster. This average is taken over all node pairs in the candidate cluster which is the union of the current cluster with the adjacent face considered for addition.

We continue enlarging the current cluster until there exist no adjacent face that satisfy the size constraints when added to the cluster . Then a new cluster is initiated with a face which was not included in any cluster, and the same process continues until there exists no face which is not included in any cluster. The clusters obtained at the termination of the algorithm form the subnetworks.

The algorithm can be summarized as follows:

Heuristic Algorithm:

1. Initiate a new cluster with an arbitrarily selected face which has not been included in any cluster. If no such face exists, stop.
2. For the current cluster find the adjacent face that has the minimum dilation and satisfies the size constraints. If no such face exists, go to Step 1.
3. Add the selected face to the current cluster, and go to Step 2.

Next, we will present the results obtained from both the ILP formulation and the heuristic algorithm.

3.3 Numerical Results

ILP formulation and the greedy heuristic algorithms are applied to two different network topologies. The 32-node topology given in Figure 3.6 is an approximation of a carrier's core network where nodes correspond to major US cities. This topology has been used in the literature before [2]. The 23-node mesh network shown in Figure 3.2 is the right-half of the 32-node topology. The lengths of the links in these networks are the actual distances between major cities corresponding to nodes.

For the 23-node network various kinds of size constraints were used in the partitioning process. We have used the same constraints for both the ILP formulation and the heuristic. The ILP formulation was implemented on CPLEX 6.5 which is a commercial optimization software package.

For $R_{max} = 2500$km, $N_{max} = 12$ and $L_{max} = 15$, both methods were able to generate a partitioning for the 23-node network shown in Figures 3.2(a) and 3.4. The ILP formulation generated 4 subnetworks whereas the heuristic produced 3 subnetworks. With the ILP formulation subnetwork sizes are 11, 4, 12 and 6 nodes and with the heuristic they are 11, 9, and 11. The main reason for heuristic partitioning produces smaller number of subnetworks than the optimum ILP partitioning is that the size constraint for a subnetwork in ILP partitioning is different from the size constraint in heuristic partitioning. Although L_{max} and N_{max} criteria are the same for both methods, R_{max} criterion is implemented entirely differently in ILP and heuristic partitionings. In the ILP formulation it is required that there are at least two link-disjoint paths with lengths not exceeding R_{max} for any two nodes in the same subnetwork. On the other hand, the heuristic algorithm guarantees only that when any link on the shortest path fails, there is an alternative path with length not exceeding R_{max} which is not necessarily link-disjoint from the shortest path.

When we increase R_{max} from 2500km to 3000km and leave the other parameters same as the previous example, the ILP formulation produces again 4 subnetworks but with different topologies as shown in Figure 3.2(b), while subnetworks generated by the heuristic algorithm are exactly the same as that of the previous example shown in Figure 3.4. With the new parameters the ILP formulation generates subnetworks with sizes 4, 9, 7 and 11 nodes. The variance of the subnetwork sizes decreases with the increase in R_{max}, and also the number of shared links in the subnetwork layer is reduced as expected.

On the other hand, with the parameters $R_{max} = 2500$km, $N_{max} = 16$, and $L_{max} = 24$, the partitionings produced by the two methods look similar as shown in Figures 3.3(a) and 3.5(a): both methods produce 3 subnetworks. With the ILP formulation subnetwork sizes are 16, 8, 6 nodes, and with the heuristic they are 16, 6 and 10. Again when we increase R_{max} to 3000km, a slight difference in partitioning with the heuristic occurs as can be seen in Figure 3.5(b), where the number of the subnetworks does not change, however their sizes are altered. The new subnetwork sizes are 16, 4, 12 nodes. When R_{max} is increased, the output of the ILP formulation changes significantly as shown in Figure 3.3(b) where two subnetworks are generated with sizes of 11 and 15 nodes leading to a significant reduction in the objective cost, that is both the number of subnetworks and the number of shared links are reduced. Another observation is that, unlike the heuristic algorithm the subnetworks generated by the ILP formulation grow in a circular fashion as R_{max} increases.

For the 32-node network the following parameters were used: $R_{max} = 3000$ km, $N_{max} = 16$, and $L_{max} = 24$ and also with the same R_{max} value $N_{max} = 12$ and $L_{max} = 15$ values are used. The ILP formulation was not able to generate a solution within a runtime of 36 hours. The greedy heuristic produced a partitioning with 5 subnetworks shown in Figure 3.6 for $N_{max} = 16$ and $L_{max} = 24$ case. For the same network with the parameters $N_{max} = 12$ and $L_{max} = 15$, the algorithm generated 6 subnetworks as shown in Figure 3.7. Since the R_{max} values are same for both cases, L_{max} and N_{max} parameters are the determining parameters. The size constraints of the latter case are smaller than the former, hence it has produced larger number of subnetworks. We observe from the solutions of the heuristic algorithm that it is inclined to build a very large subnetwork close to size constraints. This can probably be explained by the greedy nature of the heuristic, i.e., it tries to enlarge current subnetwork as mush as possible without considering the rest of the network topology.

In this chapter, we have presented the partitioning of a given network topology using an ILP formulation and a heuristic algorithm. After addressing the partitioning problem, we next examine the design problem of a partitioned network considering the restoration problem.

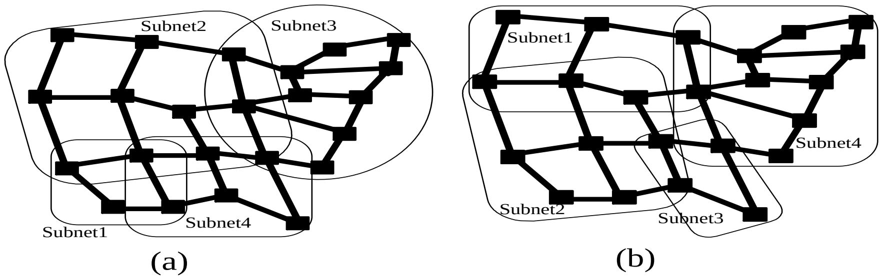


Figure 3.2: Network partitioning for 23-node network (ILP solution) with $L_{max} = 15$, $N_{max} = 12$ (a) $R_{max} = 2500$km (b) $R_{max} = 3000$km

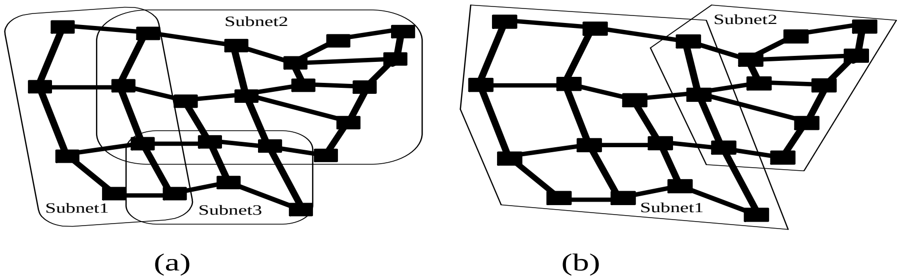


Figure 3.3: Network partitioning for 23-node network (ILP solution) with $L_{max} = 24$, $N_{max} = 16$ (a) $R_{max} = 2500$km (b) $R_{max} = 3000$km

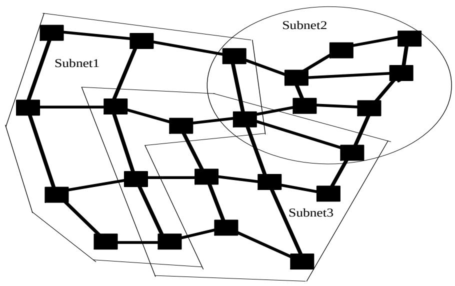


Figure 3.4: Network partitioning for 23-node network (Heuristic solution) with $R_{max} = 2500$km, $L_{max} = 15$, $N_{max} = 12$, and with $R_{max} = 3000$km, $L_{max} = 15$, $N_{max} = 12$

