2009

Survivable mesh-network design & optimization to support multiple QoP service classes

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Survivable Mesh-network Design & Optimization to Support Multiple QoP Service Classes

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by

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This thesis is presented in fulfilment of the requirements for the degree of

Doctor of Philosophy

SCHOOL OF ENGINEERING

FACULTY OF COMPUTING, HEALTH AND SCIENCE

EDITH COWAN UNIVERSITY

November 2, 2009

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ABSTRACT

Every second, vast amounts of data are transferred over communication systems around the world, and as a result, the demands on optical infrastructures are extending beyond the traditional, ring-based architecture. The range of content and services available from the Internet is increasing, and network operations are constantly under pressure to expand their optical networks in order to keep pace with the ever increasing demand for higher speed and more reliable links.

Disruptions to communication networks cause major service problems that affect businesses, governments and consumers alike. Sustainability of infrastructure with continued quality of service is a key requirement of optical network design and development. Building sustainable networks is a vital in minimizing both the risk and impact of any disruptions. Currently, optical mesh networks are the topology of choice, as they use much less resources in comparison to ring networks, while still satisfying the growth of demand. A variety of protection and restoration methods are available for optical transport networks and these include Automatic Protection Switching (APS), dedicated span and path protection and Shared Backup Path Protection (SBPP). These schemes vary in complexity, spare capacity usage and restoration speed; with each scheme presenting different advantages and disadvantages. The implementation of these schemes in the logical topology of a network is dependent on the network structure and the available capacity of the physical topology.

In this thesis, the interaction between networks' physical and logical topologies and

the efficiency of various protection schemes is investigated using new, improved mathematical models which are developed in this thesis. A new approach for establishing physical survivability of networks is proposed which has much faster computational speed than other techniques reported in the literature.

A new optimization model is developed for SBPP which reduces the number of constraints in the solution at the cost of extra variables. This model has particular advantages when dealing with large size networks. This thesis also considers the application of p-cycles to network topology design. A new definition for the fundamental cycles is proposed and applied to developing a new ILP model which reduces the complexity of the problem and arrives at the optimal solution more efficiently.

In practice, depending on the service requests, the communication demands can have various level of protection. By integrating multiple protection schemes into a network formulation, network operators can take advantage of the characteristics of different demand categories to further utilize the resources available, while still maintaining the quality of service. In addition, with the joint design of physical and logical topology in the formulation, the network design model proposed in this thesis facilitates better solutions than when these topologies are designed separately.

The last contribution of this thesis is the development new and novel formulation models to support the design and optimization of optical networks. These models are based on mixed-protection schemes that support Multiple Quality of Protection Service (MQoPS) classes of communication demands. It is shown that these models bring significant improvements to network physical topology design, as well as significantly improving the efficiency of resource allocation in the logical topology design for achieving sustainable optical mesh networks.

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LIST of ACRONYMS

ADM	Add/Drop Multiplexers
ADSL	Asymmetric Digital Subscriber Line
ANSI	American National Standards Institute
APON	ATM Passive Optical Network
APS	Automatic Protection System
ASIC	Application-Specific Integrated Circuit
ASP	Application Service Provider
AT&T	American Telephone and Telegraph
ATM	Asynchronous Transfer Mode
BER	Bit Error Rate
CBM	Constraint bases module
DPJB	Disjoint primary and joint backup
DSL	Digital Subscriber Line
DWDM	Dense Wavelength Division Multiplexing
DXC	Digital Cross Connect
FCC	Federal Communications Commission
FSAN	Full Services Access Network
FTTH	Fiber-to-the-Home
IEEE	Institute of Electrical & Electronics Engineers
ILP	Integer linear programming
IP	Internet Protocol
ISDN	Integrated Services Digital Network
ISP	Internet Service Provider
ITU	International Telecommunications Union
LAN	Local Area Network
MAN	Metropolitan Area Network

MEMS	Micro-Electromechanical Machines
MPLS	Multi-protocol Label Switching
MQoP	Multiple quality of protection
OADM	Optical Add-Drop Multiplexer
OAN	Optical Access Network
OC-12	Optical Carrier 12
OC-192	Optical Carrier 192
OC-3	Optical Carrier 3
OC-48	Optical Carrier 48
OCC	Optical Connection Controller
OEO	Optical-Electronic-Optical
OIF	Optical Internetworking Forum
OLT	Optical Line Terminal
OTN	Optical Transport Network
OXC	Optical Cross Connect
PSTN	Public Switched Telephone Network
QoS	Quality of Service
RWA	Routing and wavelength assignment
SDH	Synchronous Digital Hierarchy
SLA	Service Level Agreement
SONET	Synchronous Optical Network
STM	Synchronous Transfer Mode
SBPP	Shared Backup Path Protection
SRLG	Shared Risk Link Group
TCP/IP	Transport Control Protocol/Internet Protocol
TDM	Time Division Multiplexed
VBM	Variable bases module
VPN	Virtual Private Network
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing

List of Publications

1. **Hoang N. Nguyen**, Daryoush Habibi, Quoc V. Phung, Kungmeng Lo, " A Shared Backup Path Protection Scheme for Optical Mesh Networks", Asia-Pacific Conference on Communications (APCC2005), pp. 309-313, Novemeber 2005, Perth, Australia.

2. **Hoang N. Nguyen**, Lachowicz, S. and Eshraghian, K, (2003), "Adaptive beam control for intelligent reconfigurable holographic optical switch", 7th World Multiconference on Systemics, Cybernetics and Informatics (SCI2003), Orlando, Florida, U.S.A., July 27-30, pp. 202-207.

3. **Hoang N. Nguyen**, Rothermel, A., Lachowicz, S. and Eshraghian, K, (2003), "Simplified Color Transformations for Analog Processing in CMOS Imagers", 7th World Multiconference on Systemics, Cybernetics and Informatics (SCI2003), Orlando, Florida, U.S.A., July 27-30, pp 208-213.

4. Daryoush Habibi, **Hoang N. Nguyen**, Quoc V. Phung, and Kung-meng Lo, "Establishing Physical Survivability of Large Networks using Properties of Two Connected Graphs", Tencon 2005, Melbourne, Australia.

5. **Hoang N. Nguyen**, Daryoush Habibi, Viet Q. Phung, Kungmeng Lo, Stefan Lachowicz, Senior Member, IEEE, "Finding the Optimum Solution in p-Cycle Protection using Fundamental Cycles", IEEE Transactions on Communications (under review).

6. **Hoang N. Nguyen**, Daryoush Habibi, Viet Q. Phung, Kungmeng Lo, Stefan Lachowicz,"Networks Protection: A Mix-protection Schemes for Multiple QoP Service Classes", IEEE Transactions on Communications (under review).

7. **Hoang N. Nguyen**, Daryoush Habibi, Viet Q. Phung, Kungmeng Lo, Alexander Rassau, "A Compact ILP Model for Shared Path Protectionin WDM Mesh Networks", IEEE Transactions on Communications (under review).

8. **Hoang N. Nguyen**, Daryoush Habibi, Viet Q. Phung, Stefan Lachowicz, "Joint Optimization in Capacity Design of Networks with p-Cycle Using the Fundamental Cycle Set", in the proceedings of IEEE Global Telecommunications Conference (Globecom) December 2006, San Francisco, USA.

9. Kungmeng Lo, Daryoush Habibi, Alexander Rassau, Quoc V. Phung and **Hoang N. Nguyen**, "Efficient p-Cycle Design By Heuristic p-Cycle Selection and Refinement for Survivable WDM Mesh Networks", in the proceedings of IEEE Global Telecommunications Conference (Globecom), December 2006, San Francisco, USA.

10. Kungmeng Lo, Daryoush Habibi, Alexander Rassau, Quoc V. Phung and **Hoang N. Nguyen**, "A Hybrid p-Cycle Search Algorithm for Protection in WDM mesh Networks", in the proceedings of 14th IEEE International Conference on Networks (ICON2006), Vol. 2, pp. 262-267, September 2006.

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12. Quoc Viet Phung, Daryoush Habibi, **Hoang N. Nguyen** and Kungmeng Lo, "A segmentation method for shared protection in WDM networks", in the proceedings of IEEE International Conference on Networks (ICON2006), Vol. 2, pp. 484-489, September 2006.

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14. Quoc V. Phung, Daryoush Habibi, **Hoang N. Nguyen** and Kung-meng Lo, "K-pairs of Disjoint Paths Algorithm for Protection in WDM Networks", Asia-Pacific Conference on Communications (APCC2005), pp. 183-187, October 2005, Perth, Australia.

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(SRLG) Optical Mesh Networks, in Proceedings of the 15th IEEE Conference on Networks (ICON 2007) , pp. 246-251, 2007.

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Chapter 1

Introduction

In this day and age, information and technology are so ingrained in day to day life that many people do not even realize how large a part they actually play. Most people carry various advanced communication devices that support data and multimedia exchange over both wired and wireless networks. The constant demands for more bandwidth and a faster exchange of information around the globe is growing increasingly evident [3, 6, 7, 8]. This need has become a driving force that is pushing network technologies to new levels, requiring both flexibility and a greatly increased capacity to satisfy these world demands.

The advancement and evolution of optical technologies has placed the Wavelength Division Multiplexing (WDM) transmission system at the front end of research interest in the field of data communications and networking. The large range of content and services available from the internet is increasing globally. Table 1.1 shows the statistical data of internet usage against the population in different world areas. The average growth of world internet usage over a seven year period starting from 2000 was 208.7%; some regions, such as the Middle East, Africa and Latin America have increased their usage over 400%. Dense Wavelength Division Multiplexed (DWDM) mesh networks that route optical connections using optical cross-connects (OXCs) have been proposed in [1, 9, 10], as well as a variety of optical switching systems capable of exchanging information

Table 1.1: Internet Usage (Source: Yahoo case analysis 9/2007)

WORLD INTERNET USAGE AND POPULATION STATISTICS						
World Region	Population (2007 EST.)	Population % of World	Internet Usage	% Population (penetration)	Usage % of World	Usage Grow (2000-2007)
Africa	933,448,292	14.2%	33,334,800	3.6%	3/0%	638.4%
Asia	3,712,527,624	56.5%	398,709,065	10.7%	35.8%	248.8%
Europe	809,624,686	12.4%	314,792,225	38.9%	28.3%	199.5%
Middle East	193,452,727	2.9%	19,424,700	10.0%	1.7%	491.4%
North American	334,538,018	5.1%	233,188,086	69.7%	20.9%	115.7
Latin American /Carribean	556,606,627	8.5%	96,386,009	17.3%	8.7%	433.4%
Aceania / Australia	34,468,443	0.5%	18,439,541	53.5%	1.7%	142%
World Total	6,74,666,417	100%	1,114,274,426	16.9%	100%	208.7%

at several terabits per second. With the existence of so many data channels over a fiber infrastructure, serious problems may occur if a failure were to occur, since the amount of bandwidth lost by a single resource failure is a great deal larger than what would have been lost using traditional networks. The disruption of communication networks is easily capable of causing major service problems and more serious damage than ever before. For example, an earthquake near Taiwan in December 2006 affected more than 75% of the available network capacity; in October 2007, a network disruption occurred during business hours at Sacramento's VAs hospital regional data processing center, and this disruption severely interfered with normal hospital operation, particularly with inpatient and outpatient care [11]; in 2008, R. Brad [8] reported the alarming incident of a cable being cut in the Middle East - undersea cable lines were cut or damaged and as a result, disrupted service in Egypt, the Middle East and India. About 75% of the capacity between Europe and the Middle East was severed, and over half of India's bandwidth was cut due to the disruption, according to a report from Reuters that cited local officials [8]. Even today, network users could experience service disruptions such as network congestion, slow data transfer and some services simply being unavailable. Therefore, today's optical networks are required not only to perform the data transfer, but also provide reliable, efficient routing with fast recovery from any failures.

Protecting networks against service disruptions has become more important than ever before, and is a crucial task in network development and design. Network operators are increasing their focus on the reliability of networks which can continue to provide service under some common network failures, such as cable cuts, power outage, etc; this topic has also attracted many researchers around the world.

Mesh-based networks are considered an attractive alternative to the ring-based networks for the future of optical communications, based on dense wavelength division multiplexe (DWDM) technology [12, 13]. One of the main reasons for this technology being seen in a favorable light is that mesh-based restoration networks offer much less capacity redundancy than ring-based networks while maintaining the same restorability against

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any single span failure. A network with more complex mesh topologies and using a larger number of wavelengths usually consists of OXCs, arranged in some arbitrary topology and providing interconnection to a number of different client networks, e.g., sub-networks that support Multi-Protocol Label Switching (MPLS)/ Multi-Protocol Lambda Switching (MPS). Each OXC can switch the optical signal coming in from an input fiber link on a wavelength to an output fiber link with the same wavelength, or can be equipped with a converter if transfer to a different wavelength output fibre is required. An optical communication channel established over a network of OXCs is the lightpath (in some papers referred to as the λ-channel), which may span over a number of fiber links (physical hops). In the case of no converter being available within the network, a lightpath can be associated with the same wavelength on each hop (this situation was formerly known as the wavelength continuity constraint). If converters are available, different wavelengths may be used on each hop to create a lightpath.

Survivability techniques can be classified into three categories: 1) prevention, 2) network design, and 3) traffic management and restoration [14]. Prevention techniques focus on improving component and system reliability (such as fault tolerance in hardware architecture) while the purpose of a careful network design is to minimise the effects of system level failures. Lastly, traffic management and restoration procedures aim to manage the network load in such a way that the failure has minimum impact and connections can be re-established around the failure. In multilayer network design, each layer can have its own protection mechanism and recovery procedures to deal with failures. This research focuses mainly on the survivability of the optical transport layer. In practice, optical transport networks are mostly based on ring topology. Ring networks use simple switching mechanisms, which permit fast restoration time after failure (about 50ms- 60ms), but they require at least 100% capacity redundancy. Furthermore, in complete multi-ring networks, the working fiber/channel groups are usually not fully utilizable, and thus the ratio of installed to working capacity can be 200-300%. In contrast, mesh based networks use much less resources, but have the drawback of complicated protection mechanisms. The protection for mesh networks is usually based on paths (end-to-end) or on spans, but the

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restoration time is much longer than in the case of ring networks.

A variety of protection and restoration methods have been designed and implemented for optical transport mesh networks [15, 16, 17, 18, 2], these include automatic protection switching (APS), mesh span restoration, mesh path restoration, shared backup path protection (SBPP), and their variations in terms of complexity, spare capacity usage, restoration speed, and some other aspects. Thus, each method has its own advantages and disadvantages. For example, a network employing APS can achieve a restoration time less than 60 ms but must use more than 100% capacity redundancy. In contrast, with SBPP the restoration time after a failure can be as large as 200ms and in some cases the total redundancies as low as 21% [19, 4]. Multiple methods can be integrated into the same network providing different qualities of protection service to different connections and this has also been suggested by W. Grover [4], but thus far, not many researchers have addressed this issue. In October 2003, F. J. Blouin et al. [20] reported some research results on the mixed protection techniques applied to the optical layer. Although, the results do not highlight the benefit very well,they show that significant capacity savings can be achieved with relatively well connected networks. However, the interaction between network topology and capacity efficiency of various survivability schemes are still unclear.

1.1 Motivation and Research Objectives

Network survivability has been extensively researched, and a large range of protection methods are available that allow service providers to choose the schemes that meet their restoration time requirements with optimum spare capacity. A combination of protection schemes always provides for a solution with the smallest cost of network design. In addition, there are four different policies for the treatment of different network demands [4] known as Multiple Quality of Protection (MQoP) service classes: Demands that are guaranteed to be protected, demands that are protected with the best effort possible at the time, demands that are not protected, and lastly, demands that are not protected but can

be pre-empted. Significant reduction in the spare capacity requirements can be achieved under these service class categories as not all services need to be restored in the case of a failure. Thus, designing a mesh-restorable network with mixed service classes will allow the network to perform with enhanced operation and provide more user options. Thus, the motivation of this research was to discern which combination of service classes together with various protection schemes would give the best capacity efficiency.

It is commonly understood that logical topology design is very much dependent on the physical architecture of the network. However, not many researches address the physical network design or optimise the problems of network architecture with respect to the survivability of networks under multiple QoP service classes.

The main goals of this research were:

- To study topology design and optimisation of mesh network survivability based on a combination of a distributed restoration mechanism and a pre-planed protection mechanism, which are embedded in an optical transport network layer.

- To achieve a fundamental understanding of the interaction between topology and capacity efficiency with respect to various protection schemes, and develop new models for network design that can support MQoP service classes . The new models effectively utilise the networks' resources by integrating various protection schemes into one mathematical formulation.

1.2 Contributions

This study presents comprehensive views of the interaction between topology and capacity efficiency with respect to various protection schemes in mesh network design and implementation. It further provides insight for future research on the design and operation bases for shared risk link groups with different of service classes in the given networks. The main contributions of this thesis include:

1. A new method of verifying physical network survivability based on the theory of the 2-connected graph. This is an important requirement of protection schemes for each network, and it guarantees that the routing of the main path can be diverted to an alternative path in the case of a failure.

2. Proofs that all p-cycle components can be constructed from the network's fundamental cycles, which are the main element for formulating the p-cycle model. An algorithm for finding a set of a network's fundamental cycles is introduced. The use of fundamental cycles to formulate the Integer Linear Programming (ILP) model significantly reduces the model's complexity when compared to the conventional model when dealing with large networks.

3. The unification of mathematical formulations for span protection, path protection, shared backup path protection and the p-cycle base of static traffic demands. This offers a significant improvement in terms of the complexity of the ILP formulation.

4. Two new proposed ILP models for SBPP at the optical layer of mesh networks. The first proposed model is a Variable-Based Model (VBM). This model has a smaller number of constraints, but a larger number of variables, which are sets of Disjointed-Primary and Joint Backup (DPJB) candidates created in the pre-processing stage. Simulation shows that the multi-level optimisation technique reduces the number of variables in the VBM significantly; however, this model is still only suitable for small networks and a small amount of traffic demand. The VBM can be further developed to produce optimal solutions by balancing its number of constraints and variables.

5. A new model for network design to support MQoP using various protection schemes is developed. This type of network can respond to different quality of service demands with optimum resource usage.

6. Providing further insight for future research on the shared risk link groups network design and opimisation to support multiple QoP service classes.

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1.3 Thesis outline

The remainder of this thesis is presented as follows:

Chapter 2 Backgound: This chapter provides an overview of the development of optical
networks and network protection techniques. The advantages and disadvantages
of different protection schemes with respect to the economic effects in network
planning and capacity design are also highlighted. An overview of some topology
design methods and tools for network design and optimisation such as ILP, heuristic
methods of optimisation, graph theory etc..

Chapter 3 Connectivity of Physical Networks: The focus of this chapter is presenting a
new approach to establishing the physical survivability of networks. The algorithm
proposed by this study provides all the distinct fundamental cycles of the network,
if required, with only a small change in Algorithm 1. The technique applied is
capable of identifying node-bridges, something not previously considered in related
literature, as well as link-bridges.