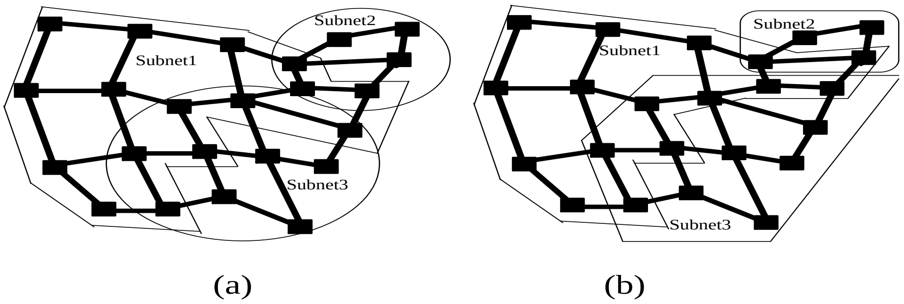


Figure 3.5: Network partitioning for 23-node network (Heuristic solution) with $L_{max} = 24$, $N_{max} = 16$ (a) $R_{max} = 2500$km (b) $R_{max} = 3000$km

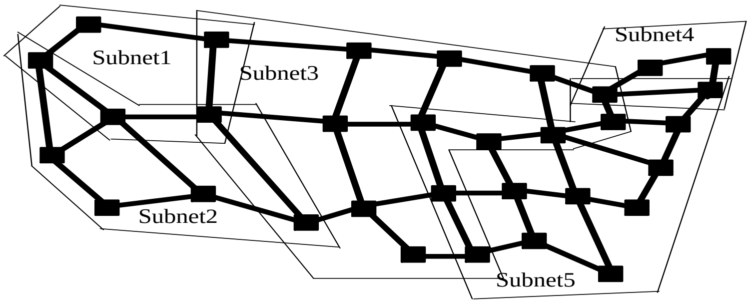


Figure 3.6: Network partitioning for 32-node network (Heuristic solution) with $L_{max} = 24$, $N_{max} = 16$ $R_{max} = 3000$km

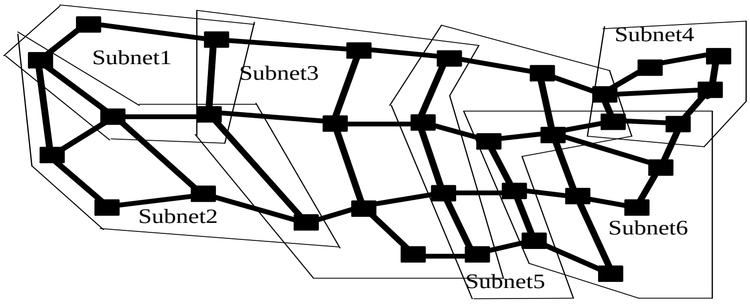


Figure 3.7: Network partitioning for 32-node network (Heuristic solution) with $L_{max} = 15$, $N_{max} = 12$ $R_{max} = 3000$km

Chapter 4

RESTORATION PROBLEM

New multiplexing techniques enable a single link to carry enormous amount of data. Failure of such a link affects thousands of high speed connections each carrying several Gb/s. Therefore, restoring the affected connections within the smallest possible amount of time is getting more and more attention. In this chapter we discuss the restoration problem in translucent optical networks. we analyze the section restoration technique and formulate the network design problem for translucent optical networks using section restoration. We then compare the performance of section restoration with other restoration methods in terms of network cost.

4.1 Restoration in Translucent Networks: Section Restoration

So far we have partitioned a network into subnetworks for the subnetwork layer where some links may be shared between subnetworks. We have not yet discussed how shared links are partitioned in the restoration layer, i.e., we have not determined which RM is in charge of the recovery in case of failure of shared links. We call this problem as the “Link Partitioning Problem”.

We propose a heuristic algorithm for this problem. This algorithm depends only on the topology of the network, hence it does not depend on the traffic, since changes in traffic demands should not affect the decisions for the link partitioning. The objective of the algorithm is that when a link fails, restoration paths used for rerouting are not much longer than the corresponding working paths.

4.1.1 Link Partitioning Heuristic

Consider a shared link l. For all subnetworks sharing this link we remove l from their topology. We then find the K-shortest paths between all node pairs in the subnetwork. We compute the average path length for all such subnetworks where the average is taken over all paths passing through l in each subnetwork. In the restoration layer we assign link l to the subnetwork with the minimum average path length.

This algorithm chooses the subnetwork which has the minimum average K-shortest path length after deleting link l from the subnetwork. The idea behind this heuristic is that, K-shortest paths which do not pass through link l are restoration path candidates for that subnetwork in case of failure of link l. And the algorithm thus chooses the subnetwork which has the restoration path candidates for link l with minimum average length.

After forming the restoration layer, we next carry out the network design by allocating link capacities for both working and restoration paths.

4.1.2 Routing and Capacity Planning

We discuss the network design problem of determining working and restoration capacities so that the network traffic is 100% restorable against all single link failures. We assume that the network is partitioned into all-optical WSXC-based subnetworks both in the subnetwork and restoration layers. Although wavelength conversion is not possible inside subnetworks, it can be performed at the boundaries of the subnetworks. We further assume that the traffic demand is static where there is one unit wavelength of traffic for each demand. However, for the same demand pair, it is possible to have more than one demands and each demand is considered separately. We also assume that the working and restoration fibers are separate. To this end we consider two different design approaches:

- **Joint Design:** All link capacities are optimized for the entire network, i.e., all subnetworks are jointly designed for both working and restoration capacities.
- **Separate Design:** First working paths and capacities are designed for the entire network independent of partitioning of the network. Then, for each subnetwork restoration capacities are computed considering all single link failures. This design is carried out for each subnetwork independent of other subnetworks. The design of each subnetwork involves only those connections that are passing through the subnetwork and their sections within the subnetwork. The restoration capacity for link l is determined by taking the maximum capacity assignment made on link l among all subnetworks sharing l.

The optimum cost of the joint design should be better than the separate design. However, the computational complexity of obtaining the solution for joint design is much larger than the one with separate design. As the number of nodes in the network increases, solving joint design optimally becomes extremely difficult since computational complexity is growing exponentially. On the other hand, with increasing number of nodes the number of subnetworks increases, but not their sizes which are determined by the size constraints in the network partitioning phase. Since solution time for each subnetwork is not affected much with the increasing number of nodes, total solution time for separate design increases almost linearly with network size.

A. Joint Design

An ILP formulation is presented for planning the network by jointly considering the main and restoration capacities. The formulation presented here is a path based formulation, so the working and restoration path are predetermined. We first find the set of K-shortest paths for all demand pairs. Each path is then divided into sections such that all links on each section are assigned to the same subnetwork in the restoration layer. For simplicity we perform this operation in such a way that all sections are maximal, i.e., no two sections can be combined. For the failure of each link on a section, restoration path candidates are found which are the K' shortest paths between the access and exit nodes of the section in the corresponding subnetwork in subnetwork layer. The restoration path candidates in case of a link failure reside in the subnetwork whose restoration layer contains the link.

Let P^{sd} denote the set of K-shortest paths for demand pair (s, d), and let P_k^{sd} be the k-th shortest path in P^{sd}. Each path is divided into its sections given by

$$P_k^{sd} = \bigcup_{i=1}^{t_k^{sd}} P_{ki}^{sd}$$

where P_{ki}^{sd} is the i-th section of P_k^{sd}, and t_k^{sd} is the number of sections on P_k^{sd}. For each $l \in P_k^{sd}$, r_{lkj}^{sd} denotes the j-th restoration path for P_k^{sd} in case of failure of link l, $1 \leq j \leq K'$. As previously defined, d_l denotes the length of link l. The number of wavelengths per fiber is denoted by W.

We define the following indicator functions:

$$\delta_{lk}^{sd} = \begin{cases} 1 & \text{if } P_k^{sd} \text{passes through link } l \\ 0 & \text{otherwise} \end{cases}$$

$$\gamma_{\bar{l}kjl}^{sd} = \begin{cases} 1 & \text{if } r_{\bar{l}kj}^{sd} \text{ passes through link } l \\ 0 & \text{otherwise} \end{cases}$$

$$\xi_{lki}^{sd} = \begin{cases} 1 & \text{if } P_{ki}^{sd} \text{ passes through link } l \\ 0 & \text{otherwise} \end{cases}$$

The decision variables given below are used in the ensuing ILP formulation:

$$Z_k^{sd} = \begin{cases} 1 & \text{if } P_k^{sd} \text{ is chosen as the working path for demand pair } (s,d) \\ 0 & \text{otherwise} \end{cases}$$

$$X_{kiw}^{sd} = \begin{cases} 1 & \text{if wavelength } w \text{ is assigned for working path on } P_{ki}^{sd} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_{lkjw}^{sd} = \begin{cases} 1 & \text{if } r_{lkj}^{sd} \text{ is assigned for restoration using wavelength } w \text{ when link } l \text{ fails} \\ 0 & \text{otherwise} \end{cases}$$

$$WC_l = \text{Working capacity on link } l \text{ (in terms of number of fibers)}$$

$$RC_l = \text{Restoration capacity on link } l \text{ (in terms of number of fibers)}$$

The optimum joint network design problem is given by

Objective: Minimize $\sum_l (WC_l + RC_l) d_l$

Subject to:

$$\sum_k Z_k^{sd} = 1 \quad \forall (s,d) \tag{4.1}$$

$$\sum_w X_{kiw}^{sd} = Z_k^{sd} \quad \forall (s,d), \forall k, \forall 1 \leq i \leq t_k^{sd} \tag{4.2}$$

$$\sum_{j}\sum_{w=1}^{W} Y_{lkjw}^{sd} = Z_k^{sd} \quad \forall (s,d), \forall k, \forall l \in P_k^{sd} \tag{4.3}$$

$$\sum_{(s,d)}\sum_{k}\sum_{i=1}^{t_k^{sd}} X_{kiw}^{sd}\xi_{lki}^{sd} \leq WC_l \quad \forall l, \forall w \tag{4.4}$$

$$\sum_{(s,d)}\sum_{k}\sum_{j} \delta_{\bar{l}k}^{sd}\gamma_{\bar{l}kjl}^{sd}Y_{\bar{l}kjw}^{sd} \leq RC_l \quad \forall l, \forall w, \forall \bar{l} \neq l \tag{4.5}$$

$$Z_k^{sd}, X_{kiw}^{sd}, Y_{lkjw}^{sd} \in \{0,1\} \tag{4.6}$$

$$WC_l, RC_l \in Z^+ \tag{4.7}$$

The objective of this formulation is to minimize the cost of the total used fiber. Constraint (4.1) ensures that among all working path candidates only one is chosen. In constraint (4.2), it is stated that for every section of a working path a wavelength should be assigned. In this constraint, wavelength conversion can be performed at the endpoints of each section. Constraint (4.3) implies that for every link failure on a working path there is a restoration path assigned. Constraints (4.1-4.3) are the path and wavelength assignments for the formulation. The constraints (4.4-4.5) are the link capacity assignments, i.e., network links are assigned working and restoration capacities enough for carrying all traffic demands and for achieving 100% restorability against all single link failures.

B. Separate Design

This formulation is the decoupled version of the joint formulation for the routing and capacity assignment problem. The working and restoration path/capacity assignment problems are separated and solved individually. On top of that, the restoration part of the problem is partitioned into multiple of subnetwork problems, i.e., the design of restoration capacities for each subnetwork is carried out separately.

Since this formulation is a partitioned version of the joint problem, the variables and the indicator functions used in this formulation are the same as that of the joint one. In addition, we define the following indicator function.

$$\alpha_{ls} = \begin{cases} 1 & \text{if link } l \text{ is in subnetwork } s \text{ in restoration layer} \\ 0 & \text{otherwise} \end{cases}$$

First, the working path and capacity assignment is presented, and the restoration part will be discussed subsequently.

Working Path and Capacity Assignment: The ILP formulation for the design of working capacities is given by

Objective: Minimize $\sum_l WC_l d_l$

Subject to:

$$\sum_k Z_k^{sd} = 1 \quad \forall (s,d) \tag{4.8}$$

$$\sum_w X_{kiw}^{sd} = Z_k^{sd} \quad \forall (s,d), \forall k, \forall 1 \leq i \leq t_k^{sd} \tag{4.9}$$

$$\sum_{(s,d)} \sum_k \sum_i^{t_k^{sd}} X_{kiw}^{sd} \xi_{lki}^{sd} \leq WC_l \quad \forall l, \forall w \tag{4.10}$$

$$Z_k^{sd}, X_{kiw}^{sd} \in (0,1) \tag{4.11}$$

$$WC_l \in Z^+ \tag{4.12}$$

The objective of this formulation is to minimize the cost of the total used fiber for working paths. Constraint (4.8) implies that only one of the working path is selected for each demand. Constraint (4.9) assigns a wavelength on each section of the selected working path. In constraint (4.10), the working capacity is determined such that all connections can be carried over the network.

Restoration Path and Capacity Assignment: In this part, we present an ILP formulation for computing the assigned restoration path and capacities for subnetwork s. The problem is given by

Objective: Minimize $\sum_l RC_l d_l$

Subject to:

$$\sum_{j}\sum_{w=1}^{W} Y^{sd}_{lkjw} = Z^{sd}_{k} \quad \forall (s,d), \forall k, \forall l \in P^{s,d}_{k} \tag{4.13}$$

$$\sum_{(s,d)}\sum_{k}\sum_{j} \delta^{sd}_{\bar{l}k}\gamma^{sd}_{\bar{l}kjl}\alpha_{\bar{l}s}Y^{sd}_{\bar{l}kjw} \leq RC_{l} \quad \forall l, \forall w, \forall \bar{l} \neq l \tag{4.14}$$

$$Y^{sd}_{lkjw} \in \{0,1\} \tag{4.15}$$

$$RC_{l} \in Z^{+} \tag{4.16}$$

The objective of this formulation is to minimize the cost of the total used fiber for restoration paths. Constraint (4.13) assigns a wavelength on one restoration path for each failed working path in case of a link failure. Constraint (4.14) determines the restoration capacity for each link in subnetwork s in case of single link failures.

This formulation is implemented successively for all subnetworks. After all subnetworks are designed individually, restoration link capacity assigned on a link is found by taking the maximum over all assignments made by design of individual subnetworks sharing the link in the subnetwork layer.

Next, we discuss the network design problem for path restoration.

4.2 Path Restoration

Similar to the section restoration, in path restoration we discuss the network design problem of determining working and restoration capacities such that the network traffic is 100% restorable against all single link failures. We again assume that the traffic demand is static where there is one unit wavelength of traffic for each demand, and again for the same demand pair, it is possible to have more than one demands and each demand is considered separately. We also assume that the working and restoration fibers are separate.

For the path restoration there are two cases to be considered with respect to the locations of the transponders. First, in order to have a fair comparison with section restoration, we locate the transponders at the same locations as in the section restoration case. Thus, in this case the wavelength conversion is allowed only at the boundaries of the subnetworks. For the second case, in order to find the lowest limit of the network cost, we allow wavelength conversion at all nodes of the network. In the preceding sections we call the former case as *fair conversion* and latter case as the *full conversion.*

4.2.1 Routing and Capacity Planning

A. Fair Conversion

As discussed previously, in the fair conversion case, the wavelength conversion is performed at the access and exit points of the subnetworks. This provides us with the fairness for the comparison of the network costs of these two restoration techniques.

We propose two approaches for path restoration with fair conversion. In the first approach we present a formulation that determines working paths/capacities and restoration paths/capacities concurrently. On the other hand, in the second approach we decouple the problem into two subproblems such that the working paths and capacities are assigned first and the corresponding restoration paths and capacities are computed subsequently. As in the section restoration case, the first approach is called the *joint design* and the latter one is *separate design.*

A.1. Joint Design

An ILP formulation is presented for planning the network by jointly considering the main and restoration capacities. The formulation presented here is a path based formulation, so the working and restoration path are predetermined. We first find the set of K-shortest paths for all demand pairs. Each path is then divided into sections such that all links on each section are in the same subnetwork. For simplicity we perform this operation in such a way that all sections are maximal, i.e., no two sections can be combined. For the failure of each link in a section, restoration path candidates are found which are the K' shortest paths between the source and destination nodes of the demand pair. And this time, unlike the section restoration case, we also determine the sections of restoration path candidates in order to locate the transponders at the access and exit points of the sections. By these transponders, we are able to have wavelength conversion at the boundaries.

As defined earlier, P^{sd} denotes the set of K-shortest paths between demand pair (s, d), and P_k^{sd} is the k-th shortest path in P^{sd}. Each path is divided into its sections given by

$$P_k^{sd} = \bigcup_{i=1}^{t_k^{sd}} P_{ki}^{sd}$$

where P_{ki}^{sd} is the i-th section of P_k^{sd}, and t_k^{sd} is the number of sections on P_k^{sd}.