Chapter 4 Span Protection: In this chapter, the most common form of network protection
is examined in depth, as well as the related mathematical formulation. This chapter
also presents the relationship between the efficiency in capacity design and network
congestion.

Chapter 5 Path Protection: This chapter details the development of path protection schemes
for dedicated protection and SBPP. A new mathematical formulation with improved
complexity for SBPP is introduced. Also in this chapter, the development of a
heuristic model for multi-level optimisation for SBPP is explained.

Chapter 6 p-cycles: Outlined in this chapter is the concept and development of the p-
cycle protection scheme. A new mathematical formulation designed for this model
is introduced. The new model also covers "non-simple p-cycles", which are usually
not taken into account by the conventional model due to the exponential increase in

the number of variables as network size increases.

Chapter 7 Network Survivability with MQoP Service Classes: This chapter presents the integration of various protection schemes, previously incorporated into one formulation, to serve various types of demands in a network. Various combinations of different capacity planning problems for each scenario are considered and simulated.

Chapter 8 Case Study: The focus of this chapter is to present and discuss a case study involving the analysis and design of metro optical networks in the cases of ring and mesh topologies. This case study originated from [5], which was designed mainly for the multi-service metro optical SONET/SDH network of the downtown metro area of a large U.S. city. The chapter mainly focuses on capacity planning and logical design of optical networks, and compares these ring and mesh networks based on their resource efficiency.

Chapter 2

Background

This chapter provides a review of optical transport networks, and in particular, examines a specific type of optical network known as an optical mesh network. In the review of optical transport networks, it is important to stress the significance of network survivability in today's data communication, and focus on some milestones in the design and development of survivable mesh networks for both physical and logical topologies while the advantages and disadvantages of different protection schemes with respect to the economic effects in network planning and capacity design are also highlighted. A mathematical optimisation of ILP problems is also presented in depth. The ILPs are special cases of linear programming problems, or more generally combinatorial optimisation problems, and will be used extensively throughout this thesis.

2.1 Communication Networks

During the 1980s, data networks only played a minor role in the definition of network architectures and Internet Protocol (IP) traffic was just an academic phenomena, which was limited to the research and development network called the '**Internet**'. The exchange of data over networks was within individual enterprises via specific protocols. The de-

velopment of browsers, web servers, HTML, and opening the Internet to commercial applications in the early 1990s have created another market where data traffic doubled every six months. The demand for high bandwidth has been increasing at an exceptional rate and has become the driving force behind the development of communication technology. Figure. 2.1 shows the evolution of the optical network with the advent of Multi Protocol Label Switching (MPLS) providing more efficient means of provisioning resources within OXCs and Table 2.1 presents the development in optical technologies.
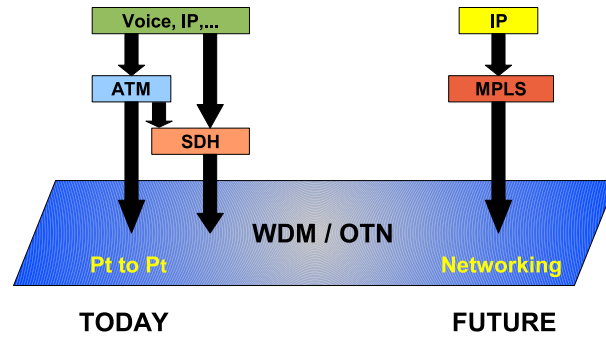
Figure 2.1: Evolution of Data Network

Optical fiber has become the transmission medium of choice because it provides large bandwidth {approximately 24 TeraHertz (THz)}, low attenuation, and low Bit Error Rate (BER). In order to share this bandwidth, various multiplexing techniques have been proposed for optical networks. These techniques include Wavelength Division Multiplexing (WDM), Optical Time Division Multiplexing (OTDM), and Optical Code Division Multiplexing (OCDM).

In WDM networks, a number of optical channels (having different wavelengths) are combined and simultaneously transmitted in the same direction over an optical fiber. "WDM is a rate and format independent technology, and it can support any combination of interface rates including synchronous or asynchronous Optical Channel (OC) such as OC3, OC12, OC48, or OC192 on the same fiber at the same time" [21]. There are three variations of WDM: Narrowband WDM (NWDM), Wideband WDM (WWDM) and

Table 2.1: Photonic Technology Timeline (Source:Photonic Network Architecture [3])

	1995 - 1997	1998 - 2000	2000 - 2005	2005 - 2010
Wavelength per fiber	4 - 16	32 - 128	128 - 512	Greater than 1024
Optical amplification bandwidth	40nm	80nm-120nm	200nm	No prediction
Wavelength spacing	3.2nm - 1.6nm	0.8nm - 0.4nm	0.8nm - 0.4nm	0.2nm
Capacity per fiber	40Gbps	320Gbps	1Tbps	2Tbps - 5Tbps
Equipment	DWDM and Static OADM	Dynamic OADM	OXC	Optical switching
Optical devices	DWDM and EDFA	Acoustic-optic tunable filter, tunable laser devices	Optical switches	Optical packet routers

Dense WDM (DWDM). Typically, NWDM is implemented by using two wavelengths: 1533 and 1577 nanometers (nm). WWDM is implemented by combining a 1310 nm wavelength with another wavelength into the low-loss window of an optical fiber cable between 1528 nm and 1560 nm. The difference between WDM and DWDM is that DWDM supports many more wavelengths. As illustrated in Figure. 2.2, optical signals having wavelengths $\lambda 1, \lambda 2, \lambda 3, \lambda 4,$ and $\lambda 5$ are multiplexed and simultaneously transmitted in the same direction over a single optical fiber cable. The number of wavelengths that a
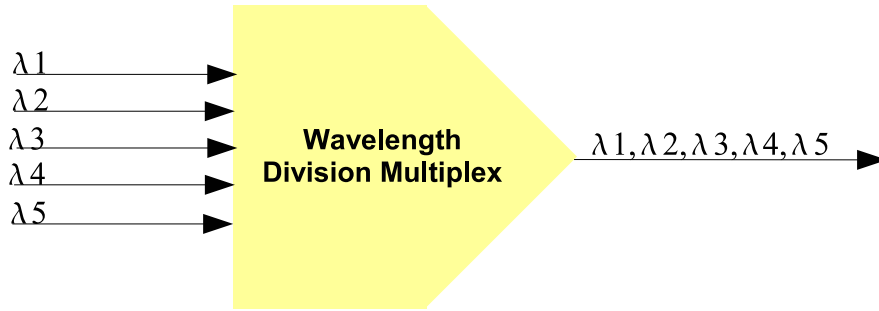
Figure 2.2: Wavelength Division Multiplex

DWDM system can support depends on the ability of the network to filter and separate them. However, current DWDM systems are capable of supporting 32 or 40 wavelengths, while recent DWDM systems capable of supporting as many as 80 and 128 wavelengths have been announced. More details and information related to these techniques can be found in [21, 15, 1].

2.1.1 Transport Networks

Transport networks are essentially the *physical facility networks* of providers. These facilities can be produced and implemented with various technologies such as WDM, synchronous optical networks, and with different equipment such as OXCs, wavelength converters etc. Different service demands are multiplexed together and routed all over a common infrastructure from their origin, to their final destination of a logical, multi-channel point-to-point transmission system.

Today, all networks operate logically as if they had their own dedicated transmission systems, but each of them is just one of several virtual *service-layer* networks supported by one underlying physical network, which is the transport network. This allows the transport network to utilise the resources available by controlling the traffic flow, balancing network load and improving throughput. As a transport network can be implemented with various types of protection schemes and techniques, the network reliability can be more readily enhanced.

Each communication network consists of a set of nodes connected by a set of links. In the case of a telephone network, the nodes are referred to as *switches*, and links are referred to as *trunks*. The trunks are cables comprising of twisted wire pairs and the switches are metallic connections between wire pairs in the trunk's cables. In the case of data communication services such as the Internet, nodes are routers and links sometimes referred to as spans. Trunks or links, and other transmission mediums may consist of a series of networks, which are administered by different providers.

Each network provider is responsible for the design and operation of their own networks. These network providers are referred to as *backbone networks*. The backbone network is an important architectural element for building enterprise networks. It provides a path for the exchange of information between different local area networks (LANs) or subnetworks. A backbone network can tie together diverse networks in the same building, in different buildings in a campus environment, or over wide areas. Generally, the capacity of the backbone network is greater than the capacity of the individual networks connected to it. Thus, a backbone network is one with a central cabling scheme to which other networks are attached. A node in one network communicates with different nodes in other networks by sending packets across the backbone network.

The different types of transport networks can be categorised into three main groups: *access networks*, *metropolitan networks* and *long-haul networks*, as shown in Figure. 2.3. The access network is responsible for connecting local customer premises to nearby central offices. The access networks attached to the backbone network may require a gate-

Long-haul
Interexchange network

Local
Access network

Metropolitan
Local-exchange network
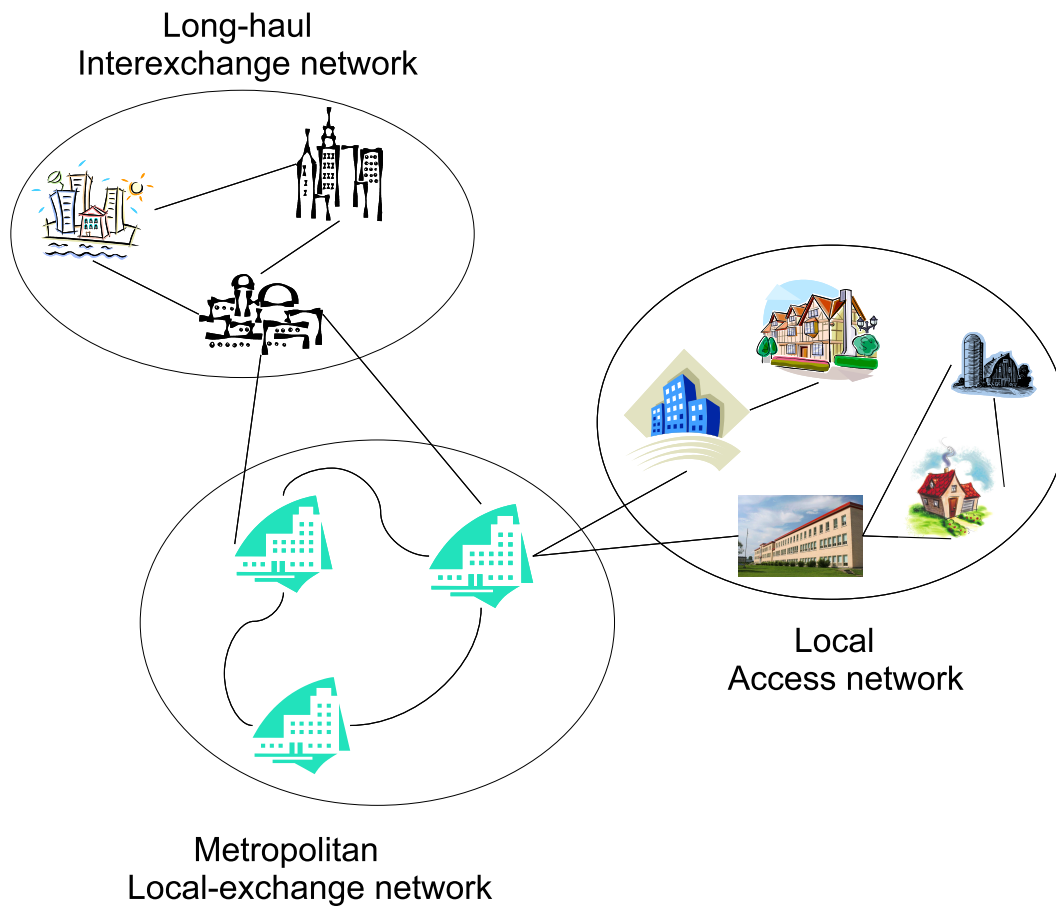
Figure 2.3: Transport Networks

way or router. These are also referred to as *local-area networks* (LANs). The networks that span a campus or metropolitan areas are called *metropolitan-area networks* (MANs). These networks typically span relatively short distances of about 50 km. The long-haul networks, or inter-exchange networks, interconnect cities and major traffic hubs.

2.1.2   WDM Architectures and Technologies

Most of today's metropolitan area and local area networks consist of ring or bus topologies. Thus, all nodes in these networks share a single wavelength channel for transceiving data. Long-haul networks use a mesh-type topology. The transmission and reception of data is handled by optical cross connects (OXCs) provided at each node. The cost of links and the OXCs is high, and therefore, these networks are usually sparsely connected [15, 1].

Network data can consist of either *broadcast and select* or *wavelength routing* architectures. In the broadcast and select architecture WDM networks, data signals are broadcast by a passive device in the center of the network to all other nodes. A tuneable optical filter is attached at each node to select the desired wavelength. The size of this type of network is limited as the wavelength cannot be reused and the transmitted power must be divided between all receivers in the network (from a node). Typical examples of networks that employ this architecture are the *bus* topology and *star* topology networks Figure. 2.4(a), Figure. 2.4(b).

In bus topologies, all nodes are connected to a single bus or to two unidirectional buses. The disadvantages of the bus topology are power loss and tapping loss within the bus. Thus, it limits the number of nodes that can be attached to the bus without optical amplifiers.

In the star topology, each node is connected to a star coupler via two-way fibers. A node transmits its information stream to the star coupler on one available wavelength. A collision will occur when two or more nodes transmit optical information streams on the

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(a)

(b)

(c)
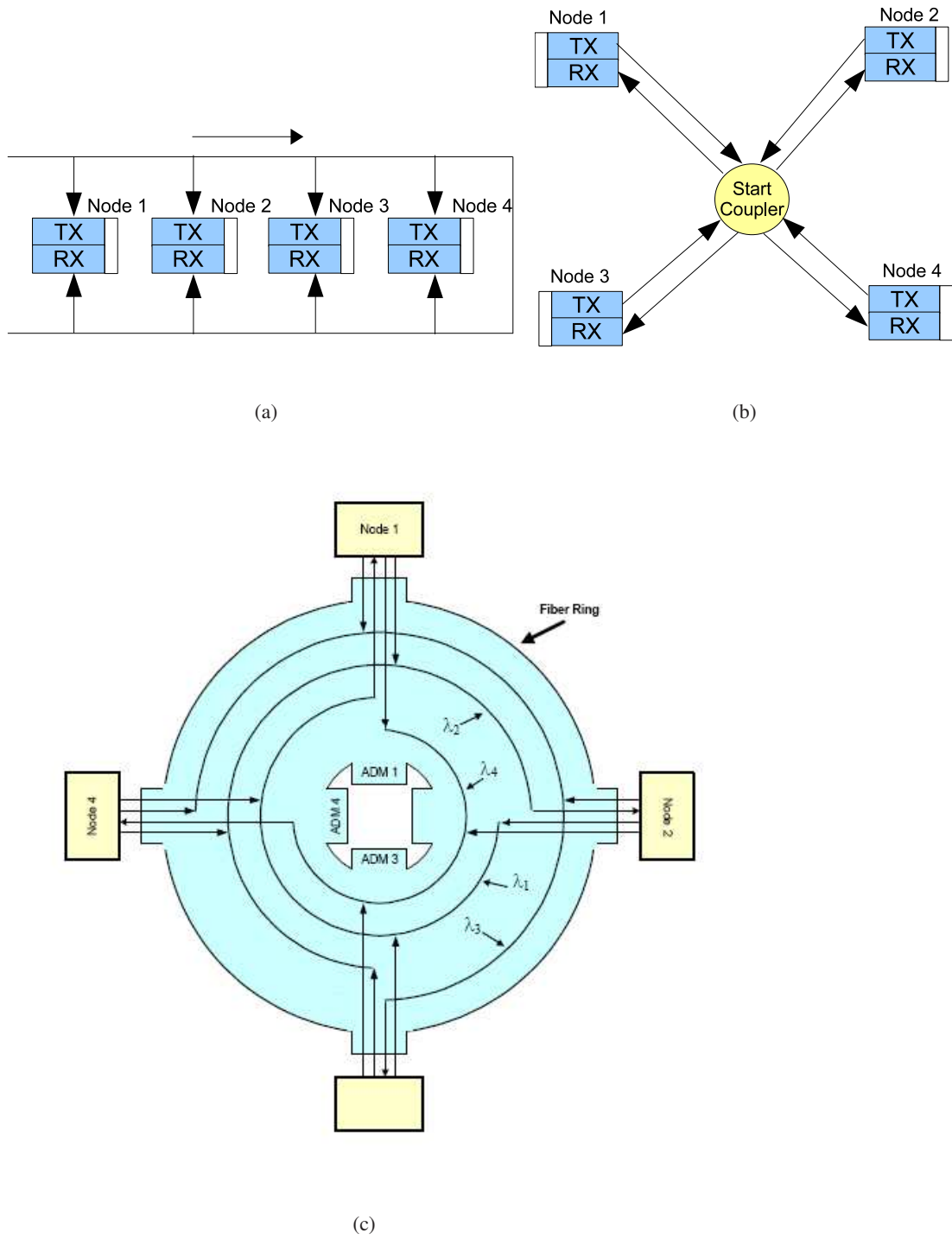
Figure 2.4: An example of (a) Bus,(b) Start and (c) Ring Topology Networks. (Source: Wavelength Division Multiplexing Networks [1])

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same wavelength, simultaneously. Each node in the star topology is connected to an Add Drop Multiplexer.

Each Add Drop Multiplexer can drop a single fixed wavelength, and can add any wavelength or any number of wavelengths simultaneously. A node can send data to any other node on the ring by transmitting on the wavelength that has dropped data to the same destination simultaneously [1]. In wavelength routing architectures, each node in the network is capable of routing various wavelengths from an input port to different output ports Figure. 2.5. Thus, the network can have many simultaneous lightpaths of the same wavelength, and have better resource utilisation. In addition, this does not use power to transmit signals to unwanted destinations as happens in the broadcast and select architecture networks.
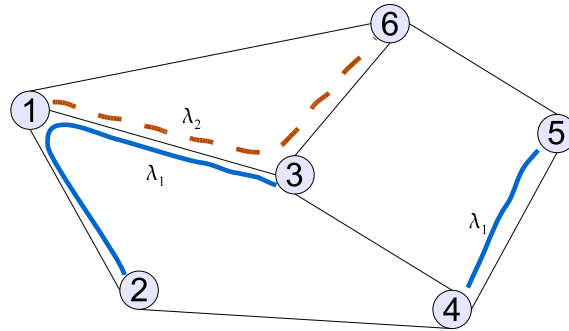
Figure 2.5: Routing Network

Optical Channel Layer Network

Optical networks are complicated and have a variety of different functions that are handled by different network components. These functions include point-to-point connections and *add/drop* functions (where part of the traffic is dropped at a desired node and the rest passed through to other nodes). In addition, network functions handle the equipment and link failures to maintain continuity of service.

The networks comprise multiple layers Figure. 2.6 that perform similar functions as

| Optical Channel Layer Network |
| Optical Multiplex Section Layer Network |
| Optical Transmission Section Layer Network |

Figure 2.6: Network Layer

discussed earlier. A network layer is a collection of transmission and/or switching equipment that provides a collection of communication services, possibly with the assistance of a sublayer. A sublayer is a network layer which provides services to another layer [22]. The existence of these layers helps to reduce equipment costs. This is because different network layers perform different functions at different bit rates. For example, it would be expensive for the SONET (Synchronous Optical Network) layer to process 10x2.5 Gb/s streams of data coming from the WDM layer, and it would not be suitable to use the WDM layer to transfer data streams at a lower granularity, eg. a few hundred megabits per second.

The Optical Channel Layer Network provides end-to-end networking of optical channels for transparently conveying client information in varying formats, such as Synchronous Digital Hierarchy (SDH), Plesiochronous Digital Hierarchy (PDH) and Asynchronous Transfer Mode (ATM). To provide end-to-end networking, the following capabilities are included in the optical channel layer network:

1. Optical channel connection rearrangement for flexible network routing;

2. Optical channel overhead processes to ensure integrity of the optical channel adapted information; and

3. Optical channel supervisory functions to enable network level operations and management functions such as connection provisioning, Quality of Service (QoS) parameter exchange, and network survivability.

Optical Multiplex Section Layer Network

Optical Multiplex Section Layer Networks provide functionality for networking of a multi-wavelength optical signal. The following networking capabilities are included in an optical multiplex section layer network:

1. Optical multiplex section connection rearrangement for flexible multi-wavelength network routing;

2. Optical multiplex section overhead processes to ensure integrity of the multi-wavelength optical multiplex section adapted information; and

3. Optical multiplex section supervisory functions to enable section level operations and management functions such as multiplex section connection provisioning and network survivability.

Optical Transmission Section Layer Network

The Optical Transmission Section Layer Network provides functionality for transmission of optical signals via optical medias of various types such as single-mode optical fibers and multi-mode optical fibers. This functionality also includes capabilities for supervision of optical amplifiers or repeaters when present in the optical transmission section layer network.

The optical transport network (OTN) employs various components. Within these, there are a few main devices that define the characteristics of the OTN: optical cross connects (OXC), optical add and-drop multiplexers (OADM) and wavelength converters.

Optical Cross Connects (OXC)

OXCs Figure. 2.7 are used to route wavelengths between inputs and outputs while adding and dropping local traffic. The OXCs can be any of free space type optical switching

devices, optical solid-state devices or electromechanical mirror-based devices including technology that enables the control of miniature mechanical devices such as very small mirrors called MEMS.
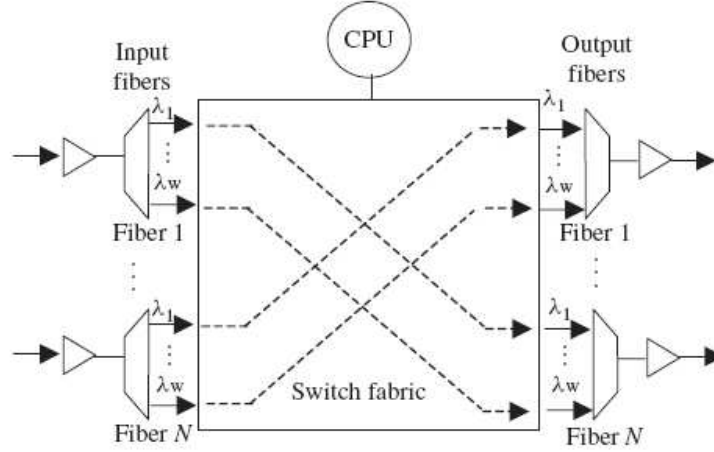
Figure 2.7: A Logical Diagram of an OXC

An OXC consists of amplifiers, multiplexers/demultiplexers, a switch fabric, and a CPU. The CPU is used to control the switch fabric and to run communications related software, such as routing, signaling, and network management. There are N input and N output optical fibers, where each fiber carries W wavelengths $\lambda_1, \lambda_2, \ldots, \lambda_w$. The optical signal from each input fiber is pre-amplified and then it is demultiplexed into W wavelengths. Each wavelength enters the switch fabric through an input port and the switch fabric then directs each wavelength to an output fiber. The W wavelengths switched to the same output fiber are multiplexed onto the same output fiber, and the multiplexed signal is amplified before it is propagated out onto the link. The switch fabric has NW input ports (one per incoming wavelength) and NW output ports (one per outgoing wavelength).

Optical Add and Drop Multiplexer (OADM)

Optical Add-Drop Multiplexers (OADM) are responsible for adding or removing individual signals (wavelengths) at individual points along the optical transport channel. OADMs function fully in the optical domain without performing an OEO conversion. OADMs operate as peripherals to the OXCs, providing the OXCs with the appropriate signals to direct Figure. 2.8.
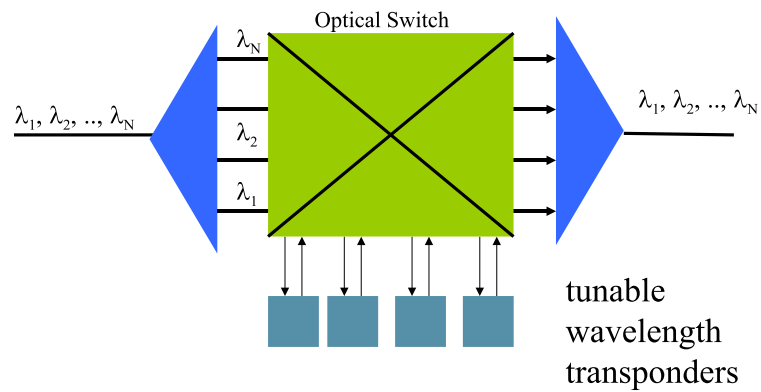
Figure 2.8: A logical diagram of an OADM

Wavelength Converter

Wavelength converters convert data on an input wavelength onto a different output wavelength. Wavelength converters improve the efficiency of the network by resolving wavelength conflicts in the lightpath. Wavelength converters employ one of several available techniques for wavelength conversion. These techniques can be broadly classified into two types: opto-electronic wavelength conversion and all-optical wavelength conversion. In opto-electronic wavelength conversion the optical signal is first converted into an electronic signal while in all-optical wavelength conversions the signal remains optical.

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2.1.3 Ring Networks vs. Mesh Networks

Optical networks can be configured as point-to-point, linear, ring, or mesh. Currently, optical networks are primarily rings, although point-to-point and linear networks are utilised for certain applications.

A point-to-point network is simply a network of one optical link, with terminating multiplexers (TMs) at each end. A linear network is similar to a point-to-point network, but contains intermediate nodes, called add/drop multiplexers (ADMs). In practice, the TMs are the same as the ADMs but have only one optical connection. A ring is a linear network which folds back on itself.

Mesh-based networks are being widely considered as an alternative to ring-based networks for future optical communications based on Dense Wavelength Division Multiplexing (DWDM) technology [12]. One of the main reasons is that mesh-based restoration networks offer much less capacity redundancy than ring-based networks to obtain the same restorability against any single span failure.

The optimisation in design of mesh-restorable networks on a given topology with respect to resource utilisation and cost of the service have been attractive subjects for researchers around the world in recent years [2, 23, 4, 24, 25, 12, 26, 27, 28]. It has been recognized that the efficiency in capacity usage of mesh-restorable networks is highly dependent on the physical topology. There has been little research published about physical topology design for mesh-based networks with respect to the survivability, and particularly for multiple QoP service classes. One of the reasons for this is that topology extension is extremely expensive and topology changes will affect service and network operations. Hence, upgrading existing networks would be carried out on a case by case basis depending on demand, rather than as part of the overall design. In addition, current ILP formulations for survivable mesh networks require large number of input variables, even when dealing with moderate size networks. This causes the time complexity of the model to be increased exponentially and to take a significant amount of time to obtain the

optimal solution.

2.1.4 Optical Network Survivability & Protection Techniques

Survivable networks can be defined as networks which can continue to provide service even during some network element failures such as, cable cuts and power outage, etc. Such networks are implemented with some survivability technology, which can be classified into three categories: 1) prevention, 2) network design, and 3) traffic management and restoration [14]. Prevention techniques focus on improving component and system reliability (such as fault tolerance in hardware architecture). The purpose of network design is to minimise the effects of system level failures. Traffic management and restoration procedures manage the network load in such a way that the failure has minimum impact and connections are re-established around the failure.

The approaches to the solution of network survivability involve a range of tradeoffs between network resource utilisation and service interruption time. J.B Slevinsky et al. proposed the decomposition of mesh-network into multiple self healing rings (SHR). In this approach, a set of rings, such that each link in the network is traversed by two rings (one in each direction) is found, and the fibers of one ring are backed up by the fibers on the other [24, 29].

Since a single failure can cause the simultaneous loss of service on several optical channels, a design algorithm called the disjoint alternate path (DAP) is presented by Crochat et al. [6, 21, 22]. The purpose of DAP is to maintain connectivity between all port pairs under single failure scenarios, and to minimise the impact of a WDM layer failure on the higher layers. The results from tests on ARPA2 physical networks show that the number of affected node pairs could be made zero by using the DAP algorithm, while it ranges from 3 to 37 for the shortest path routing (SPR) algorithm [30, 26].

Ramamurthy et al. compare different protection schemes in mesh networks under a single failure scenario [31, 32]. In this study, dedicated path protection, shared path pro-

tection, and shared link protection schemes were examined in a 15 node network under the assumption of no wavelength conversion and static demand. The results show that shared backup path protection has significant capacity efficiency over the other two schemes. The number of wavelengths required in a dedicated path, a shared path protection, and a shared link protection scheme are 163, 99, and 189 respectively.

The search for improving recovery switching time and reducing capacity redundancy leads to the discovery of preconfigured protection cycle (p-cycle), introduced by Grover et al. [33, 34, 20, 35]. Mauz has shown that it is important to do the wavelength assignment and the p-cycle search jointly to achieve the most capacity saving p-cycle on WP networks. He also emphasized the use of wavelength conversion to give a significant spare capacity saving due to the better sharing of protection resources [19, 36]. Recently, a new, promising concept to support dynamic demand environments has been introduced by Grover [20, 37] namely, self-organizing strategies for continual adaptation of a set of network protecting p-cycles, and the distributed cycle pre-configuration (DCPC) protocol, which is an adaptation of the processing rule of the self-healing network (SHN).

2.1.5   Network Protection and Recovery Time

In practice, optical transport networks are mostly based on a ring topology. Ring networks use simple switching mechanisms, which permit fast restoration time after failure (about 50ms- 60ms), but they require at least 100% capacity redundancy. Furthermore, in complete multi-ring networks, the working fiber/channel groups are usually not fully utilizable, thus the ratio of installed to working capacity can be 200-300%. In contrast, mesh based networks use fewer resources, but have the drawback of complicated protection mechanisms. Mesh network protection is usually based on paths (end-to-end) or on spans, but the restoration time is much longer than in the case of ring networks [31, 32].

2.1.6 Resource Allocation

A variety of protection and restoration methods have been designed and implemented for optical transport mesh networks [38, 23, 24, 24, 39, 40] , including automatic protection switching (APS), mesh span restoration, mesh path restoration, shared backup path protection (SBPP), and their variations in terms of complexity, spare capacity usage, restoration speed, and some other aspects. Thus, each method has its own advantages and disadvantages. For example, a network employing APS can achieve a restoration time less than 60 ms but must use more than 100% capacity redundancy. In contrast, with SBPP, the restoration time after a failure can be as large as 200ms [41, 40]. Multiple methods can be integrated into the same network providing different qualities of protection services to different connections and this has also been suggested by Grover in [20], but not many research publications have addressed this issue. Although the results in [20] show that significant capacity savings can be achieved with relatively well connected networks, the interaction between network topology and the capacity efficiency of various survivability schemes is still unclear.

2.1.7 Survivability Schemes at the Optical Layer

The survivability at the optical layer in WDM optical networks is based on two paradigms: path protection/restoration and link protection/restoration.

Link protection : all connections that traverse the failed link are rerouted around that link through alternate paths. The alternate paths and wavelength channels must be configured in advance for protection. Link protection can be dedicated or shared. In dedicated link protection, for each link of the working path, backup capacity is reserved around that link, depending on whether the signal is sent over the backup path during normal operation or not. In shared link protection, for each link of the working path, a backup path is reserved around that link. However, the backup wavelength on the links of the backup path may be shared with other backup paths,

thus the backup channels are multiplexed among different failure scenarios. For instance, automatic protection switching (APS) is a typical technique used for protecting link failures. APS has three main configurations: 1+1, 1:1, and 1:N. The differences between these are the way that they assign resources, 1+1 denotes a dedicated standby arrangement, the source node transmits the information on both working and protection links. The signal which arrives at the receiver with better quality is chosen. In the case of one link failure, the signal can still be transmitted on the operational link. In the case of 1:1 APS, every working link has it protection, but the source and destination nodes switch to the protection link only in cases of failure detection on the working link. 1:N APS refers to N number of working links that share a single protection link, but this configuration is not intended to protect against cable cuts. An extended version of this type of configuration is m:N, where for every N units of working capacity, there will be m units of spare capacity used for protection in the network on average.

Path protection: the source and destination nodes of each connection reserve backup paths on an end-to-end basis. Path protection can also be dedicated or shared. In the case of dedicated path protection, a (1:1) configuration is used, and the backup wavelength on the protection path is reserved only for a specific working connection. This implies that if there are two overlapping protection paths, different wavelengths must be used. Dedicated path protection therefore requires a larger amount of spare capacity for protection purposes, but is able to provide recovery from multiple link failures. In contrast, shared backup path protection uses the same wavelength on a link for two different protection paths provided that the corresponding working paths are link disjointed.

Restoration Schemes

In mesh based networks, the restoration issue can be further classified based on: the route computation and execution mechanism (as centralised or distributed), the re-routing (as

path/ link based), the computation timing (as pre-computed/ real-time), and the capacity sharing (as dedicated or shared) Figure. 2.9.
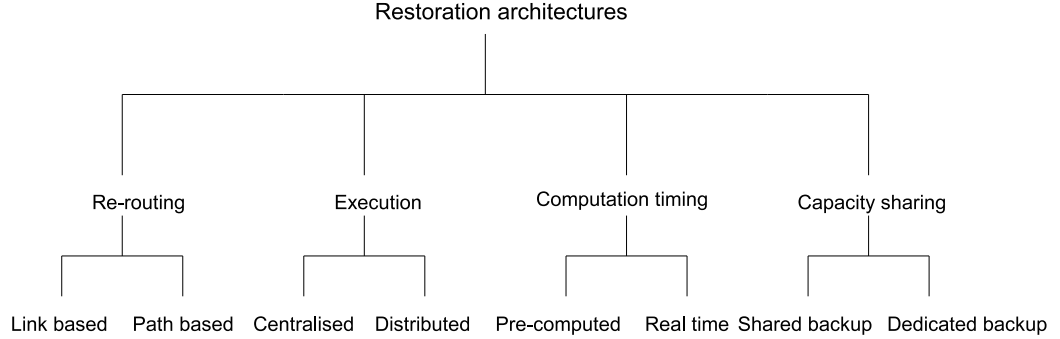
Figure 2.9: Restoration Architectures for Survivable WDM Networks [2]

Link based restoration methods re-route the disrupted traffic around the failed link. A new path is dynamically discovered and established between the end nodes of the failed link. In case of a new route being found for the broken connection, that connection is blocked. This approach requires the ability to identify the failed link at both ends and makes restoration more difficult when there is a node failure. The choice of restoration path is limited and may use more capacity.

Path based restoration re-routing replaces the whole path between the source and the destination of a demand.

Pre-computed methods calculate restoration paths before a failure occurs, and the real time approach does so after the failure occurs.

Centralised restoration methods compute primary restoration paths for all demands at a central controller, where the current status of a network is assumed to be available.

A *Distributed* method may involve pre-computed tables and discovered capacities, and routes in real-time. However, real time capacity discovery is slow and may not be efficient. Thus, distributed pre-computation of restoration routes is a more attractive approach.

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Capacity sharing is among the primary methods used for restoration paths and can be dedicated or shared - The dedicated method uses (1+1) or (1:1) protection, where each primary path has a corresponding restoration path. In the shared case, several primaries can share the same backup path as long as the primaries are node and link disjoint. This is called the backup multiplex technique.

In the bidirectional line-switched ring (BLSR) system, the most commonly used technique is the bidirectional line-switched protection mechanism. The ring network can be implemented either by using two-fiber or four-fiber systems.

In the two-fiber BLSRs network, each fiber carries working and protection channels. If a fiber is cut, the working channel targeted for a node beyond the failure will switch to the protection bandwidth available on the second fiber. The traffic now travels in the opposite direction on the protection bandwidth until it gets to its destination node. This can be seen in Figure. 2.10.
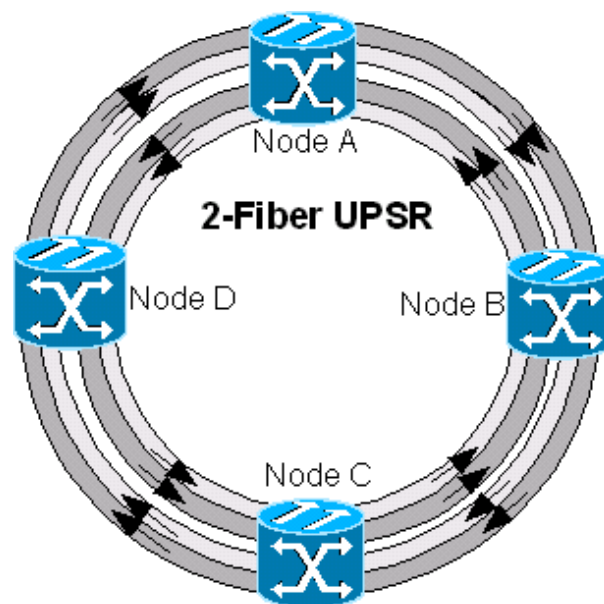
Figure 2.10: Two-Fiber BLSR Protection

Four-fiber BLSRs have double the bandwidth of the two-fiber BLSRs. With this type

of protection, two fibers are dedicated to working traffic and the other two fibers are dedicated to signal protection. The four-fiber BLSR allows both span switching and ring switching. The span switching occurs when there is a span failure. In this case, traffic is switched to the protection fibers between the nodes and then put back to the working fibers. In the case of ring switching, if the span switch cannot recover from failure (both the working and protection fibers fail on the same span), the traffic is routed over the protection fibers through the full ring as shown in Figure. 2.11.
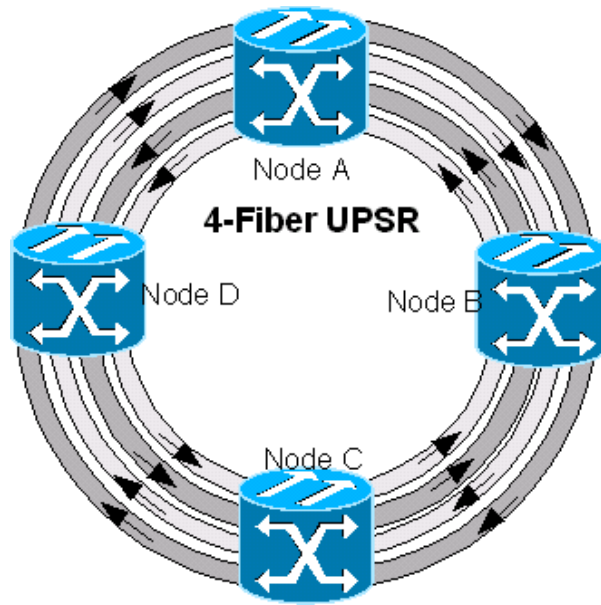
Figure 2.11: Four-Fiber BLSR Protection

2.1.8 Multilayer Network Survivability

WDM optical networks can be modeled as four sub-layers at which survivability techniques can be employed, namely: the service layer, logical layer, system layer and physical layer. Each lower layer has its own type of demand unit, which it provides to the next higher layer, and each layer can have its own protection mechanism and recovery procedures to deal with failures. However, it is not necessary to apply one or more methods on top of each other, e.g. if survivability for a ring network has been implemented at the

system layer, there may be no need to implement it at the logical layer and vice versa. Additionally, some service layers can operate directly over the physical layer, providing their own survivability through adaptive routing.