For each $l \in P_k^{sd}$, r_{lkj}^{sd} denotes the j-th restoration path for P_k^{sd} in case of failure of link l, $1 \leq j \leq K'$. And since for this case the restoration path candidates are also divided into sections, we define r_{lkj}^{sd} as

$$r_{lkj}^{sd} = \bigcup_{i=1}^{q_{lkj}^{sd}} r_{lkji}^{sd}$$

where r_{lkji}^{sd} is the i-th section of r_{lkj}^{sd}, and q_{lkj}^{sd} is the number of sections on r_{lkj}^{sd}. As previously defined, d_l denotes the length of link l. The number of wavelengths per fiber is denoted by W.

We define the following indicator functions:

$$\delta_{lk}^{sd} = \begin{cases} 1 & \text{if } P_k^{sd} \text{passes through link } l \\ 0 & \text{otherwise} \end{cases}$$

$$\gamma_{\bar{l}kjil}^{sd} = \begin{cases} 1 & \text{if } r_{\bar{l}kji}^{sd} \text{ passes through link } l \\ 0 & \text{otherwise} \end{cases}$$

$$\xi_{lki}^{sd} = \begin{cases} 1 & \text{if } P_{ki}^{sd} \text{ passes through link } l \\ 0 & \text{otherwise} \end{cases}$$

The decision variables given below are used in the ensuing ILP formulation:

$$Z_{k}^{sd} = \begin{cases} 1 & \text{if } P_{k}^{sd} \text{ is chosen as the working path for demand pair } (s,d) \\ 0 & \text{otherwise} \end{cases}$$

$$X_{kiw}^{sd} = \begin{cases} 1 & \text{if wavelength } w \text{ is assigned for working path on } P_{ki}^{sd} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_{lkjiw}^{sd} = \begin{cases} 1 & \text{if } r_{lkji}^{sd} \text{ is assigned for restoration using wavelength } w \text{ when link } l \text{ fails} \\ 0 & \text{otherwise} \end{cases}$$

$$\beta_{lkj}^{sd} = \begin{cases} 1 & \text{if } r_{lkj}^{sd} \text{ is chosen to be a restoration path when link } l \text{ fails} \\ 0 & \text{otherwise} \end{cases}$$

$$WC_l = \text{Working capacity on link } l \text{ (in terms of number of fibers)}$$

$$RC_l = \text{Restoration capacity on link } l \text{ (in terms of number of fibers)}$$

The optimum joint network design problem is given by

Objective: Minimize $\sum_l (WC_l + RC_l) d_l$

Subject to:

$$\sum_k Z_k^{sd} = 1 \quad \forall (s,d) \tag{4.17}$$

$$\sum_w X_{kiw}^{sd} = Z_k^{sd} \quad \forall (s,d), \forall k, \forall i : 1 \le i \le t_k^{sd} \tag{4.18}$$

$$\sum_{j=1}^{K'} \beta_{lkj}^{sd} = Z_k^{sd} \quad \forall (s,d), \forall k, \forall l \in P_k^{sd} \tag{4.19}$$

$$\sum_{w=1}^{W} Y_{lkjiw}^{sd} = \beta_{lkj}^{sd} \quad \forall (s,d), \forall k, \forall l \in P_k^{sd} \quad \forall j \quad \forall i : 1 \le i \le q_{lkj}^{sd} \tag{4.20}$$

$$\sum_{(s,d)} \sum_k \sum_{i=1}^{t_k^{sd}} X_{kiw}^{sd} \xi_{lki}^{sd} \le WC_l \quad \forall l, \forall w \tag{4.21}$$

$$\sum_{(s,d)}\sum_{k}\sum_{j}\sum_{i=1}^{q^{sd}_{\bar{l}kj}} \delta^{sd}_{\bar{l}k}\gamma^{sd}_{\bar{l}kjil}Y^{sd}_{\bar{l}kjiw} \leq RC_l \quad \forall l, \forall w, \forall \bar{l} \neq l \tag{4.22}$$

$$Z^{sd}_{k}, X^{sd}_{kiw}, Y^{sd}_{lkjw}, \beta^{sd}_{lkj} \in \{0, 1\} \tag{4.23}$$

$$WC_l, RC_l \in Z^{+} \tag{4.24}$$

The objective of this formulation is to minimize the cost of the total used fiber. Constraint (4.17) ensures that among all working path candidates only one is chosen. In constraint (4.18), it is stated that for every section of a working path a wavelength should be assigned. In this constraint, wavelength conversion can be performed at the endpoints of each section. Constraint (4.19) implies that for every link failure on a working path there is a restoration path assigned. Constraint (4.20) assures that when one of the restoration path candidates is chosen, for each section of that restoration path one wavelength should be assigned, where for each section a different wavelength can be assigned.

Constraints (4.17-4.20) are the path and wavelength assignments for the formulation. The constraints (4.21-4.22) are the link capacity assignments, i.e., network links are assigned working and restoration capacities enough for carrying all traffic demands and for achieving 100% restorability against all single link failures.

Next we decouple the path restoration problem with fair conversion such that the working paths/capacities are designed independent of restoration paths/capacitites.

A.2. Separate Design

This version of the formulation is nothing but the decoupled version of the previous joint formulation. Thus all the variables and indicator function are the same as the previous formulation.

First, we present the formulation that assigns the working path and capacities.

Objective: Minimize $\sum_l WC_l d_l$

Subject to:

$$\sum_k Z_k^{sd} = 1 \quad \forall (s,d) \tag{4.25}$$

$$\sum_w X_{kiw}^{sd} = Z_k^{sd} \quad \forall (s,d), \forall k, \forall i : 1 \leq i \leq t_k^{sd} \tag{4.26}$$

$$\sum_{(s,d)} \sum_k \sum_{i=1}^{t_k^{sd}} X_{kiw}^{sd} \xi_{lki}^{sd} \leq WC_l \quad \forall l, \forall w \tag{4.27}$$

$$Z_k^{sd}, X_{kiw}^{sd} \in \{0,1\} \tag{4.28}$$

$$WC_l \in Z^+ \tag{4.29}$$

The objective of this formulation is to minimize the total length of fiber used for working paths. Since the constraints are the same as those of the joint design, we will not explain these constraint once more.

Solving the above problem and determining $\{WC_l\}$ and $\{Z_k^{sd}\}$, we are now able to design the formulation for the restoration part of the routing and capacity assignment problem. The formulation is given by.

Objective: Minimize $\sum_l RC_l d_l$

Subject to:

$$\sum_{j=1}^{K'} \beta_{lkj}^{sd} = Z_k^{sd} \quad \forall (s,d), \forall k, \forall l \in P_k^{sd} \tag{4.30}$$

$$\sum_{w=1}^{W} Y_{lkjiw}^{sd} = \beta_{lkj}^{sd} \quad \forall (s,d), \forall k, \forall l \in P_k^{sd} \quad \forall j \quad \forall i : 1 \leq i \leq q_{l,k,j}^{s,d} \tag{4.31}$$

$$\sum_{(s,d)} \sum_k \sum_j \sum_{i=1}^{q_{lkj}^{sd}} \delta_{\bar{l}k}^{sd} \gamma_{\bar{l}kjil}^{sd} Y_{\bar{l}kjiw}^{sd} \leq RC_l \quad \forall l, \forall w, \forall \bar{l} \neq l \tag{4.32}$$

$$Y_{lkjw}^{sd}, \beta_{lkj}^{sd} \in \{0,1\} \tag{4.33}$$

$$RC_l \in Z^+ \tag{4.34}$$

The objective of this part of the formulation is to minimize the total length of fiber used for the restoration paths. Since the constraints are the same as those of the joint design, we omit the explanation of these constraints.

B. Full Conversion

Unlike the fair conversion case, in full conversion we allow the wavelength conversion at all nodes of the network. In this formulation our goal is to determine the lowest limit for the network cost. By comparing the results of section restoration with fair conversion and path restoration with full conversion, we will see how section restoration performs with respect to the ideal case.

Similar to the fair conversion situation, in full conversion we present joint and separate designs. In the joint design, working and restoration parameters are determined simultaneously, whereas in the separate design working part is handled first, and then the restoration part is solved.

We first present the joint design approach, and afterwards the decoupled version of the formulation is discussed.

B.1. Joint Design

An ILP formulation is presented for planning the network by jointly considering the main and restoration capacities. The formulation presented here is again a path based formulation, so the working and restoration path are predetermined. We first find the set of K-shortest paths for all demand pairs. For the failure of each link in a section, restoration path candidates are found which are the K' shortest paths between the source and destination nodes of the demand pair. With full conversion there is no need for the sectioning of the paths, since wavelength conversion can be performed not only at the boundaries of the subnetworks but at all nodes of the network. So we do not require section information for both working and restoration path candidates.