2.1.9   Service Layer Survivability

Service layer protection techniques are the last safeguards before physical failure becomes apparent to a clients applications. Service layer survivability is usually software based implementation that attempts rerouting within the working capacity. However, this consists only of partly utilised capacity that is visible to the service layer. If the response rerouting at a service layer is incomplete it can be complemented with a lower layer response by logical reconfiguration of its paths, thereby reducing delay or packet loss.

Typically at the service layer, under failure, blocking or congestion, delay levels may rise, but basic functionality will be maintained. Thus, except for special cases, service layer schemes tend to prevent outage, trading for performance degradation instead.

2.1.10   Physical Layer Survivability

The physical layer is the infrastructure of physical resources on which a network is based, for example, cable ducts, cables, buildings, etc. The survivability of this layer is mainly concerned with physical protection and ensuring that the layer topology has a basic spatial diversity, which allows higher layer survivability techniques to function.

2.1.11   System Layer Survivability

At the system layer, almost all the protection techniques react against single channel failure or span failure. These can consist of techniques such as linear APS schemes, ring schemes, and p-cycle techniques. In addition, the survivability techniques at the system layer also include the design of basic equipment redundancy to support the survivability

Table 2.2: Layered View of Networks for Survivability.*(Mesh Based Survivable Network [4])*

Layer	Elements	Service and Functions	Demand units generated	Capacity units provided	Generic survivability techniques
Service	IP routers,LSRs telephone switch, ATM switch, smart channel banks	Circuit-switch telephony and data, Internet, BISDN private networks, Multimedia	OC-3 OC-12 STS-1s DS-1s DS-3s GbE, etc...	NA	Adaptive routing, demand splitting, application reattempt
Logical	OXC, DCS, ATM, VP Xconnects	Services grooming, Logical transport configuration, bandwidth allocation and management	OC-48, OC-192, wavelength channels, wavebands	OC-3 OC-12 STS-1s DS-1s DS-3s GbE, etc	Mesh protection or restoration. DCS-based ring P-cycles
System	SONET OC-n TM, LTE, ADMs, OADMs, WDM transmission systems	Point-to point bit-transmission at 10 to 40 Gb/s. Point-to-point fiber or wavelengths	Fibers, cables	OC-48, OC-192, wave-length channels, wavebands	1:N APS 1+1 DP APS rings
Physical	Right-of way, conduits, polelines, huts, cables, ducts	Physical medium of transmission connectivity	NA	Fibers, cables	Physical encasement, physical diversity

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methods applied.

In general, survivability techniques that can be applied at this level are referred to as protection schemes. The main characteristic of protection schemes is that the protection routes and spare capacities are pre-defined, and the mechanism is self-contained within the layer itself.

System layer protection schemes rely on fixed transmission and protection structures, which have the advantage that once installed and tested, their operation is relatively simple. Their operation in general does not involve any reaction over the network, and the restoration path taken for any failure is clearly defined in advance. However, protection implementations at this layer are essentially static, and hence are not easy to re-configure if the designed topology turns out to be unsuitable for demand. Furthermore, when a failure occurs, the network cannot withstand a second failure during the period of physical repair.

2.1.12   Logical Layer Survivability

The flexibility of a logical layer allows the development of techniques to create paths on demand between designed end points. This becomes the natural domain of a number of survivability schemes (also referred to as mesh-restoration schemes) with features that are not provided by the techniques used at the system layer. Another consideration is the higher capacity efficiency through the sharing of protection capacity over non-simultaneous failure scenarios. However, minimizing the number of un-severed demands, and reducing restoration speeds still remain major goals for research at this level of protection.
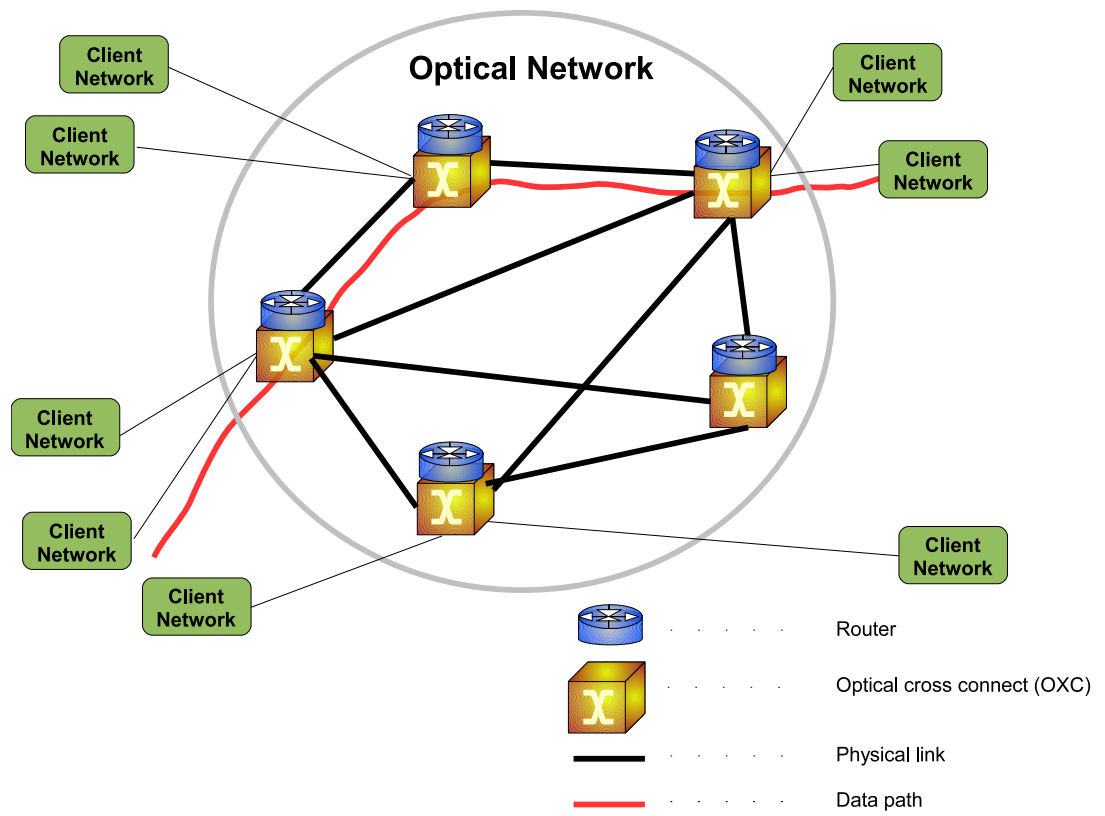
Figure 2.12: Optical Mesh Network

2.1.13 Topology Design

"*Topology design is the art of combining network infrastructure and operation strategies to satisfy certain traffic demands*" [23]. The traffic demands in network design can be either static or dynamic. In a dynamic traffic environment, the traffic demands arrive at a network in a random manner. Once a demand is honored, the objective is to increase the acceptance ratio. In the case of static traffic demand, the set of demands is given in advance. Thus the objective in this case is to assign lightpaths with the restoration capability to minimise resource placement but still satisfing the restorability requested, while minimizing total network cost, or maximizing resource utilisation [4, 15, 25, 28, 42]. According to Yufeng [43], the topology design problem can be divided into two sub-problems: network design and routing and wavelength assignment (RWA). Network design is concerned with physical topology design and configuration design, while RWA involves the mapping of lightpaths onto the given physical topology and assigning wavelengths to these lightpaths, also referred to as the logical (or virtual) topology problem.

Physical topology design

Almost all research on the physical topology design of mesh-restorable networks has so far been based on the assumptions that node positions are known, and the number of OXCs within **N** nodes have unbounded switching capacity. On that basis, the physical topology design is reduced to forecast the demand and deciding on a topology between OXCs, how to connect client sub-networks through OXCs, and the placement of other resources such as amplifiers, converters, and power splitters.

In practice, if the physical topology has to be designed from scratch, many providers will take a cautious approach by initially building a skeleton network and then adding new resources if necessary, depending on the actual user demands - as a way to minimise the additional capacity [12]. Physical topology design problems have been studied in [43]. In this, the author aimed to minimise the number of OXCs and wavelengths used for a given

number of label switching routers (LSRs) and to create a set of lightpaths which would be setup amongst pairs of OXCs. This text dealt with a combination of physical and logical topology design problems, where the routing and wavelength assignment for the lightpaths had already been determined. In [43], Y. Xin has shown that physical topology design problems can be formulated as an integer program (IP). An iteration approach was developed for this problem, whereby a genetic algorithm (GA) was used to generate feasible physical topologies, and heuristic techniques were employed for RWA on a given physical topology, which generated the fitness reference value for GA solutions. Some other studies regarding physical topology design have focused on different aspects such as placement of converters, connectivity, nodal degrees, and average hop distance [4, 15, 43, 18, 44].

The economic attractiveness of mesh-restorable networks depends on how the capacity is shared for restoration. This has a strong dependency on topology, and the next step in research on mesh-restorable networks design is to bring the graph of physical topology into the optimisation problem as a variable [12, 4]. A. J. Glenstrup [14] has researched the optimisation of the link cost based on different protection scenarios and treated them as green-field network planning. In this work, Glenstrup has also proposed a way of minimizing the node cost by grouping the wavelengths that share a common sub-path and employing multi-granular switch components, thus effectively reducing both switch ports and link costs. In [4], W.D. Grover has summarized the factors that interact with mesh survivable topology design as:

1. Spare capacity for restorability: For protecting working flows on one span (path), the topology must support spare capacity rerouting over diverse surviving spans (paths).

2. Edge establishment costs: Every new span added to the topology has some possible significant one-time cost. The total of new spans established is proportional to the number of spans and their distances.

3. Working path routing cost: This factor favors a greater number of spans. Every

span added permits a shortened routing for some number of working paths. Total working capacity is reduced as working routes shorten, and generally the network as a whole becomes less redundant as the average nodal degree increases. In mesh restoration, the spare capacity is desirable between $40\% - 60\%$ of working capacity. Thus a fixed charge routing (FCR)[1] solution for the working flows and edges is still an important part of good overall topology.

4. Modularity and economy of scale effects: This is another factor with high connectivity. Strong economy of scale can be less expensive as it tends to group many flows together and takes a longer route than if there were extra edges that make shorter routes possible. However, only the large volume of modularity contributes to sparseness, and that depends on the volume of demand relative to the available capacity modules.

5. Two-connected (or preferably a bi-connectivity) requirement: This is a requirement for a mesh network to be survivable. The average nodal degree must greater than or equal to two.

6. Access to demand sources: this involves to the topology extension problem.

The physical topology design problem is quite complex because the interdependence between physical and logical architectures, such as the link, OXCs capacities, location of optical devices (amplifiers and converters) is dependent on the routing of lightpaths and the wavelength assignment strategy, and vice versa [4, 44, 45].

Logical or Virtual Topology Design

In an optical network, where there is no wavelength conversion or limited conversion ability, logical design encounters the RWA problem. Thus blocking can occur either through

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[1]The FCR problem is to select a subset of all possible edges and routes working flows over them at minimum total cost for flows and edges.

capacity blocking or wavelength mismatch blocking. RWA problems can be either on-line (dynamic) or off-line (static). An off-line RWA assumes all lightpath requirements are known and seeks a single overall solution for the assignment of routes and wavelengths to meet lightpath requirements. It creates a logical topology among the edge nodes. The typical objective of RWA is to satisfy all the requirements with a minimum number of wavelength usage, and to minimise the number of un-severed demands. The wavelength assigned to each path must be free on at least one fiber pair on each hop of the route assigned to the same demand [4]. The type of logical topology that can be created is usually constrained by the underlying physical topology. Generally, the RWA problem is specified by providing the physical topology of the network and traffic requirements. RWA is considered as an optimisation problem that can be readily solved using an integer programming (ILP) formulation. Usually, the objective is to minimise the maximum congestion level in the network that is subject to network resource constraints [46]. The ILP formulation has a very large number of variables, and becomes intractable for large networks. This has led to the development of heuristic approaches for finding feasible solutions to large scale network problems [4, 15] [14]. Static RWA can be decomposed into four sub-problems [15]. Solving these subproblems may not give the optimal solution, but according to Rouskas [46], the decomposition provides insight into the structure of the RWA problem and is a first step to achieve the design of effective heuristics. The sub-problems are as follows (assume no WC): The sub-problems can be typically defined as follows by Rouskas:

Topology subproblem: Determines the logical topology to be imposed on the given physical topology, that is, determines the lightpaths in terms of their source and destination edge nodes.

Lightpath Routing subproblem: Determines the physical links which each lightpath consists of, that is, routes the lightpaths over the physical topology.

Wavelength Assignment subproblem: Determines the wavelength each lightpath uses, that is, assigns a wavelength to each lightpath in the virtual topology so that wavelength

restrictions are obeyed for each physical link.

Traffic Routing subproblem: Routes packet traffic between source and destination nodes over the virtual topology obtained.

There have been a number of heuristic algorithms targeting the general static RWA problems. Overall, they can be classified into three broad categories: (1) Algorithms which solve the overall ILP problem optimally. (2) Algorithms which target only a sub-set of the above mentioned four sub-problems. (3) Algorithms which address the problem of embedding regular logical topologies onto the physical topology. Optimal solution can be achieved by using LP-relaxation followed by rounding [15]. The integer constraints in this case are relaxed creating non-integral problems that can be solved by linear programming techniques, then a rounding algorithm can be applied to obtain a new solution with respect to the design constraints. However, LP-relaxation may lead to solutions which are difficult to apply the rounding algorithm. Other methods such as a genetic algorithm or simulated annealing [23] can be applied to obtain optimal solutions locally, but the main drawback of these approaches is that it is difficult to control the quality of the final solution for large size networks.

2.1.14 Concept of Multiple Quality of Protection Service Classes

Studies of capacity-design for transport networks assume that all the service classes must be restorable against failures of network components. However, in reality, there are at least four different policies for the treatment of different demands in mesh-restorable networks [4]. The combination of these different network demands are called Multiple Quality of Protection (MQoP) service classes. The definitions of the service classes, order form high grade to low grade based on the complexity of implementation at the optical layer and the level of availability that they can provide are as follows:

1. Lightpaths that are guaranteed to be protected by the optical layer with specific restoration time requirement.

2. Lightpaths that are protected by best efforts, and should be restored if possible following the full restoration of any of the higher class service capacities.

3. Lightpaths that are not protected, and do not receive any restoration effort, but are not subject to be preempted.

4. Low priority lightpaths that under normal conditions utilise protection bandwidth. These are channels that do not receive any protection, and are preempted when other lightpaths need to being protected.

The research results in [47] show a significant reduction in the spare capacity requirements, because not all services require restoration. Thus, design and optimisation of the mesh-restorable network with mix-service classes allows the network to enhance operation and provide more customer options.

The study of Clouquer *et al* in [47], however, was based on span protection only. This type of protection scheme requires a high level of resource redundancy. In this study, network design and optimisation with a mix of three different protection schemes is examined. These schemes are: dedicated path protection, SBPP and *p*-cycles. The *p*-cycle scheme is a new span protection technique, which takes advantage of the existing straddling links, and, in some cases, the efficiency can be as high as that of SBPP.

2.1.15 Issues in Integer Linear Programming Models for Survivable Network Design with Multiple Quality of Protection Service Classes.

In [41, 32], the authors have examined the resource requirements for routing and the wavelength assignment of primary and backup paths in both path based and link based protection. This study also examines the protection-switching time and the restoration time for each of these schemes. The path protection scheme provides significant capacity savings over link protection, and shared protection provides significant savings over dedicated protection. However, the recovery time after failures is much greater. Conversely, path

protection is more susceptible to multiple link failures than link protection, and shared protection is more susceptible to multiple link failures than dedicated protection.

Rather than providing the networks with one type of protection scheme as in [47], the path protection (dedicated and SBPP), link protection , and p-cycle schemes can all be integrated into one formulation such as in [20]. Integrating multiple protection schemes into one formulation to serve multiple demands of quality service is a complicated task. In addition, due to the high number of constraints and variables involved in the formulation, such as in SBPP and p-cycles (particularly when one includes all the non-simple p-cycle in the set of candidates) the complexity of the ILP model increases exponentially. Therefore, before putting all these schemes together into one final mathematical form, it is necessary to find a way to reduce the the complexity of the individual case as much as possible.

2.2   Integer Linear Programming

Integer programming problems are special cases of linear programming problems, or more generally combinatorial optimisation problems. In these, the unknown variables are integers. One well known classical network design problem is the Traveling Salesman Problem. This problem has been proved as being Nondeterministic Polynomial-time (NP) Complete. Solving an NP Complete problem is difficult , especially for large numbers of unknown variables. So far there is no efficient algorithm to solve NP Complete problems.

The process of formulating an optimal design for network routing and resource allocation leads to the creation of ILP problems. The ILP programs consist of an objective and a list of constraints, and all are parameterized by the decision variables eg. x_i which are free variables whose optimal values are to be determined. The ILP solvers take the inputs of the ILP model and produce outputs as optimal values of the objective function.

Network design problems are subject to variants of the multi-commodity flow prob-

lem, where input and output flows are balanced for all nodes, or link-path formulation, and each traffic flow has be to satisfied with some degree of constraints. This may limit the optimality of the solution [23]. Cheng-Shong Wu et al.(1999) introduced detailed algorithms for solving some ILP programs based on Lagrangian relaxation and sub-gradient optimisation techniques [48]. Jan et al. (1993) developed a branch and bound algorithm just for backup capacity [14]. By removing the integer constraints, the ILP problems can be simplified down to the LP problems, but the solution then no longer provides an optimal value. The ILP formulation typically has the following form:

$$\text{minimise/ Maximize}: \quad c_1 x_1 + c_2 x_2 + \cdots + c_n x_n \qquad (Objective)$$

$$\text{Subject to} \quad \left. \begin{array}{l} c_1 x_1 + c_2 x_2 + \cdots + c_n x_n \quad \{\leq | = | \geq\} \quad b_1 \\ \ldots \\ \ldots \\ c_m x_1 + c_m x_2 + \cdots + c_m x_n \quad \{\leq | = | \geq\} \quad b_m \end{array} \right\} (Constraints)$$

$$x_j \geq 0, j = 1 \ldots n \} \quad (Bounds)$$

$$x : integer$$

For larger sized networks, solving ILP problems is not possible within a reasonable time. Thus, either the problems must be broken down and refined or a suitable heuristic approach must be considered and applied. Heuristics are a method of finding a solution close to the optimal solution through evaluating a number of feasible solutions, but this technique does not assure optimal results. Heuristic algorithms can be developed with respect to the ILP model if the problem has an objective function with no other dependency. Meta-heuristic approaches can also be considered. There are three well developed meta-heuristic methods: simulated annealing (SA), a genetic algorithm, and tabu search [49, 50, 51] (more details are in Appendices).

There are two common approaches to solving an ILP problem. The first method is based on cutting planes, where constraints are added to force integrality. The second

technique is based on dividing the problem into a number of smaller problems. This method is called branch and bound, and will be illustrated in the following example.

Solving Linear Integer Programs

The first step in the branch-and-bound method is to solve the linear program. This is called the LP-relaxation of the ILP. The optimal solution is one where all the variables have taken on integer values. The branch-and-bound process is as follows:

$$\text{Maximize}: S = \quad 17x_1 + 12x_2 \qquad (Objective)$$

$$\text{Subject to} \qquad \left. \begin{array}{rcl} 10x_1 + 7x_2 & \leq & 40 \\ x_1 + x_2 & \leq & 5 \end{array} \right\} (Constraints)$$

$$x_j \geq 0, j = 1, 2\}$$
$$x_1, x_2 : integer$$

The first linear relaxation solution is: $x_1 = 1.67$, $x_2 = 3.33$ and $S_0 = 68.33$. As x_1, x_2 are not both integers, and thus S_0 is not the integer solution. The value of S_0 provides the upper bound on the optimal solution. Therefore, there won't be any integer solution that is greater than 68.33.

$$\boxed{\begin{array}{c} S_0 = 68.33\,; \\ x_1 = 1.67\,; x_2 = 3.33 \end{array}}$$

Figure 2.13: First LP solution

Either x_1 or x_2 may be selected to continue the process. With x_1, two cases result: $x_1 \leq 1$ and $x_1 \geq 2$.

Solve the LP with $x_1 = 1$. and therefore: $x_1 = 1$, $x_2 = 4$ and $S_1 = 65$.

Solve the LP with $x_1 = 2$. and therefore: $x_1 = 2$, $x_2 = 2.86$ and $S_2 = 68.29$.

Both of the solutions can be illustrated as follows:
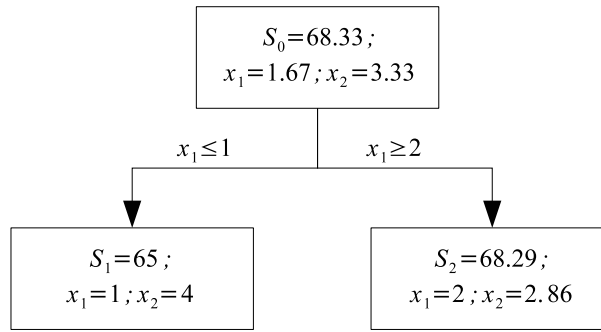
Figure 2.14: 1st level branching

The final step gives a feasible solution of $S = 65$. There is no further branching necessary in this instance, however, there may be a value greater than 65 on another branch. There are two cases that need to be evaluated: $x_2 \leq 2$ and $x_2 \geq 3$.

Solve the LP with $x_2 = 2$. The results here are: $x_1 = 2.6$, $x_2 = 2$ and $S_1 = 68.2$. S_4 with $x_2 \geq 3$ will be dealt with later in the ILP solving process.
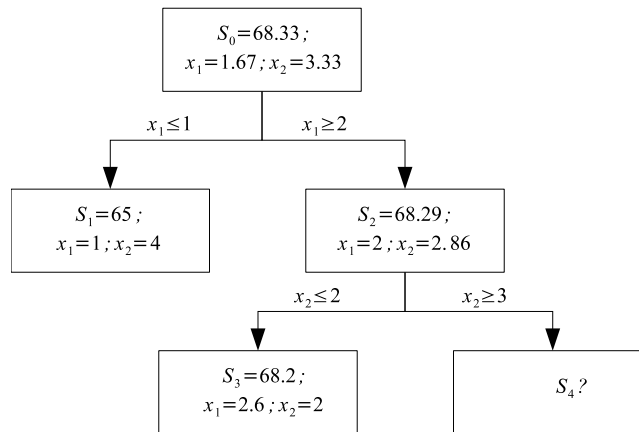
Figure 2.15: 2nd level branching

Continue branching, for $x_1 \leq 2$ and $x_1 \geq 3$. and therefore:

Solve the LP with $x_1 = 2$. and therefore: $x_1 = 2$, $x_2 = 2$ and $S_5 = 58$. This is feasible, thus no need for further branching in this case.

Solve the LP with $x_1 = 3$. and therefore: $x_1 = 3$, $x_2 = 1.43$ and $S_6 = 68.14$. Continue branching, for $x_2 \leq 1$ and $x_2 \geq 2$. Solve the LP with $x_2 = 1$. and therefore: $x_1 = 3.3$,
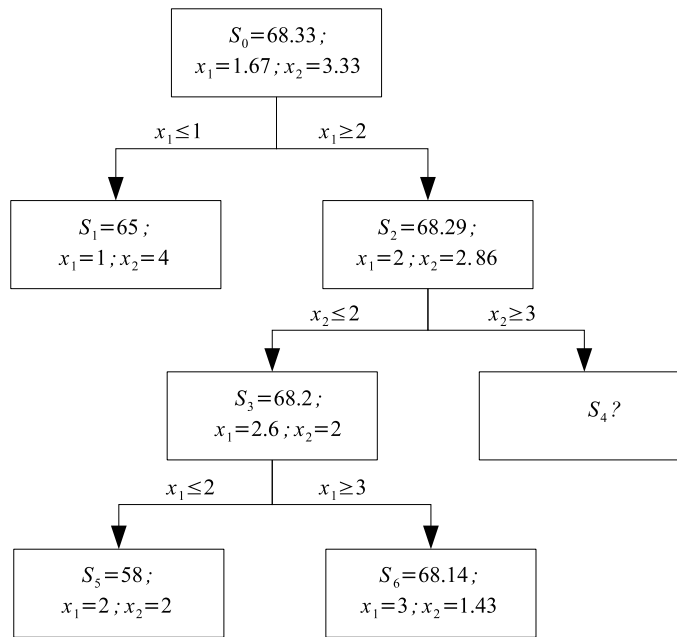
Figure 2.16: 3rd level branching

$x_2 = 1$ and $S_7 = 68.1$. S_8 with $x_2 \geq 2$ are left for consideration later in this process.
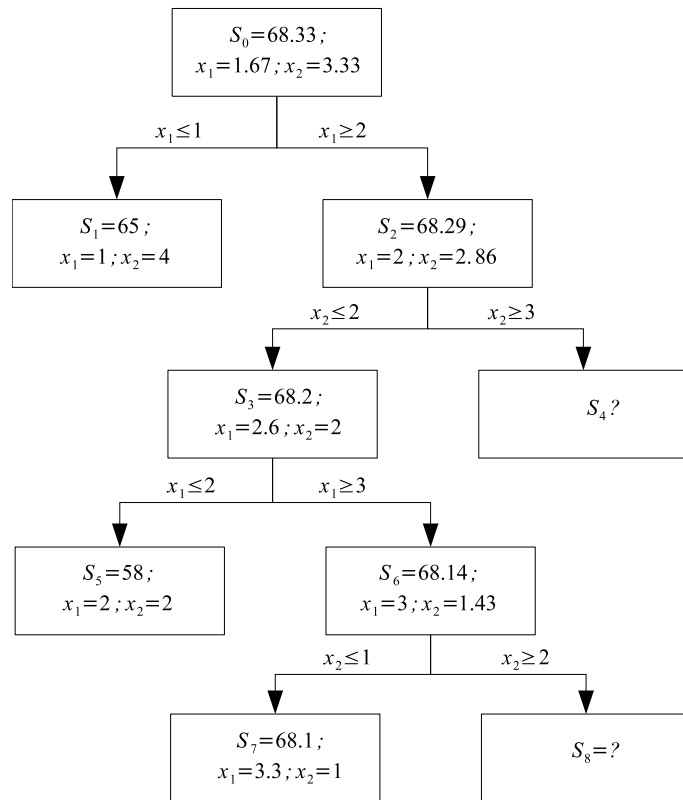
Figure 2.17: 4th level branching

Remaining now are two other cases, which are $x_1 \leq 3$ and $x_1 \geq 4$.

Solve the LP with $x_1 = 3$. and therefore: $x_1 = 3$, $x_2 = 1$ and $S_5 = 63$. This is feasible, thus there no need for further branching in this case.

Solve the LP with $x_1 = 4$. and therefore: $x_1 = 4$, $x_2 = 0$ and $S_{10} = 68$. This is feasible, thus there no need for further branching in this instance.

To complete the process, the previously unsolved branches are considered and solved for S_4 and S_8: With $x_2 \geq 3$, S_4 is infeasible, and with $x_2 \geq 2$, S_8 is also infeasible.
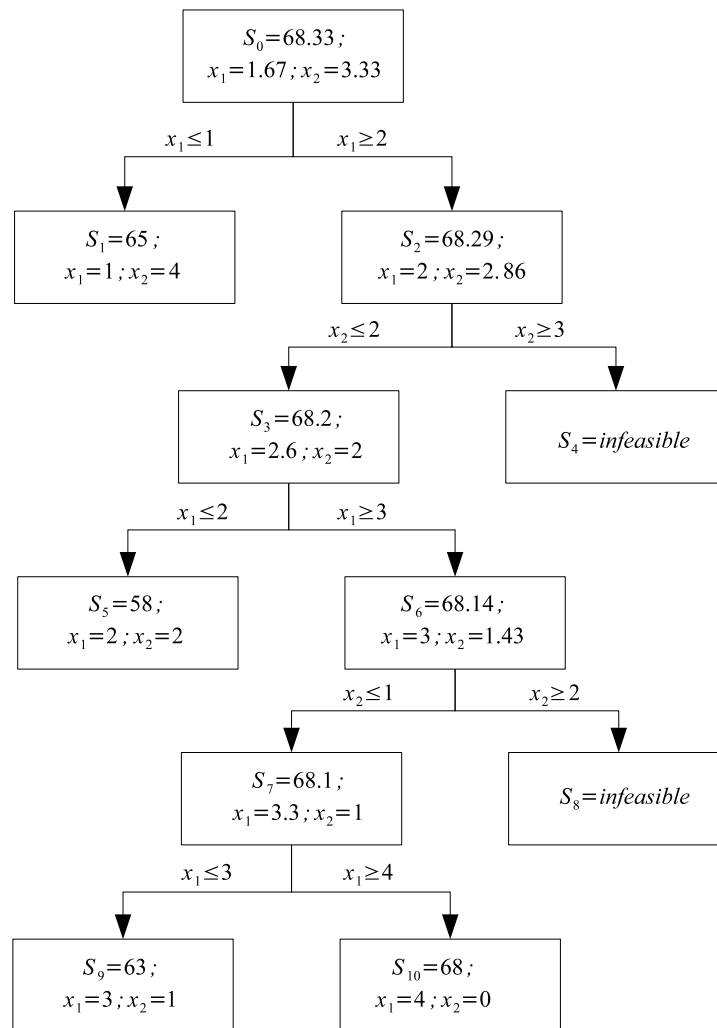
Figure 2.18: 5th level branching

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There are three integer solutions $S_1 = 65$, $S_5 = 58$, $S_9 = 63$ and $S_{10} = 68$. The optimal solution is then $S_{10} = 68$ with $x_1 = 4$, $x_2 = 0$.

2.3 Brief Review of Graph Theory

Graph theory is a natural way of representing the transport network which implies an abstraction of the reality by a set of nodes and connections between them. Graph theory is a well established, and has been used for network design and optimisation since the early days of network design, and many basic algorithms such as, finding shortest path, k-shortest path and shortest two-disjoint path for routing and protection, graph coloring for wavelength assignment, min-cut max-flow theorem for finding the maximum flow between two nodes ...etc. have been developed.

A network's physical topology can be modeled as an undirected graph $G(V,E)$, where $V = \{v_1, v_2, \ldots, v_N\}$ is a set of N *vertices* and $E = \{e_1, e_2, \ldots, e_M\}$ is a set of M network *edges*. In communications networks, the terms vertex and edge are used interchangeably with node and span respectively. For a span $e = \{x, y\}$, nodes x and y are end nodes of e. x and y are called *adjacent* nodes and jointed by the span e. Figure. 2.21 is a graph representing an arbitrary network with $N = 9$ and $M = 14$. The nodal degree, denotes deg(v), is the number of edges incident to v; and the average nodal degree is denoted $\widetilde{d} = \frac{2M}{N}$. Note that, throughout this study, *span* is used to imply the physical connection between two end nodes, and *link* refers to a logical connection between the two end nodes.

Table 2.3 shows the degree of nodes in the network in Figure. 2.21.

Table 2.3: Nodal Degree of Network in Figure. 2.21

Node v	1	2	3	4	5	6	7	8	9
$deg(v)$	2	3	4	3	4	4	3	3	2

A graph can be represented by a matrix called an *adjacency matrix*. An adjacency
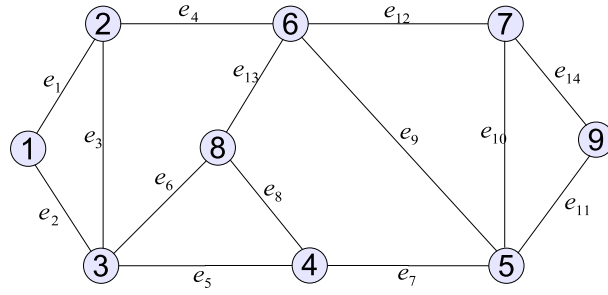
Figure 2.19: An Example of a Network Represented as a Graph

$$
\begin{pmatrix}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
2 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\
3 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\
4 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\
5 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 \\
6 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \\
7 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\
8 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\
9 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\
\end{pmatrix}
$$

Figure 2.20: adjacency Matrix of Network in Figure. 2.21

matrix of a graph G is defined as: $A_{i,j} = 1$ if i and j are adjacent, 0 otherwise; where $i, j \in V$. Figure. 2.3 presents the adjacency matrix of the example.

A network configuration matrix that contains information relates to the link, nodes and also the cost of each network's link. The configuration matrix is as in Table 2.4. The cost of each link and the nodes that are incident to the link are easily obtained by using the link index.

Given a graph $G(V,E)$, a chain W is a sequence of nodes and links. For example, $\{v_1 e_1 v_2 e_4 v_6 e_{12} v_7\}$. It is also possible to represent the walk by splitting it into two closely

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Table 2.4: Network Configuration

Link index	Node i	Node j	Cost
1	1	2	1
2	1	3	1
3	2	3	1
4	2	6	1
5	3	4	1
6	3	8	1
7	4	5	1
8	4	8	1
9	5	6	1
10	5	7	1
11	5	9	1
12	6	7	1
13	6	8	1
14	7	9	1

related forms, which are node forms or link forms as below:

Node form $\{v_1 - v_2 - v_6 - v_7\}$

Link form $\{e_1 - e_4 - e_{12}\}$

In graph theory, a *trail* is a walk with no repeated edges, and a *path* is a walk with no repeated vertices. The length of a walk is the total number of its links (this is often known as hop length in communication network).
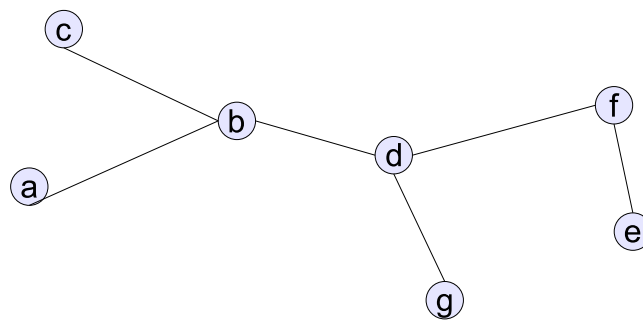
(a)
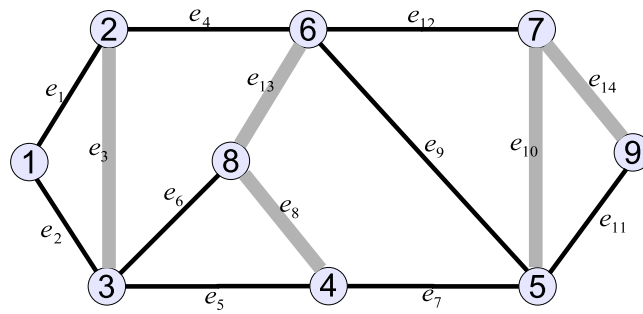
(b)

Figure 2.21: An Example of (a) a Tree and (b) a Spanning Tree (dark lines)

A *cycle* is a trail with the same star and end nodes, where all other nodes are distinct. Another way to describe this is that a cycle is a closed path.

A cycle crossing all edges in a graph is an Eulerian cycle, and a graph containing at least one Eulerian cycle is called an Eulerian graph.

A cycle traversing all vertices of a graph is called a Hamiltonian cycle, and a graph containing at least one is called a Hamiltonian graph.

A graph is said to be connected if, for every pair of nodes i, j, there is a walk from i and j and vice versa.

A graph that contains no cycles is called an *acyclic* graph or *forest*

A connected graph that has no cycle is called a tree.

A *subgraph $H = (V(H), E(H))$* of a graph G is a graph with the set of nodes $V(H) \subseteq V(G)$ and the set of edges $E(H) \subseteq E(G)$. Both ends at every edges of H are nodes of H.

An acyclic subgraph $G' \subseteq G$ that contains every vertex in G is called a spanning tree.