As previously defined, P^{sd} denote the set of K-shortest paths between demand pair (s, d), and P_k^{sd} is the k-th shortest path in P^{sd}. For each $l \in P_k^{sd}$, r_{lkj}^{sd} denotes the j-th restoration path for P_k^{sd} in case of failure of link l, $1 \leq j \leq K'$. As defined earlier, d_l denotes the length of link l. The number of wavelengths per fiber is denoted by W.

We define the following indicator functions:

$$\delta_{lk}^{sd} = \begin{cases} 1 & \text{if } P_k^{sd} \text{ passes through link } l \\ 0 & \text{otherwise} \end{cases}$$

$$\gamma_{\bar{l}kjl}^{sd} = \begin{cases} 1 & \text{if } r_{\bar{l}kj}^{sd} \text{ passes through link } l \\ 0 & \text{otherwise} \end{cases}$$

The decision variables given below are used in the ensuing ILP formulation:

$$X_k^{sd} = \begin{cases} 1 & \text{if working path candidate } P_k^{sd} \text{ is chosen} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_{lkj}^{sd} = \begin{cases} 1 & \text{if } r_{lkj}^{sd} \text{ is assigned for restoration, when link } l \text{ fails} \\ 0 & \text{otherwise} \end{cases}$$

$$WC_l = \text{Working capacity on link } l \text{ (in terms of number of fibers)}$$

$$RC_l = \text{Restoration capacity on link } l \text{ (in terms of number of fibers)}$$

The optimum joint network design problem is given by

Objective: Minimize $\sum_l (WC_l + RC_l) d_l$

Subject to:

$$\sum_k X_k^{sd} = 1 \quad \forall (s, d) \tag{4.35}$$

$$\sum_{j=1}^{K'} Y_{lkj}^{sd} = X_k^{sd} \quad \forall (s, d), \forall k, \forall l \in P_k^{sd} \tag{4.36}$$

$$\sum_{(s,d)} \sum_{k} X_k^{sd} \delta_{lk}^{sd} \leq W.WC_l \quad \forall l \tag{4.37}$$

$$\sum_{(s,d)} \sum_{k} \sum_{j} \delta_{\bar{l}k}^{sd} \gamma_{\bar{l}kjl}^{sd} Y_{\bar{l}kj}^{sd} \leq W.RC_l \quad \forall l, \forall w, \forall \bar{l} \neq l \tag{4.38}$$

$$X_k^{sd}, Y_{lkj}^{sd} \in \{0, 1\} \tag{4.39}$$

$$WC_l, RC_l \in Z^+ \tag{4.40}$$

The objective of this formulation is to minimize the cost of the total used fiber. Constraint (4.35) ensures that among all working path candidates only one is chosen. In constraint (4.36), it is stated that for the failure of each link on a working path a restoration path should be assigned.

Constraints (4.35-4.36) are the path and wavelength assignments for the formulation. Constraints (4.37-4.38) are the link capacity assignments, i.e., network links are assigned working and restoration capacities enough for carrying all traffic demands and for achieving 100% restorability against all single link failures.

Next, we decouple the path restoration problem with full conversion.

B.2. Separate Design

As carried out in the previous separate design approaches, we partition the problem into two subproblems. First we design the working portion of the problem, and the restoration part is presented afterwards.

First, the working portion of the problem is presented.

Objective: Minimize $\sum_l WC_l d_l$

Subject to:

$$\sum_{k} X_k^{sd} = 1 \quad \forall (s,d) \tag{4.41}$$

$$\sum_{(s,d)} \sum_{k} X_k^{sd} \delta_{lk}^{sd} \leq W.WC_l \quad \forall l \tag{4.42}$$

$$X_k^{sd} \in \{0, 1\} \tag{4.43}$$

$$WC_l \in Z^+ \tag{4.44}$$

The aim of the above formulation is to minimize the total length of fibers used in the working paths. The above constraints are the same as those of the joint design, thus we do not describe them here one more time.

The restoration paths/capacities design problem is given by
Objective: Minimize $\sum_l RC_l d_l$
Subject to:

$$\sum_{j=1}^{K'} Y_{lkj}^{sd} = X_k^{sd} \quad \forall (s,d), \forall k, \forall l \in P_k^{sd} \tag{4.45}$$

$$\sum_{(s,d)} \sum_{k} \sum_{j} \delta_{\bar{l}k}^{sd} \gamma_{\bar{l}kjl}^{sd} Y_{\bar{l}kj}^{sd} \leq W.RC_l \quad \forall l, \forall w, \forall \bar{l} \neq l \tag{4.46}$$

$$Y_{lkj}^{sd} \in \{0,1\} \tag{4.47}$$

$$RC_l \in Z^+ \tag{4.48}$$

The objective of this formulation is to minimize the total length of fiber used for restoration purposes. The above constraints are the same as the ones in the joint formulation.

So far we have implemented section restoration with fair conversion such that the wavelength conversion is only allowed at the boundaries of the subnetworks in the restoration layer. Furthermore, we have implemented path restoration with fair conversion (sparse conversion) and full conversion (wavelength conversion allowed at all nodes). For all the formulations, we have designed both the joint and decoupled versions.

Next, we examine the results obtained from these implementations.

4.3 Numerical Results

Joint and separate design methods were applied to 23 and 32-node mesh networks shown in Figures 3.3(a) and 3.6. For each network topology we have generated 4 different sets of traffic demands. For all problems the following parameters were used: number of candidate paths for working and restoration paths $K = K' = 4$, and number of wavelengths $W = 8$. The ILP formulation was implemented on CPLEX 6.5 which is a commercial optimization software package.

Both partitionings obtained by the ILP formulation and heuristic algorithm for the 23-node network were considered. Since ILP formulation did not produce any results for partitioning of the 32-node network, only the partitioning obtained by the heuristic algorithm was used. For the joint design algorithm, the maximum running time of CPLEX was limited to 36 hours. For the 23-node network, joint design produced suboptimum solutions within the run-time limit. For the 32-node network, joint design was not able to generate any integer feasible solution within 36 hours for all demand sets. On the other hand, with separate optimization we have also limited both the main and the restoration parts of the problem with a maximum running time of 36 hours, and generally the main part of the problems generated suboptimal solutions within the limited amount of time whereas the restoration parts produced optimal solutions.

In order to compare the performance of the design problems, we have generated 4 different sets of traffic demands having 63, 67, 69, and 63 demand pairs, respectively. For each demand set we have obtained a network cost under different conditions,i.e., with section or path restoration, with separate or joint design, with heuristic or ILP partitioning, and with fair or full conversion.

The results are shown in Tables 4.1 to 4.5. For the 23-node network with optimum ILP partitioning and parameters $R_{max} = 2500$km, $L_{max} = 24$ and $N_{max} = 16$, the fiber costs for section restoration obtained by joint and separate designs are very close as shown in Table 4.1. The highest difference is 10.5% for demand set 4. In fact, for demand set 1 separate design was able to better the joint design. This is possible since the solution with joint design and separate designs are suboptimal, so the decoupled design may generate better results within the same time limits. When the same analysis for the heuristic partitioning with parameters $R_{max} = 2500$, $L_{max} = 24$ and $N_{max} = 16$ is performed a similar situation is observed as shown in Figure 4.2. The cost values for the joint and separate design are again very close, the highest difference is for demand pair 6.1% with demand set 3 and for the other 3 demand sets separate design performes better than the joint design within the same time limits.

The network costs with path restoration using fair conversion are given in Table 4.3 for the 23-node ILP partitioned network. In the three of the demand sets suboptimal solutions for the separate design are better than the joint design solutions. The above experiment is repeated for the 23-node heuristic partitioned network and the results are shown in Table 4.4. In this case, all suboptimum solutions with the separate design are lower than the corresponding joint design solutions.