A graph is called two-connected if there are at least two edge-disjoint paths between every pair of its vertices, and called bi-connected if there are at least two vertex-disjointed paths between every pair of its vertices. Thus a bi-connected graph is also a two-connected graph but a two-connected graph is not a bi-connected graph.

2.4   Summary

Optical networks have enabled significant contributions to the development of the world today. The concepts of layering, transport demands, working and spare capacities, plus network topologies designs with regards to survivability, and resource efficiency are important ones. Routing behaviors between protection schemes such as span and path based protection have been discussed in this chapter with general comments on their relative recovery times and resource efficiencies. The mathematical formulations known as ILPs, which are used for modeling of the network topologies against the demand forecast were introduced. A relevant portion of "Graph theory", which is a natural way of representing

the transport network implies an abstraction of the reality by a set of nodes and connections between them is useful in network modeling, was also presented.

Chapter 3

Connectivity of Physical Networks

Establishing the physical survivability of large networks is not a trivial task. Some techniques for assessing physical survivability such as the cutset method cannot deal with large size networks [52, 53, 54]. A fast technique for finding biconnected components of a graph and testing the network for node/ link-bridges, presented in [55, 4], does not provide any further information, such as identifying the fundamental cycles within the network, which would significantly benefit the next phase of network design for protection using such techniques as shared backup path protection (SBPP), p-cycle, or ring protection [4]. This chapter presents an alternative technique, based on graph theory, for evaluating the physical survivability of networks. This technique deals with network sizes of many thousands of nodes whilst providing more information about the susceptibility of a network in relation to individual link and node failures, and preparation for the next phase of network protection design.

3.1   Background

Design of survivable communication networks is a challenging problem. Without establishing network survivability at the physical layer, there can be severe consequences

when a physical link fails. Network failures which may be caused by dig-ups, vehicle crashes, human errors, malfunctional systems, fire, rodents, sabotage, natural disaster (eg. floods, earthquakes, lightning storms), and some other factors, occur quite frequently and sometimes with unpredictable consequences. To tackle these, survivability measures can be implemented at the service layer, the logical layer, the system layer, and the physical layer. The physical layer is obviously the base resource infrastructure of the network, and to be able to protect it, it is necessary to ensure that the physical topology of the network has sufficient link and node diversity. Without this, protection at higher layers will not be feasible. With the implementation of Dense Wavelength Division Multiplexing (DWDM) in the optical backbone of networks, greater flexibility can be achieved in providing alternate routes for lightpath connections. However, the survivability problem at the physical layer remains the same. In fact, it becomes even more critical because, being a backbone network, there is a huge amount of traffic exchanged on any link of the network at any one time, hence the failure of an optical component, such as a fiber cut or a node failure, may cause a very serious problem in terms of loss of data and profit. For instance, the direct voice-calling revenue loss from the failure of a major trunk group is frequently quoted at $100,000 per minute or more [56, 57, 58]. Network survivability, therefore, is becoming a critical and imperative problem in telecommunication networks today, particularly in optical networks.

A network is considered to be survivable if its physical topology can cope with any single failure of network components by rerouting the connections affected through an alternative path. However, this requires some redundancies in the network. Hence, a survivable network must be a two-connected graph or a biconnected graph [4]. Menger's theorem gives the necessary and sufficient condition for survivability of networks at the physical layer. This relates the network connectivity to its cut-sets [28]. However, it is impractical to use cut-sets to determine the survivability of the network due to computational complexity increasing exponentially with the network size, eg. a network of N nodes would yield $2^N - 2$ cutsets. Testing for survivability of large size networks can be done using biconnected components of a graph introduced by W.D. Grover [4]. This

technique can determine vulnerable links and nodes in the network. However, verifying network survivability is just the first step in network planning, after which it is necessary to apply appropriate protection routing schemes using such techniques as Shared Backup Path Protection (SBPP), *p*-cycle, or ring topology [32, 41, 59, 60]. It is therefore very helpful if the algorithm used for determining the physical survivability of the network can also provide additional information which is of benefit to protection design. Figure. 3.1 shows a typical network consists of a link bridge *e* and a node bridge *v*.

The following sections introduce a new method for examining the physical survivability of networks using properties of 2-connected graphs. This technique also determines all simple distinct cycles in the network which is useful for the protection design.
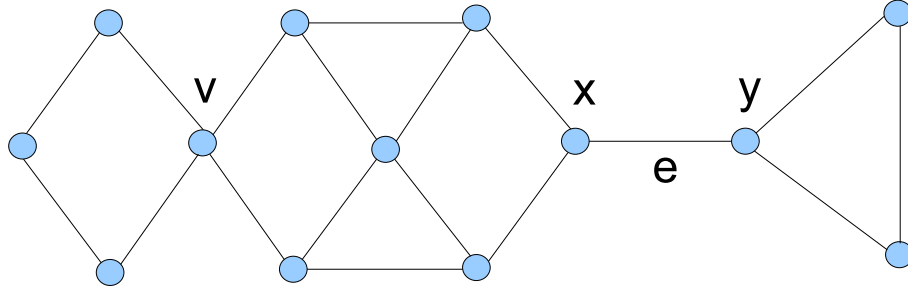
Figure 3.1: A network with a link bridge (*e*) and a node-bridge (*v*)

3.2 Survivability Verification Framework

In this section, it is necessary to first outline some notations and definitions related to graph theory. This assists in the understanding of the theorems and techniques for establishing the physical survivability of the network that are next presented.

3.2.1 Definitions

The following definitions are from [54] and [53].

- *Graph*: A graph G is a pair of sets V and E satisfying $E \subseteq [V]^2$, where V is a set of vertices (or nodes) and E is the set of edges connecting two distinct vertices in V.

- *Connected graph*: a non-empty graph G is *connected* if any two of its vertices are linked by a path in G, and is k-connected if any two of its vertices can be joined by k independent paths.

- *Subgraph*: a graph $G'(V', E')$ is called a subgraph of a graph $G(V, E)$, denoted by $G' \subseteq G$, if $V' \subseteq V$ and $E' \subseteq E$.

- *Component*: a maximum connected subgraph of G is called a *component* of G.

- *Cutvertex and Bridge*: a vertex $v \in V$ of graph $G(V, E)$ is called a *cutvertex* if it separates two other vertices of the same component. An edge $e \in E$ is called *cutedge* (bridge) if it separates its ends.

- *H-path*: a path P is called H-path if P is non-trivial, and meets a graph H exactly in its ends.

- *Block*: A block in a graph G will either be a maximal 2-connected sub-graph, a bridge, or an isolated vertex. Conversely, every such sub-graph is a block. Different blocks of G overlap in at most one vertex, which is then a cutvertex of G. Thus, every edge of G lies in a unique block, and G is the union of its blocks. This is demonstrated in Figure. 3.2.

Based on the above definitions, the two existing techniques for determining the physical survivability of networks will be defined in detail.

3.2.2 Survivability via Cut-Sets

A cut divides the graph which represents the network into two subgraphs, referred to as a cut-set, and the size of a cut-set is the number of edges connecting these two subgraphs. If, for all possible cut-sets, there are two or more links between the two subgraphs in a
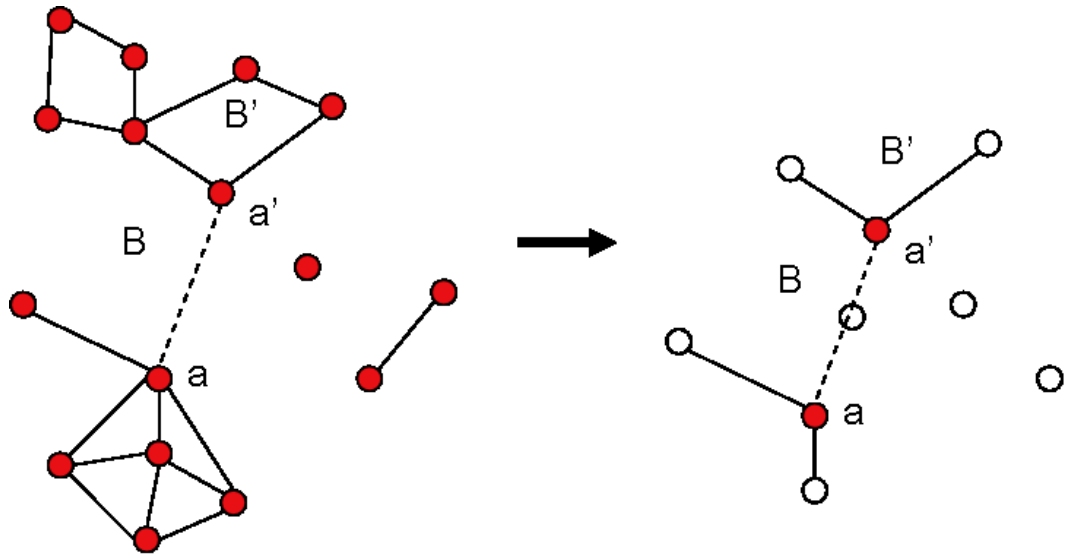
Figure 3.2: A graph and its blocks

cut-set, then the network is survivable. Menger's theorem [54], given below, determines the connectivity of a network by examining its cut-sets.

Theorem 3.2.1 *A topology with the set of nodes N and the set of edges E is 2-connected if and only if every non-trivial cut $\langle S, N-S \rangle$ has a corresponding size of cut-set greater than or equal to 2 [28].*

Network survivability can be verified using Menger's theorem. However, as discussed earlier, the complexity of the algorithm increases exponentially with the number of nodes and it cannot deal with large networks.

3.2.3 Survivability via 2-Connected Graphs

From Theorem 3.2.1, it can be seen that a cycle always has cut-set of size equal to 2. Furthermore, a 2-connected graph can easily be constructed from simple cycles Figure. 3.3. The following proposition implies a method to construct such graphs:

Proposition 1 *A graph is 2-connected if and only if it can be constructed from a cycle by successively adding H-paths to graphs H already constructed.*

Proof: Clearly, every graph constructed as proposed is 2-connected. Conversely, let G be a 2-connected graph, then G contains a cycle, and a subgraph H is constructible. Any edge $x, y \in E(G) \backslash E(H)$ with $x, y \in H$ defines a H-path. Then, H is an induced sub-graph of G. If $H \neq G$, then by the connectedness of G, there is an edge vw with $v \in G - H$ and $w \in H$. As G is 2-connected, $G - w$ has a $v - H$ path P. Then wvP is a H-path in G, and $H \cup wvP$ is a constructible sub-graph of G. ∎
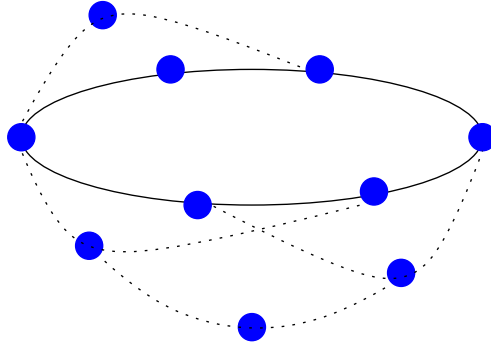
Figure 3.3: 2-connected graphs

3.3   Proposed Technique

From Proposition 1, it is possible to deduce the relation between the two 2-connected graph presented by two blocks G' and G'' resulting in a graph G, to hold the following cases:

1. G' and G'' have at least 2 common vertices: G is a 2-connected graph with no node or link bridge.

2. G' and G'' have one common vertex: G is a 2-connected graph with a cut vertex or called node bridge.

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3. G' and G'' are separated by a cutedge: G is not a 2-connected graph, and the cutedge is called link bridge, and has no survivability.

4. G' and G'' have no relation: G is not a 2-connected graph, and has no survivability.

Based on the above discussion, it is possible to use the relation between network cycles or 2-connected graphs to verify the survivability of its physical topology. An undirected graph thus is seen as the combination of all the fundamental cycles. These fundamental cycles can be found from a spanning tree $\{V, T\}$ of a graph $G = \{V, E\}$ (represented as thick lines on the Figure. 3.4). All the fundamental cycles in the graph, however, may

---

Algorithm 1 *Finding cycle*

Input : A tree T and an edge e whose end-nodes are in T;

Output: A cycle P formed by T and e;

  $(s, d) \leftarrow$ end-nodes of e;

  $queue \leftarrow [node.s, node.d]; check \leftarrow 0$;

  while $check == 0 \& queue \neq \emptyset$ **do**

    $[v] \leftarrow head(queue); queue \leftarrow queue - \{head(queue)\}$;

    if $v.s == d$ **then**

      $check = 1; P \leftarrow v.P$

    else

      for all v_k is neighbour of $v.s$; **do**

        $node.s \leftarrow v_k; node.P \leftarrow P \cup v_k$;

        push *node* into *queue*;

      end for

    end if

  end while

---

not be easily picked. For instance, Figure. 3.4 shows that any edge $e \in E$ but $e \notin T$ *(the remaining links)* forms a unique cycle with the tree branch when added to the tree, and those cycles are not always fundamental cycles. However, fundamental cycles can be identified by evaluating the length of cycles resulting from a spanning tree of the graph

by connecting paths in the spanning tree with the remain links. The next step is to create a substitution list of links for the cycles which are not fundamental. Another efficient method for finding fundamental cycles of a graph, referred to as *Paton's* algorithm, is represented in [61]. This is, however, outside the scope of this work. Any set of cycles found from the spanning tree can be used to verify the survivability of the topology that it is generated from. An algorithm for finding a set of cycles through spanning tree of a graph is represented in Algorithm 1. Algorithm 1 results in a set of cycles on which any

Figure 3.4: Spanning tree on an arbitrary graph

vertex in the graph is contained in at least one cycle when the graph is 2-connected. Hence, this set of cycles is sufficient to verify the survivability of the graph. Next introduced is an algorithm which is used not only to verify the survivability of a graph, but also to determine the weaknesses of the graph such as cutvertices and link-bridges if they exist. This is presented in Algorithm 2

3.4   Illustration and Simulation

In this section, an example of how the approach works over an arbitrary physical topology G as shown in Figure. 3.5, with the set of nodes V and edges E is provided.

The Algorithm 1 and Algorithm 2 produce a tree T, being a subgraph of G, and an unconnected node 13, shown in Figure. 3.5(b). T is a subgraph of the set of nodes V_T and edges E_T, where $V_T = V - \{13\}$, and $E_T = E - \{(2,4),(2,5),(8,9),(11,12)\}$ (The spanning tree can be determined using Prim's algorithm or Kruskal's algorithm [50, 51]).

Algorithm 2 Survivability verification

Input : *cycles* :list of cycles; $deep = 1$; $back = 1$; m = number of cycles; E : Network
links

Output: Nodebridges, 2-connected subgraphs, linkbridge

  init

  $currentCycle \leftarrow firstcycle$

  while $newcycles \neq cycles$ **do**

    for $i = size(back) : m - 1$ **do**

      $|loc| = cycles(i+1) \bigcap currentCycle$

      case $|loc| > 1$ // joined at more than 2 vertices

      $newcycle = \bigcup currentCycle, cycles(i+1)$

      $cycles = \{cycles \setminus \{cycles(1), cycles(i+1)\}\}$

      $cycles = \bigcup \{cycles, newcycles\}$

      $currentCycle \leftarrow firstcycle$

      case $|loc| = 1$ // possible cut vertex at *loc*

      push i into *queue*;

      $possibBridge \leftarrow loc$ // add *loc* to *possibBridge*

      $back \leftarrow back - 1$

      $deep \leftarrow deep + 1$

      if $i = m - 1$ & $length(deep) > 1$ **then**

        $Nodebridges = \bigcup \{Nodebridges, possibBridge(last)\}$

        2-connected $= \bigcup \{$*2-connected, cycles(deep(last))*$\}$

      end if

    end for

  end while

  for $i = 1$ to $|E|$ **do**

    if E(i) intersect two distinct blocks (2-connected or single node subgraphs) **then**

      $linkbridges = \bigcup \{linkbridges, E(i)\}$

    end if

  end for

Algorithm 1 also generate a set of cycles $\{c_1, c_2, c_3, c_4\}$ shown in Figure. 3.5(c). The configuration of the resulting spanning tree found allows us to conclude that G is an unconnected topology. However, further analysis of the physical topology is necessary to identify if there is any other unprotect able link. Algorithm 2 creates 3 possible survivable-bases using the set of cycles found previously, namely as $S_1 = \{c_1\}$, $S_2 = \{c_2, c_3\}$, and $S_3 = \{c_4\}$. S_1 and S_2 share node 2 in graph G, hence node 2 is a *node-bridge*. There are 3 link-bridges exist which are $(5-6), (6-7)$ and $(9-10)$. Nodes $6, 10, 13$ are referred as single nodes. The network verifying process gives the following remarks:

- Graph G is unconnected graph with unconnected node 13.

- Graph G contains three node-survivable subnetworks.

- Graph G contains one link-survivable subnetwork that is $S_1 \cup S_2$.

- Graph G contains at least one link bridge.

To demonstrate the computational efficiency of the proposed algorithm, it was necessary to utilise randomly generated networks of various sizes. Figure. 3.6 represents the simulated results of 10 randomly generated networks with the number of nodes varying from 15 to 375 nodes. The graph shows that the verification time increases almost linearly with the increasing of network nodes. The proposed technique can be used to verifying the survivability of a given network as well as using *biconnected components* in [4]. In addition, this technique can be used to determine the weak nodes or links of a given network, and also provides all the distinct cycles for the next phase of network planning.

3.5 Summary

This chapter presented a new approach to establishing the physical survivability of networks. The proposed algorithm proved to be many orders of magnitude, whilst providing all the distinct fundamental cycles of the networks if required with only a small change
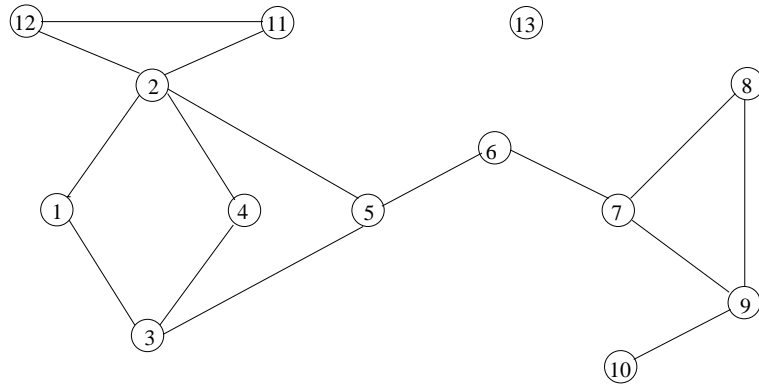
(a) An arbitrary topology
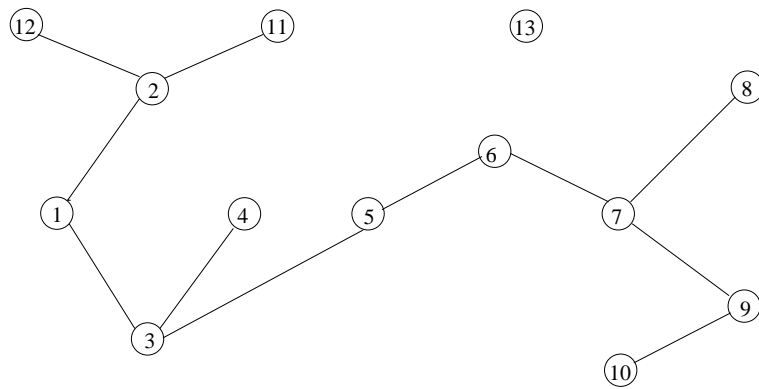
(b) The spanning tree
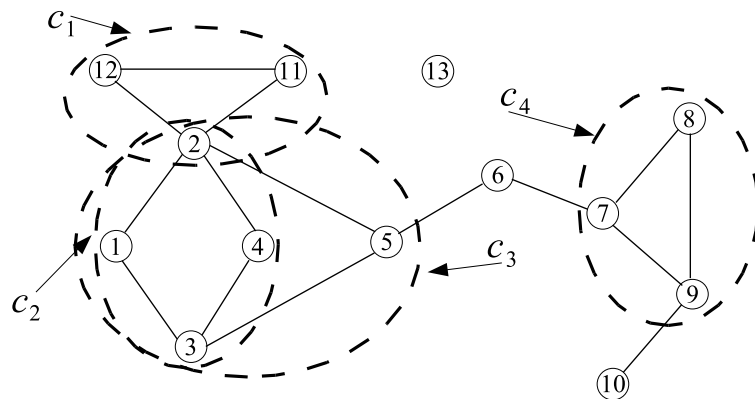
(c) Survivable subnetworks

Figure 3.5: Illustration of an arbitrary network and its spanning tree
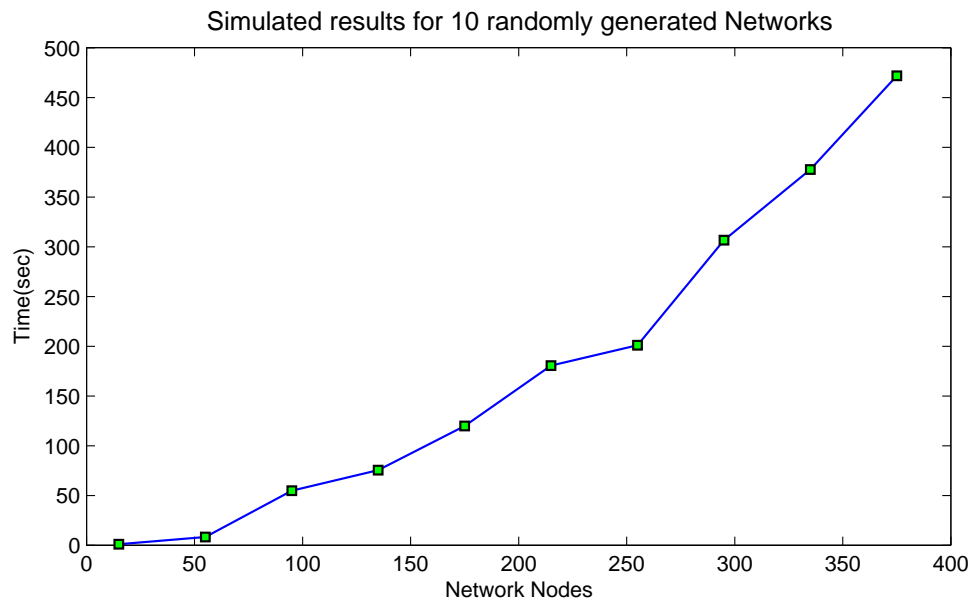
Figure 3.6: Simulated results for 10 randomly generated networks

in Algorithm 1. The proposed technique is capable of identifying both node-bridges and link-bridges not previously considered in the literature.

Chapter 4

Cost vs. Congestion in Capacity Allocation for Span Protection Networking

This chapter presents the most common form of network protection and its mathematical formulations, which is called span protection. Cost and maximum network congestion are also presented and discussed in detail. The methods and importance of controlling of congestion levels should be taken into account in network design to avoid the unbalancing of a network's load and assuring the continuation of service while maintaining reasonable cost.

4.1 Background

Link survivability is based on two paradigms: *link protection* and *link restoration*. In link protection, all connections that traverse the failed link are rerouted around that link through alternate paths. The alternate paths and wavelength channels must be configured in advance for protection. Link protection can also be further divided into dedicated or

shared protection. In dedicated link protection (1+1) or (1:1), for each link of the working path, backup capacity is reserved around that link, depending on whether the signal is sent over the backup path during normal operation or not. In shared link protection, for each link of working path, a backup path is reserved around that link. However, the backup wavelength on the links of the backup path may be shared with other backup paths, thus the backup channels are multiplexed among different failure scenarios. Link protection capacity design based on static traffic, thus the back up paths are known in advance.

Link restoration techniques, on the other hand, re-route the disrupted traffic around the failed link. A new path is dynamically discovered and established between the end nodes of the failed link. When a new path is discovered, it replaces the broken connection, and the broken connection is blocked. This approach requires the ability to identify the failed link at both ends and makes restoration more difficult when there is a node failure. The choice of the restoration path can be limited in number of hop-length and may use more capacity.

(a) Dedicated link protection.

(b) Shared link protection.
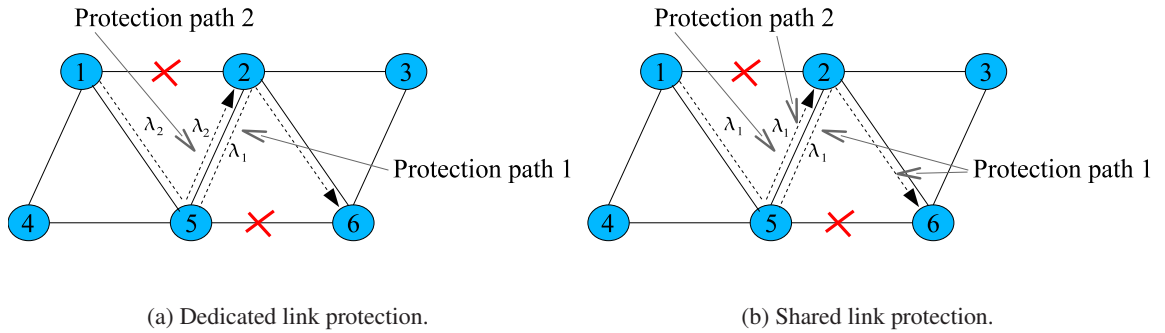
Figure 4.1: Link based protection

In Figure. 4.1(a), λ_1 on path **5-2-6** (dotted line) is the protection path for link *5-6*, and protection path **1-5-2** for link *1-2*. Different wavelength must be used for protection path 2, as there is overlapping on link *5-2*. In shared link protection Figure. 4.1(b), for each link of the working path, a backup path is reserved around that link. However, the backup wavelength on the links of the backup path may be shared with other backup paths

providing that the corresponding working channels are on different links, thus the backup channels are multiplexed among different failure scenarios.

"*Distributed automation*" span restoration was first proposed by D.W. Grover in 1987, which is also known as "*Self-Healing ring*" diverse route protection [62], a partial form of automatic span restoration has been built into most transmission systems. The capacity design problem was established and carried out by many researchers, and a typical study published in "*Design and dimensioning of survivable SDH/SONET Networks*" by P. Soriano et al [63]. In recent years, various studies on span protection for mesh networks that have been done focus mainly on the capacity design problem and recovery time after failure(s). Within these studies, there were major contributions such as:

- The study on economic scale effect, which lead to the design of "*Modularity*" of span restorable and capacity design [64]. The approach here is that the authors combined both capacity modularity and the economies of scale effects in the design optimisation model. The capacity design using this can achieve up to 15% cost improvement depending on network topologies and demand patterns.

- The design of multiple qualities of protection capacity for span restoration integrated with the modularity concept. This is an important achievement in span restoration capacity design. It not only improves the resource efficiency, but opens a new view about network design issues for the service oriented capacity optimisation [4, 47]. The needs for these improvements was driven by the modern business environment where there is considerable interest in the ability to deliver different ranges of service and at various level and subject to various charges accordingly depended on the service. This study also indicates the potential to design and operate mesh-based restorable networks which have no spare capacity at all in the sense that all the capacity is bearing some type of paying service.

- An in-depth review on survival of WDM optical networks by S. Ramamurthy et al [41, 32, 40]. This study examines the wavelength capacity requirements for routing and wavelength assignment of primary and backup paths in both path and

link based protection. The authors propose distributed protocols for path and link restoration. This study also examines the protection-switching time and the restoration time for each of these schemes. The numerical results have shown that there is a tradeoff between the capacity utilisation and the susceptibility to multiple link failures. The study pointed out that path protection provides significant capacity savings over link protection, and shared protection provides significant savings over dedicated protection; while on the other hand, path protection is more susceptible to multiple link failures than link protection, and shared protection is more susceptible to multiple link failures than dedicated protection.

- An extension to span-based restoration or protection namely "*Node-Inclusive Span Survivability In An Optical Mesh Transport Network*" was introduced in [65] by J. Doucette. In this study, the author allowed the original technique to cover node failure, as well as span failure, while retaining the span restoration characteristics. This study was based on the concept of operating between custodial node regions, instead of between the two traditional custodial nodes. These regions are defined as one hop removed from the node or span failure [65].

4.2   Mathematical Formulations for Span Protection

In this section, two basic ILP formulations for link protection SCA problems are reviewed, namely: Link-Node and Link-Path formulations. Due to the complication of the Link-Node technique, this section only introduces the general model for routing for referencing purposes. The basic routing for the Link-Path model is also introduced before the protection model in order to make the work easier to follow. These models are based on the examples in [49].

General Network Notation

A network physical topology can be modeled as an undirected graph $G(V, E)$, where V is a set of network nodes and E is a set of physical spans. $V = \{v_1, v_2, \ldots, v_N\}$, where N is

the number of network nodes. $E = \{e_1, e_2, \ldots, e_M\}$, where M is the number of network spans.

4.2.1 Link-Path Model

Model 1 *Basic Link-Path routing model.*

Notation

$\mathbf{D} = \{d_1, d_2, \ldots, d_D\}$ Set of demands,
and D is the number of demands
$\mathbf{P} = \{p_1^i, p_2^j, \ldots, p_P^k\}$ Set of path candidates between end nodes of demands; $i, j, k \in \mathbf{D}$

Constants

$\delta_{edp} = \quad$ 1, if path p^{th} of demand d cross span e; 0, otherwise.
$h_d \quad$ volume of demand d.
$\xi_e \quad$ unit cost of link e.
$c_e \quad$ upper bound on the capacity of span e.

Variables

$x_{dp} \quad$ flow variable allocated to path p^{th} of demand d.
$w_e \quad$ capacity allocated on span e.

- **ILP Model**

  – Objective

$$\text{minimise}: \quad : \sum_e \xi_e w_e \tag{4.1}$$

– Constraints

1) Demand constraints:

$$\sum_p x_{dp} = h_d , \quad d \in D \tag{4.2}$$

2) Working capacity allocated on span e:

$$\sum_d \sum_p x_{dp} \delta_{edp} = w_e , \quad e \in E \tag{4.3}$$

3) Congestion constraints:

$$w_e \leq c_e , \quad e \in E \tag{4.4}$$

4) Flow variables are non-negative:

$$x_{dp} \geq 0 , \quad \forall d, p \tag{4.5}$$

In Model 1, the main objective is to minimise the total cost of the working capacity allocated for a given set of demands Equation 4.1. Equation 4.2 asserts that for every demand, the total working flow assignments to the eligible routes must be equal to the total demand. This implies that, for a given demand volume, each demand can be assigned with the same route or split up over several possible different routes. This helps to reduce the maximum congestion of the routing process. The given candidate paths are usually the *k*-shortest paths, and this way of modelling is referred to as *shortest-path routing*, which is different from another popular method of modelling known as *shortest-path allocation*[1]. Equation 4.3 gives the working capacity w_e by intercepting all the assignments of working flow to eligible routes that cross span e. Equation 4.4 makes sure that the total working capacity allocated on each physical span e cannot be greater than the available capacity of that span.

In the following example, the link-path model for a simple 3-node network as illustrated in Figure. 4.2, and its possible path candidates presented in Figure. 4.3, are consid-

---

[1]*In shortest-path allocation*, for each demand, the entire demand volume is allocated to the shortest path. In the case there is more than one shortest path for a demand with respect to the link unit costs, then the demand volume can be arbitrarily split among the shortest paths. On the other hand, *shortest-path routing*, the selection is based on the given system link-weights

ered.
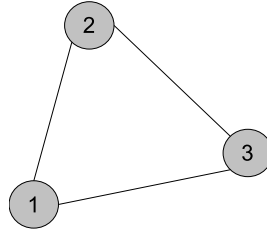
Figure 4.2: 3-node network
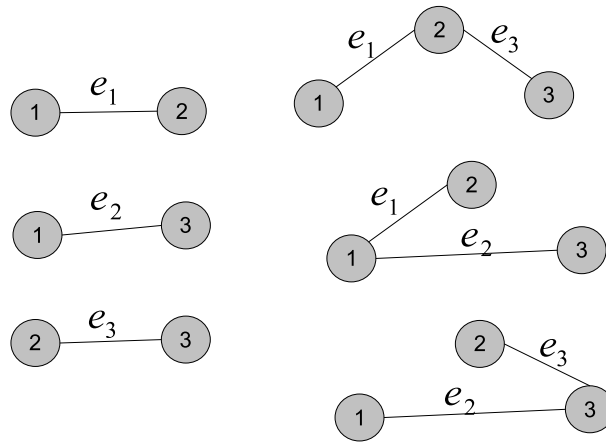
Figure 4.3: All possible candidate paths for 3-node network of Figure. 4.2

Given a set of demand D=1,2,3, with the volume and connection details as follows: $h_1 = 4$ for the connection (1-2), $h_2 = 3$ for the connection (1-3) and $h_3 = 7$ for the connection (2-3).

For demand $d = 1$, there are 2 candidate paths that can be used to establish the connection: $\{(1-2), (1-3-2)\}$, and how much demand volume will be routed over each path depends on the objective of the model. Thus, for this demand, Equation 4.2 can be presented as:

$$x_{1,1} + x_{1,2} = h_1 = 4.$$

Similarly, it is possible to have for demand 2 and 3:

$$x_{2,1} + x_{2,2} = h_2 = 3;$$

$$x_{3,1} + x_{3,2} = h_3 = 7.$$

$$(4.6)$$

where $x_{2,1}$ is path (1-3), $x_{2,2}$ is path (1-2-3), $x_{3,1}$ is path (2-3), and $x_{3,2}$ is path (2-1-3).

Also, for each demand:

d=1: $\delta_{1,1,1} = 1$ as the path p_1 of demand d_1 crosses span e_1, $\delta_{2,1,2} = 1$ as the path p_2 of demand d_1 crosses span e_2, and $\delta_{3,1,2} = 1$ as the path p_2 of demand d_1 crosses span e_3.

d=2: $\delta_{2,2,1} = 1$, $\delta_{1,2,2} = 1$, and $\delta_{3,2,2} = 1$.

d=3: $\delta_{3,3,1} = 1$, $\delta_{1,3,2} = 1$, and $\delta_{2,3,2} = 1$.

The result is as follows:

$$\delta_{1,1,1} \; \delta_{1,1,2} \; \delta_{1,2,1} \; \delta_{1,2,2} \; \delta_{1,3,1} \; \delta_{1,3,2} \equiv 1\,0\,0\,1\,0\,1$$

$$\delta_{2,1,1} \; \delta_{2,1,2} \; \delta_{2,2,1} \; \delta_{2,2,2} \; \delta_{2,3,1} \; \delta_{2,3,2} \equiv 0\,1\,1\,0\,0\,1$$

$$\delta_{3,1,1} \; \delta_{3,1,2} \; \delta_{3,2,1} \; \delta_{3,2,2} \; \delta_{3,3,1} \; \delta_{3,3,2} \equiv 0\,1\,0\,1\,1\,0$$

Each equation represents the span with path candidates crossing it. Thus, its sum would equal to the total capacity allocated to that corresponding span. Assume, each physical span is assigned with the same available capacity $c_e = 20$. Put together, the routing model will be:

$$
\begin{array}{ccccccl}
x_{1,1} & x_{1,2} & 0 & 0 & 0 & 0 & = 4 \\
0 & 0 & x_{2,1} & x_{2,2} & 0 & 0 & = 3 \\
0 & 0 & 0 & 0 & x_{3,1} & x_{3,2} & = 7 \\
1 & 0 & 0 & 1 & 0 & 1 & \leq 20 \\
0 & 1 & 1 & 0 & 0 & 1 & \leq 20 \\
0 & 1 & 0 & 1 & 1 & 0 & \leq 20
\end{array}
$$

$$(4.7)$$

Assume that the cost of service routing across all network spans is the same and equal 1. Hence, the cost for each candidate path is just equal to its length. Let F be the optimisation

function, and it can be represented as:

$$F = x_{1,1} + 2x_{1,2} + x_{2,1} + 2x_{2,2} + x_{3,1} + 2x_{3,2} \qquad (4.8)$$

The solution for the above objective is $F = 14$, with $x_{1,1} = 4$, $x_{2,1} = 3$, $x_{3,1} = 7$. It is easy to see that this is the optimal solution as these paths are the shortest.

The following is an extension of the link-path model for networks with span protection. This model uses an extra set of candidates known as the set of restoration candidates. Each candidate represents a restoration path corresponding to the eth span failure. Thus, this model contains two different sets of candidate paths: one set is for routing primary paths and the other is for protection of the associated primary paths.

Model 2 *Basic Link-Path Model for Span protection.*

- **Notation**

    - Network Notation

        As in Model 1

    - Indices

        $d = 1, 2, \ldots, D$ demands.

        $p = 1, 2, \ldots, P_d$ candidate paths between end nodes of demand d.

        $q = 1, 2, \ldots, Q_e$ candidate restoration flow for the eth span failure.

        $e = 1, 2, \ldots, M$ links.

    - Constants

δ_{edp} = 1, if path p^{th} of demand d cross span e; 0, otherwise.

ζ_{ej}^{q} = 1, if route q^{th} for failure on span e cross span j; 0, otherwise.

h_d: volume of demand d.

ξ_e: unit cost of link e.

c_e: upper bound on the capacity of span e.

– Variables

x_{dp}:   working flow variable allocated to path p^{th} of demand d.

w_e: capacity allocated on span e.

s_e: spare capacity allocated on span e.

y_e^q: restoration flow allocated to the qth for restoration of link e.