The performance of section restoration with joint optimization for the 23-node ILP partitioned network with parameters $R_{max} = 2500$, $L_{max} = 24$ and $N_{max} = 16$ compared with the path restoration with joint optimization using fair and full conversions for the same network is shown in Figure 4.1. The cost of all three methods are very close to each other. For demand sets 1 and 4, path restoration outperform section restoration. This is expected since path restoration with fair conversion has a larger choice of paths for restoration purposes compared to section restoration. However, with demand sets 2 and 3, path restoration with fair conversion differs from this anticipated behavior. The reason for this is again the suboptimal characteristics of the solutions. Generally, the performance of section restoration and the path restoration with fair conversion are very close each other. The difference between the costs of section restoration and path restoration/fair conversion ranges from -5% to 8%. Moreover, the path restoration with full conversion achieves the lowest cost, since full conversion allows more efficient packing of wavelengths reducing the network cost. The differences for 4 demand sets between the section restoration and the path restoration with full conversion are 25%, 8%, 6%, 6%. Even though we have not a fair comparison because the path restoration has the advantage of full conversion while section restoration has only conversion at the boundaries of the subnetworks, the cost of section restoration is only slightly higher than path restoration with full conversion for 3 demand sets.

When we make the above comparison for the heuristic algorithm partitioned 23-node network, a similar picture with ILP partitioned case is observed shown in Figure 4.2. The difference between the cost of section restoration and the cost of path restoration/fair conversion is between -7% and 5%. Moreover, the difference between the section restoration and the path restoration with full conversion ranges from 5% to 8% for all demand sets. We also observe that the cost values in this case are generally less than those of the ILP partitioned network.

The same comparisons are repeated with separate optimizations of the section and path restorations for both the ILP and heuristic partitioned 23-node networks and the results are shown in Figures 4.3 and 4.4. In each case the cost of the section restoration is slightly higher than that of path restoration with fair conversion which is also higher than the cost of the path restoration with full conversion. The difference between section restoration with separate design and the path restoration with full conversion/separate/design for the 23-node ILP partitioned network ranges from 11% to 15%. When we compare the same methods for the heuristic partitioned network, the difference in costs comes out between -1.5% and 13%. The negative percent for the difference comes out due to again the suboptimal behaviour of the solutions.

After comparing the performances of joint design with separate design and section restoration with path restoration under joint and separate designs, we next compare the performances of the ILP and heuristic partitionings in terms of the network costs when section restoration is used. As shown in Figure 4.5 the costs under joint optimization for heuristic partitioned 23-node network is lower than those of ILP partitioning for three out of four demand sets. When we consider the separate design, we observe a relatively similar picture as shown in Figure 4.6. Except for the demand set 3, the costs for the heuristic partitioned network are lower than those for ILP partitioned network. The comparison of fiber costs for the 23-node network with two different partitionings demonstrate that the partitioning with the heuristic algorithm produces costs that are 4-7% lower than the costs with ILP partitioning.

We repeat the above experiments for the 32-node network which is partitioned by the heuristic algorithm with parameters $R_{max} = 3000$km, $L_{max} = 24$, and $N_{max} = 16$. We have randomly generated 4 demand sets which have 89, 73, 86, and 66 number of demand pairs, respectivey. The fiber costs for the 32-node network are given in Tables 4.6 and 4.7 and they are also plotted in Figure 4.7. The cost values of section restoration/separate design, and path restoration/separate design/ fair conversion are very close to each other. The highest difference between the costs is 7.3% as shown in Table 4.6. The costs of path restoration with full conversion using separate and joint designs are presented in Table 4.7. As can be seen from the table, the separate design generally produce better results than the joint design. The reason for this is that both the results of separate and joint designs are suboptimal, and it is possible that the decoupled versions may yield better results than the joint versions. The differences between the costs of section restoration/separate design and the costs of the path restoration/full conversion/separate design do not exceed 10%, which is again a promising result for the section restoration.

We complete this chapter by summarizing the following observations based on our numerical studies.

- Separate design generates fiber costs that are generally very close (even superior in many cases) to those of joint design for both section and path restoration within the same run-time limits.
- Section restoration generates fiber costs that are generally within 15% of path restoration with full conversion. Considering the high cost of wavelength conversion, the results will be even more favorable for section restoration when total network cost is considered.
- The network designs using the heuristic partitioned networks produce fiber costs that are generally 4-7% lower than the fiber costs for the ILP partitioned networks.

Demand set	Number of demands	Joint design	Separate design	Difference (%)
D1	63	24136	22124	-8.0
D2	67	24838	25347	2.0
D3	69	22715	24280	6.9
D4	63	21581	23866	10.5

Table 4.1: Total fiber costs for the 23-node network partitioned by ILP formulation with $R_{max} = 2500$km $N_{max} = 16$ and $L_{max} = 24$ using section restoration with joint and separate designs.

Demand set	Number of demands	Joint design	Separate design	Difference (%)
D1	63	20944	20340	-2.9
D2	67	24183	24125	-0.2
D3	69	23174	24581	6.1
D4	63	21453	20440	-4.7

Table 4.2: Total fiber costs for the 23-node network partitioned by Heuristic with $R_{max} = 2500$km $N_{max} = 16$ and $L_{max} = 24$ using section restoration with joint and separate designs.

Demand set	Number of demands	Joint design	Separate design	Difference (%)
D1	63	22275	19761	-11.3
D2	67	26396	22478	-14.8
D3	69	23934	22057	-7.8
D4	63	21095	21580	2.3

Table 4.3: Total fiber costs for the 23-node network partitioned by ILP formulation with $R_{max} = 2500$km $N_{max} = 16$ and $L_{max} = 24$ using path restoration with fair conversion and joint and separate designs.

Demand set	Number of demands	Joint design	Separate design	Difference (%)
D1	63	19865	19764	-0.5
D2	67	25979	23821	-8.3
D3	69	23858	23585	-1.1
D4	63	21432	20825	-2.8

Table 4.4: Total fiber costs for the 23-node network partitioned by Heuristic with $R_{max} = 2500$km $N_{max} = 16$ and $L_{max} = 24$ using path restoration with fair conversion and joint and separate designs.

Demand set	Number of demands	Joint design	Separate design	Difference (%)
D1	63	19327	19641	1.6
D2	67	22821	22478	-1.5
D3	69	21361	21784	2.0
D4	63	20391	20771	1.9

Table 4.5: Total fiber costs for the 23-node network using path restoration, full conversion and joint and separate designs.

Demand set	Number of demands	Sec. Rest., Sep. Des.	Path Rest., Fair Conv., Sep. Des.	Difference (%)
D5	89	45212	42129	7.3
D6	73	40360	39303	2.7
D7	86	44151	43856	0.7
D8	66	36221	37416	-3.2

Table 4.6: Total fiber costs for the 32-node network with parameters $R_{max} = 3000$km, $L_{max} = 24$, $N_{max} = 16$.

Demand set	Number of demands	Joint design	Separate design	Difference (%)
D5	89	44452	42107	-5.3
D6	73	39230	36903	-5.9
D7	86	41957	41974	0.04
D8	66	35724	35256	-1.3

Table 4.7: Total fiber costs for the 32-node network using path restoration, full conversion and joint and separate designs.

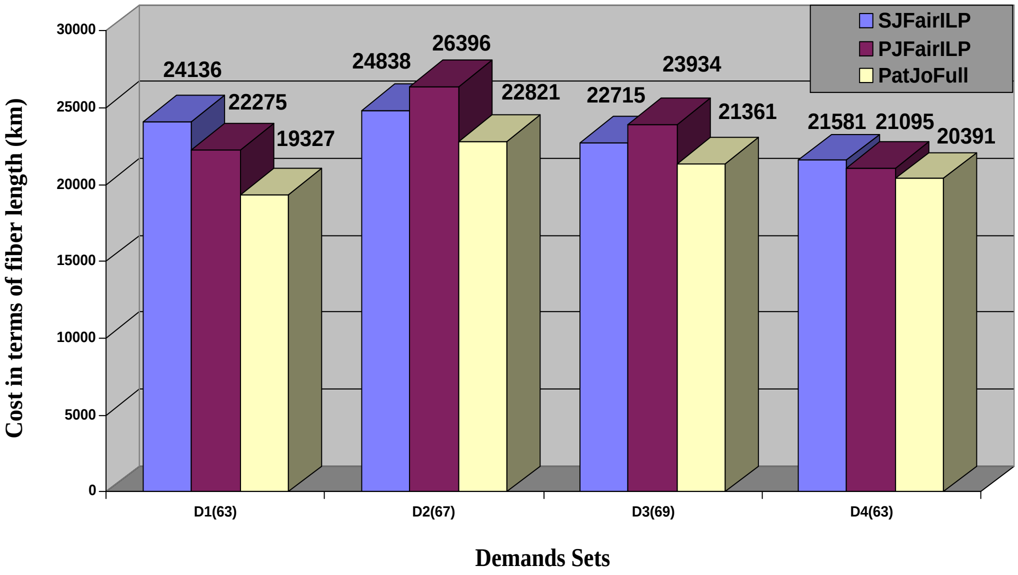


Figure 4.1: Cost comparisons among SJFairILP (Section Restoration,Joint Design, Fair Conversion, ILP Partition), PJFairILP (Path Restoration, Joint Design, Fair Conversion, ILP Partition), and PatJoFull (Path Restoration, Joint Design, Full Conversion).

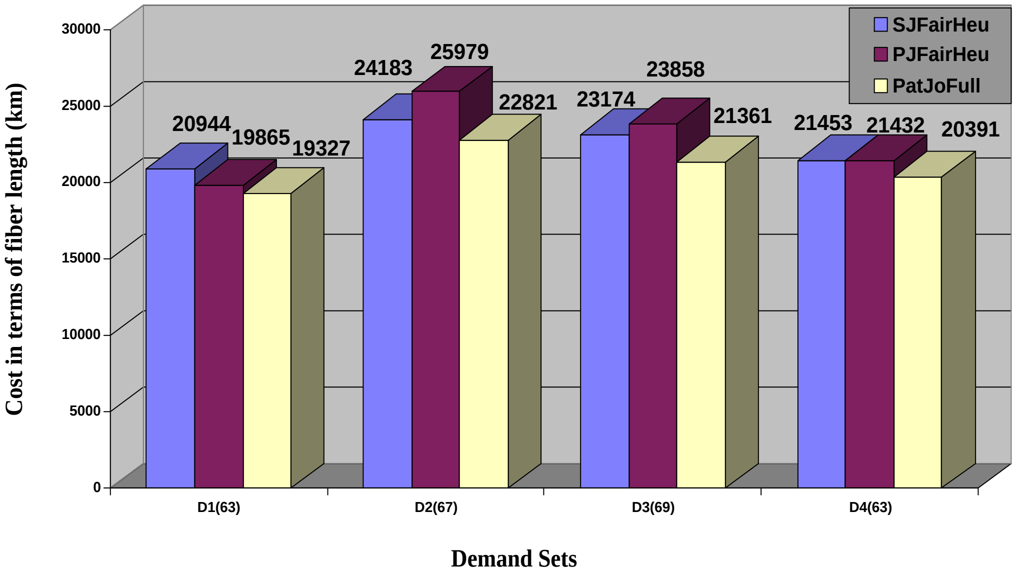


Figure 4.2: Cost comparisons among SJFairHeu (Section Restoration,Joint Design, Fair Conversion, Heuristic Partition), PJFairHeu (Path Restoration, Joint Design, Fair Conversion, Heuristic Partition), and PatJoFull (Path Restoration, Joint Design, Full Conversion).

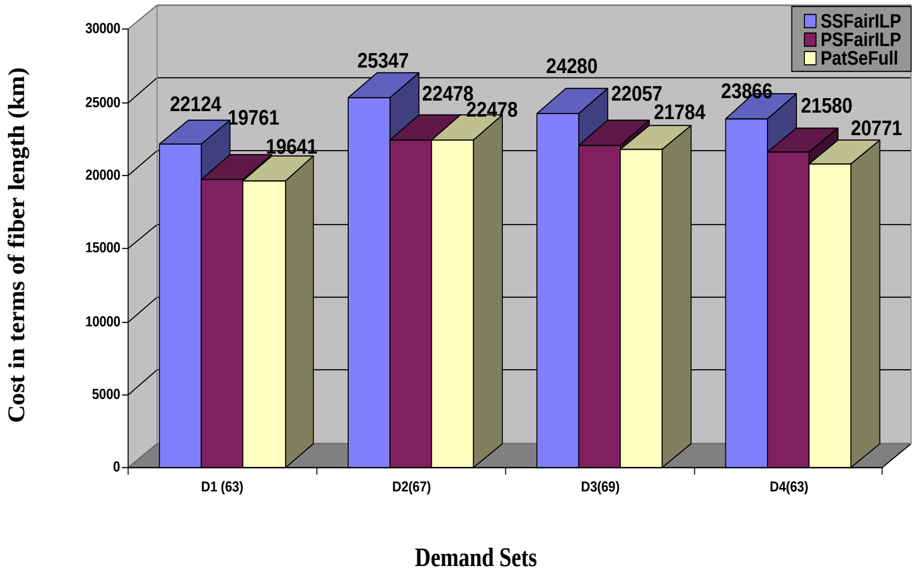


Figure 4.3: Cost comparisons among SSFairILP (Section Restoration, Separate Design, Fair Conversion, ILP Partition), PSFairILP (Path Restoration, Separate Design, Fair Conversion, ILP Partition), and PatSeFull (Path Restoration, Separate Design, Full Conversion).

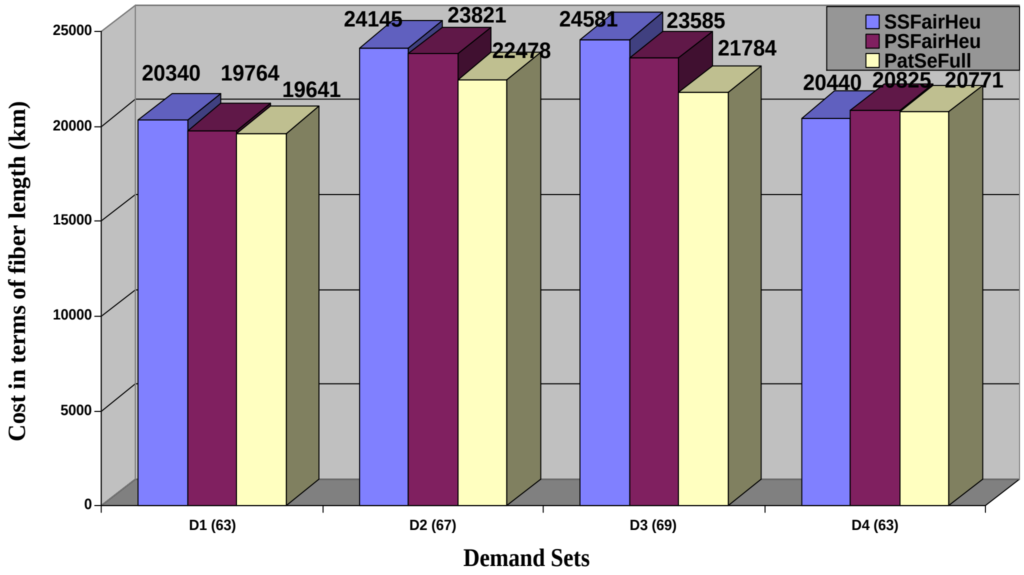


Figure 4.4: Cost comparisons among SSFairHeu (Section Restoration,Separate Design, Fair Conversion, Heuristic Partition), PSFairHeu (Path Restoration, Separate Design, Fair Conversion, Heuristic Partition), and PatSeFull (Path Restoration, Separate Design, Full Conversion).

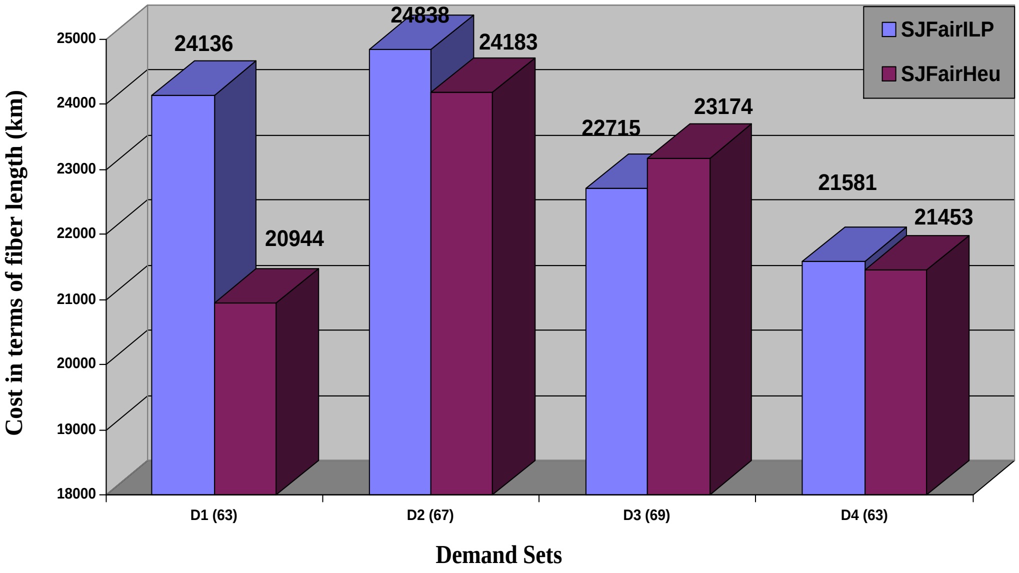


Figure 4.5: Cost comparison between SJFairILP (Section Restoration,Joint Design, Fair Conversion, ILP Partition), and SJFairHeu (Section Restoration, Joint Design, Fair Conversion, Heuristic Partition).

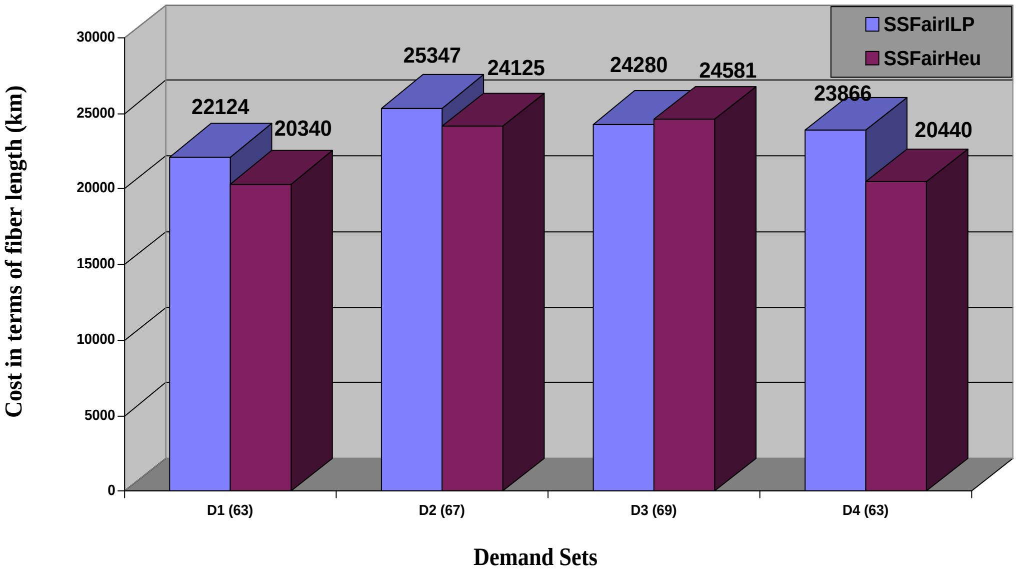


Figure 4.6: Cost comparison between SSFairILP (Section Restoration,Separate Design, Fair Conversion, ILP Partition), and SSFairHeu (Section Restoration, Separate Design, Fair Conversion, Heuristic Partition).

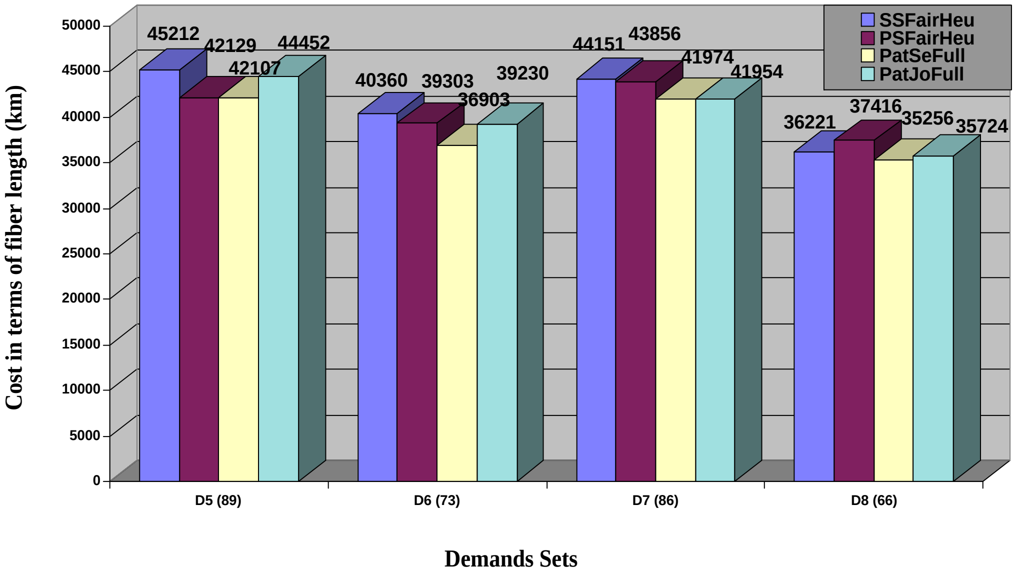


Figure 4.7: Cost comparison between SSFairHeu (Section Restoration, Separate Design, Fair Conversion, Heuristic Partition), and PSFairHeu (Path Restoration, Separate Design, Fair Conversion, Heuristic Partition), PatSeFull (Path Restoration, Separate Design, Full Conversion), PatJoFull (Path Restoration, Joint Design, Full Conversion).

Chapter 5

CONCLUSION

As the volume of the data traffic continues to increase enormously, there is an unrelenting demand for new technologies providing high-speed transmission and switching systems. Among these technologies, optical communication plays a great role in satisfying this never-ceasing demand by providing huge bandwidth and low cost.

From the first experiments on sending data on the optical fiber, to the latest technology, optical communications has evolved tremendously. The switching and processing part has been handled by electronics in the first generation optical networks. However, optics has a great potential not only in transmission but also in switching and other tasks. It has been observed through the years that the speed of electronics is not able to keep up with the speed of optics. Therefore, second generation optical networks using optics also in switching have attracted intense attention.

There are two main types of architectures for second generation optical networks: all-optical and opaque network architectures. In all-optical networks, traffic is carried entirely in optical domain. On the other hand, in opaque networks, there are transponders on either side of optical links that convert the incoming optical signal to electronic form and regenerate a fresh copy of the signal electronically and finally retransmit the signal in optical domain.

There are many advantages and disadvantages of all-optical and opaque networks. Transparency and cost reduction are some advantages of all-optical networks, whereas fault management, multivendor interoperability are the fields where opaque networks are superior to all-optical networks.

Optical networking evolve from opaque to a transparent architecture. However, due to some limitations in optics, currently it is not viable to build national scale all-optical networks. Therefore, a new architecture which is a compromise between opaque and transparent networks is recently being considered in the literature. It is called islands of transparent network architecture. In this thesis we call this new architecture as translucent optical networks.

Translucent optical networks provide several advantages over all-optical and opaque networks in term of easier interoperability, reduced transponder costs, simpler network management, scalable network architecture and faster restoration times. With their flexible architecture they may be seen as the future of transport networks. Although the architectural aspects of translucent networks have been discussed to some extent in the literature, the design problems introduced by this new architecture have not been addressed.

In this thesis, we consider two design problems for translucent optical networks: network partitioning and restoration capacity design. Both problems are studied as optimization problems and ILP formulations are presented for both. Due to the high computational complexity of the ILP optimization, alternative methods are also introduced. For the network partitioning problem we present a greedy heuristic algorithm which performs comparable with the ILP formulation in terms of the number of subnetworks in the partitioning.

For the design of working and restoration capacities we introduce an ILP formulation based on separate design of subnetworks, as an alternative to highly complicated joint design method for section restoration. Numerical results demonstrate that the separate design produces fiber costs close to the results of joint design for section restoration. The outcome of the separate design is best when it is used in conjunction with network partitioning obtained from the heuristic algorithm. Moreover, the section restoration costs in all cases are very close to cost of path restoration in case of not only fair conversion but also full conversion. Also, the separate design method scales nicely with the number of nodes in the network. Therefore, separate design is a promising method for the design of translucent networks both in terms of cost and scalability.

In summary, the quasi-distributed section restoration with its nice scalability , easier manageability and competitive network cost constitutes a viable alternative to centralized path restoration in translucent optical networks. Section restoration may enable easier evolution of optical networks from its current high-cost opaque architecture to translucent architecture with lower costs and easier management. At the end of this evolution we may end up with all-optical national-scale networks with quasi-distributed network management functions including restoration.

Our future studies will be focused on developing new heuristic algorithms and ILP formulations for network partitioning that result in lower network costs. We also plan to incorporate other cost factors, such as OXCs, transponders, into our design framework.

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