• **ILP model**

– Objective

$$\text{minimise}: \quad \sum_e \xi_e(w_e + s_e) \tag{4.9}$$

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– Constraints

1) Demand constraints:

$$\sum_p x_{dp} = h_d , \quad d = 1, 2, \ldots, D \tag{4.10}$$

2) Working capacity allocated on span e:

$$\sum_d \sum_p x_{dp} \delta_{edp} = w_e , \quad e = 1, 2, \ldots, E \tag{4.11}$$

3) protection capacity allocated for span e to support

all the flows imposed on it:

$$\sum_{q \in Q_e} y_e^q \zeta_{ej}^q = s_e \tag{4.12}$$

4) Total restoration flow for span e meet 100% requirement for protection:

$$\sum_{q \in Q_e} \zeta_{ej}^q = w_e \tag{4.13}$$

5) Congestion constraints:

$$w_e + s_e \leq c_e , \quad e = 1, 2, \ldots, E \tag{4.14}$$

6) Flow variables are non-negative:

$$x_{dp} \geq 0 , \quad \forall d, p$$

$$y_e^q \geq 0 , \quad \forall e, q \tag{4.15}$$

Equation 4.10 ensures that for every demand, the total working flow assignments to the eligible routes must be equal to the total demand. Equation 4.11 gives the working capacity w_e by intercepting all the assignments of working flow to eligible routes that cross span e. Equation 4.12 is the total protection capacity allocated to each span e to support all the working flows imposed on it. Equation 4.13 ensures that each of the eligible working capacity of span e must be protected by a backup route. Equation 4.14 makes sure that the total working capacity allocated on each physical span e cannot be greater than the available capacity of that span.

4.2.2 Link-Node Model

Model 3 *Basic Link-Node routing model.*

- **Notation**

  - Network notation

    As in Model 2

  - Indices

    $d = 1, 2, \ldots, D$ demands.

    $e = 1, 2, \ldots, M$ links.

  - Constants

    $h_{\widetilde{sd}}$:   volume of demand originating at node s

             and is destined for node d.

    ξ_{ij}:   unit cost of link ij.

    c_{ij}:   upper bound on the capacity of span ij.

  - Variables

    $x_{ij}^{\widetilde{sd}}$:   flow on link ij for demand pair $\widetilde{sd}$.

    b_{ij}:   = 1, if the design virtual topology uses link ij.

    w_{ij}:   number of working capacity units allocated to span ij.

- **ILP model**

  - Objective

$$\text{minimise} : \quad \sum_i \sum_j \xi_{ij} w_{ij} \qquad (4.16)$$

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– Constraints

    1) Flow conservation:

$$\sum_j x_{ij}^{\widetilde{sd}} b_{ij} - \sum_j x_{ji}^{\widetilde{sd}} b_{ji} = \begin{cases} h_{\widetilde{sd}} & \text{if s=i,} \\ -h_{\widetilde{sd}} & \text{if d=i,} \quad \forall \, s,d,i. \\ 0 & \text{otherwise.} \end{cases} \tag{4.17}$$

    2) Total traffic from all sd pairs that is routed over link ij:

$$\sum_{\widetilde{sd}} x_{ij}^{\widetilde{sd}} = w_{ij}, \tag{4.18}$$

    3) Capacity constraints:

$$w_{ij} \le c_{ij}, \tag{4.19}$$

    4) Flow variables are non-negative:

$$x_{ij} \ge 0 \,, \quad \forall i,j$$
$$w_{ij} \ge 0 \,, \quad \forall i,j \tag{4.20}$$

Equation 4.17 is the conservation constraint, and at node i in the network computers the total flows out of node i for each commodity sd. The net flow is equal but different in sign between the outgoing and incoming flow. The net flow is 0 if the node is neither source nor the destination for that commodity sd, which $i \ne s,d$. Equation 4.18 gives the working capacity w_{ij} by intercepting all the assignment of working flow to eligible routes that cross span ij. Equation 4.31 ensures that the total working capacity allocated to each span ij is always less than or equal to the allowable capacity assigned for it.

In the following example, the same network and demand as in the previous example is used. The given set of demands is D=1,2,3, with the volume and connection details as follows: $h_{\widetilde{12}} = 4$ for the connection (1-2), $h_{\widetilde{13}} = 3$ for the connection (1-3) and $h_{\widetilde{23}} = 7$ for the connection (2-3).

According to Equation 4.17, the set of flow conservation for each demand is as follows:

For d=1:

$$x_{12}^{\widetilde{12}} + x_{13}^{\widetilde{12}} = h_{\widetilde{12}}$$

$$-x_{13}^{\widetilde{12}} + x_{32}^{\widetilde{12}} = 0$$

$$-x_{12}^{\widetilde{12}} - x_{32}^{\widetilde{12}} = -h_{\widetilde{12}}$$

For d=2:

$$x_{12}^{\widetilde{13}} + x_{13}^{\widetilde{13}} = h_{\widetilde{13}}$$

$$-x_{12}^{\widetilde{13}} + x_{23}^{\widetilde{13}} = 0$$

$$-x_{13}^{\widetilde{13}} - x_{23}^{\widetilde{13}} = -h_{\widetilde{13}}$$

For d=3:

$$x_{21}^{\widetilde{23}} + x_{23}^{\widetilde{23}} = h_{\widetilde{23}}$$

$$-x_{21}^{\widetilde{23}} + x_{13}^{\widetilde{23}} = 0$$

$$-x_{13}^{\widetilde{23}} - x_{23}^{\widetilde{23}} = -h_{\widetilde{23}}$$

In the above system equation, there are three cases that have to be considered for each demand. With the first demand, $sd = 1 - 2$ has the source node s is 1, and the destination node d is 2. The flows out of the a node have positive signs, and have negative signs if they are flowing into a node.

In the first case, the flow out of the source node $s = 1$ must be considered. There are two ways that the flow of this demand can leave node 1: $x_{12}^{\widetilde{13}}$ (link 1-2 for demand $sd = 13$), and $x_{13}^{\widetilde{13}}$ (link 1-3 for demand $sd = 13$). The total of the flows out of the source node s is equal to the volume of demand 1. Thus, $(x_{21}^{\widetilde{23}} + x_{23}^{\widetilde{23}} = h_{\widetilde{23}})$

In the second case, it is necessary to take into account the intermediate node, which now is node 3. As the total flows in and out of each intermediate node, it must be equal to 0. Thus in this case, $-x_{12}^{\widetilde{13}}$ is the flow into node 3 from the source node s and $x_{23}^{\widetilde{13}}$ is the flow out of node 3 to destination node d. In this case, $-x_{13}^{\widetilde{12}} + x_{32}^{\widetilde{12}} = 0$.

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For the third case, the destination node $d = 2$ is considered. All the flows must be now going into, rather than out of the node. Therefore, it is expected that all the flow will be negative. The first flow is $-x_{12}^{\widetilde{12}}$, which is the flow into node 2 from node 1. The second is $-x_{32}^{\widetilde{12}}$, which is the flow into node 2 from node 3. The total number of flows going into d must be equal to the volume of the demand. Therefore, the following equation holds true: $-x_{13}^{\widetilde{13}} - x_{23}^{\widetilde{13}} = -h_{\widetilde{13}}$.

The sum of all flows for each span should be within its capacity according to Equation 4.18, Equation 4.31. Thus the capacity constrain for each network's span is as follows:

For span 1:

$$x_{12}^{\widetilde{12}} + x_{12}^{\widetilde{13}} \leq c_{12}$$

For span 2:

$$x_{13}^{\widetilde{12}} + x_{13}^{\widetilde{13}} + x_{13}^{\widetilde{23}} \leq c_{13}$$

For span 3:

$$x_{23}^{\widetilde{13}} + x_{23}^{\widetilde{23}} A \leq c_{23}$$
$$x_{32}^{\widetilde{12}} \leq c_{32}$$

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Putting together, the following flow model results:

$$
\begin{array}{cccccccccl}
x^{\widetilde{12}}_{12} & x^{\widetilde{12}}_{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & = h_{\widetilde{12}} \\
0 & -x^{\widetilde{12}}_{13} & x^{\widetilde{12}}_{32} & 0 & 0 & 0 & 0 & 0 & 0 & = 0 \\
-x^{\widetilde{12}}_{12} & 0 & -x^{\widetilde{12}}_{32} & 0 & 0 & 0 & 0 & 0 & 0 & = -h_{\widetilde{12}} \\
0 & 0 & 0 & x^{\widetilde{13}}_{12} & x^{\widetilde{13}}_{13} & 0 & 0 & 0 & 0 & = h_{\widetilde{13}} \\
0 & 0 & 0 & -x^{\widetilde{13}}_{12} & 0 & x^{\widetilde{13}}_{23} & 0 & 0 & 0 & = 0 \\
0 & 0 & 0 & 0 & -x^{\widetilde{13}}_{13} & -x^{\widetilde{13}}_{23} & 0 & 0 & 0 & = -h_{\widetilde{13}} \\
0 & 0 & 0 & 0 & 0 & 0 & x^{\widetilde{23}}_{21} & x^{\widetilde{23}}_{23} & 0 & = h_{\widetilde{23}} \\
0 & 0 & 0 & 0 & 0 & 0 & -x^{\widetilde{23}}_{21} & 0 & x^{\widetilde{23}}_{13} & = 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -x^{\widetilde{23}}_{23} & -x^{\widetilde{23}}_{13} & = -h_{\widetilde{23}} \\
x^{\widetilde{12}}_{12} & 0 & 0 & x^{\widetilde{13}}_{12} & 0 & 0 & 0 & 0 & 0 & \le c_{12} \\
0 & x^{\widetilde{12}}_{13} & 0 & 0 & x^{\widetilde{13}}_{13} & 0 & 0 & 0 & x^{\widetilde{23}}_{13} & \le c_{13} \\
0 & 0 & 0 & 0 & 0 & x^{\widetilde{13}}_{23} & 0 & x^{\widetilde{23}}_{23} & 0 & \le c_{23} \\
0 & 0 & x^{\widetilde{12}}_{32} & 0 & 0 & 0 & 0 & 0 & 0 & \le c_{32}
\end{array}
\tag{4.21}
$$

4.3   Effect of Load Balancing on Capacity Redundancy

Most network optimisation functions are subject to minimising the total cost of capacity usage or capacity redundancy. However, minimising the cost may not guarantee good or continued service, which is the main goal of a network designer. This is because in this case, the model will be optimised using shortest paths as long as the allocated capacity to each span does not exceed the available capacity desired. The result of this is high congestion in some spans and less in others. This is known as load unbalancing.

Optimisation models for wavelength routing can have objective functions aimed at reducing either the network congestion level (referred to as *CongMin*) or the total wavelength channels used (referred to as *CapMin*) [66]. The purpose of the *CongMin* scheme is balancing the network load, thus lowering the number of wavelength channels needed and reducing the blocking probability for future connections. However, the total cost (total capacity) used by *CongMin* is usually higher compared to the *CapMin* scheme. In

contrast, when the objective function has employed the *CapMin* scheme, the total network capacities used may be reduced, but the utilised wavelength channels on some links in the network can reach their upper limit, thus no future demands can be served via those links.

By combining the above two schemes into the objective function of the ILP model, it is possible to control and balance the capacity utilisation and congestion level of the network. To do this, it is necessary to introduce some identities for congestion control into Model 2 as follows:

- Variables

  α max congestion of the network

  Defining f_{sum} and f_{max} as $f_{sum} = \Sigma_e \xi_e(w_e + s_e)$ and $f_{max} = k\alpha$, where k is the controlling factor, then it follows that:

- Objective

$$\text{minimise} \qquad f_{sum} + f_{max} \tag{4.22}$$

The constraint Equation 4.14 becomes:

- Constraints

$$w_e + s_e \leq \alpha , \ \ e = 1, 2, \ldots, E \tag{4.23}$$

$$\alpha \leq c_{min} , \ \ c_{min} = min\{c_e : e = 1, 2, ..., M\} \tag{4.24}$$

Equation 4.24 has an entity c_{min}, which is the minimum capacity available on a single network's span. This implies that, in the case of load balancing and controlling of congestion levels, each span on the network is likely to have the same amount of available capacity. The relation between cost and congestion is illustrated in the following simulations: The first network has 9 nodes 14 physical links "NetN9L14" (Figure. 4.4) arbitrary network. The second network is the NFSNET with 21 physical links. Each network is simulated with 10 randomly generated traffic demands and applied to both scenarios: "Total cost optimisation" and " Cost optimisation under congestion control".

Figure. 4.5 and Figure. 4.7 show the simulation results of the two scenarios: cost optimisation without congestion control (the first blue column of each case) and with congestion control (the second maroon column of each case). The total routing cost in the case of non congestion control is usually less than when there is congestion control. There are few cases the congestion are equal in both scenarios. In most cases, the maximum congestion will be lower when being controlled (the second dark purple column of each case) than just simply optimising routing cost. This is particularly important when the connection demand volumes are high, which in practice is often the case. The maximum congestion will be significantly reduced. Thus, congestion level control should be taken into account to avoid the unbalancing of a network's load and to ensure the continuation of service.
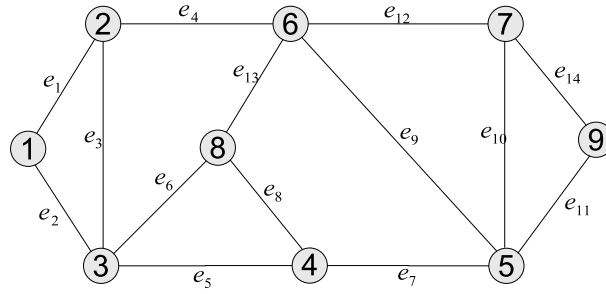
Figure 4.4: NetN9L14
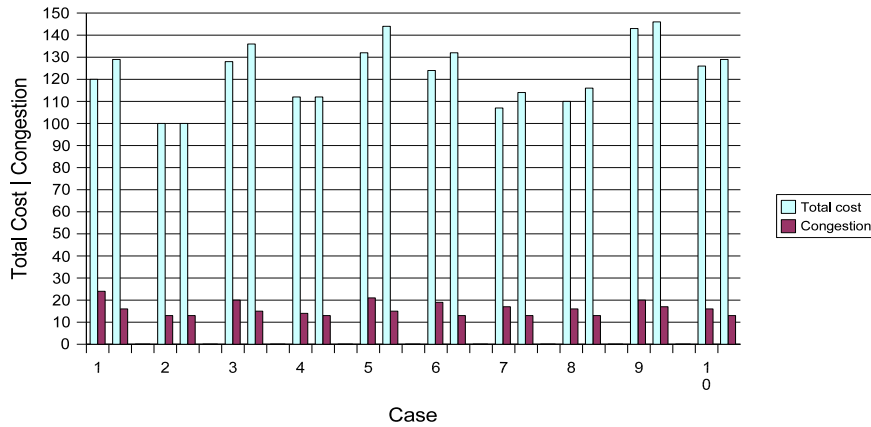
Figure 4.5: Cost vs. congestion control optimisation for span protection of NetN9L14
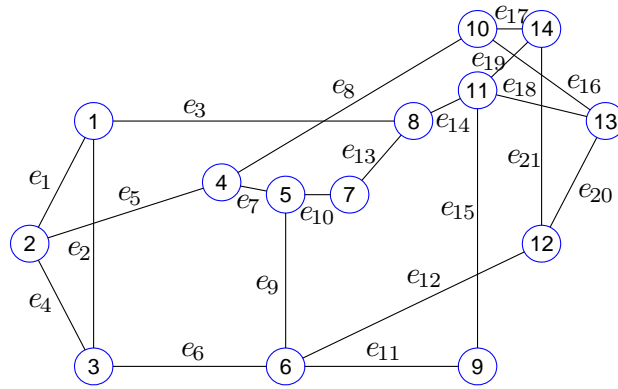
Figure 4.6: NSFNET
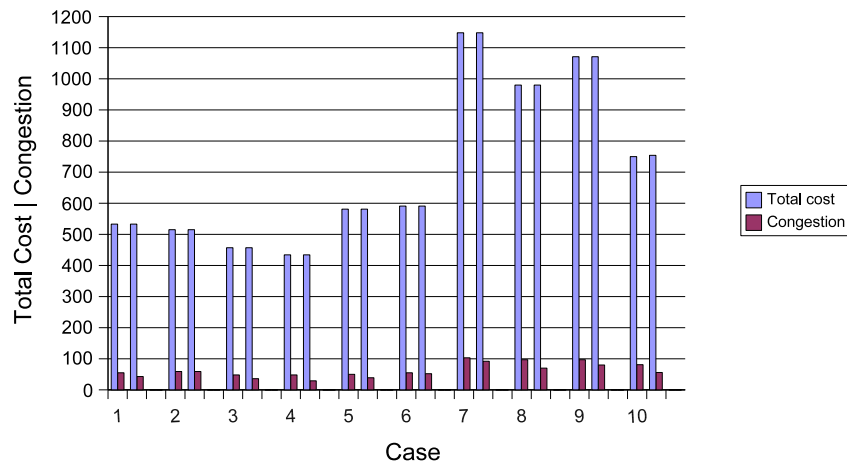
Figure 4.7: Cost vs Congestion control optimisation for span protection of NFSNET

4.4   Multiple Quality of Protection Capacity Design

It is possible for different service requests to exist for any different group of demands in a communication network. According to M. Clouquer *et al.* [47], the communication demands can be categorised into four groups with respect to the level of priority as follows:

1. Gold (assured restoration): these are working channels that must be restored and are guaranteed to be protected by the optical layer.

2. Silver (best efforts restoration): these are channels that are protected with best effort, and are working channels that should be restored if possible following the full restoration of any of the higher classes of service capacity.

3. Bronze (non-protected): these are channels that are not protected, and are working channels that do not receive any restoration effort, but are not subject to being pre-empted.

4. Economy (pre-emptible): these are channels that utilise protection bandwidth under normal conditions, and which do not receive any protection. These are pre-empted when other lightpaths need to be protected.

Model 4 *Span Protection Model for MULTI-QoP.*

- Network notation as in Model 1

- Indices

  $$\mathbb{D}^G = \{d_1^G, d_2^G, \ldots, d_D^G\} \qquad \text{set of gold demands.}$$
  $$\mathbb{D}^{S,B} = \{d_1^{S,B}, d_2^{S,B}, \ldots, d_D^{S,B}\} \quad \text{set of gold demands.}$$
  $$\mathbb{D}^E = \{d_1^E, d_2^E, \ldots, d_D^E\} \qquad \text{set of gold demands.}$$
  $$\mathbb{P}^d = \{p_1^d, p_2^d, \ldots, p_P^d\} \qquad \text{set of candidate paths between end nodes for demand } d.$$
  $$\mathbb{Q}_e = \{q_1^e, q_2^e, \ldots, q_Q^e\} \qquad \text{set of candidate restoration paths for the } e^{th} \text{ span failure.}$$
  $$\mathbb{E} = \{e_1, e_2, \ldots, e_M\} \qquad \text{set of network spans.}$$

- Constants

δ_{edp}	$= 1$, if path p^{th} of demand d cross span e; 0, otherwise.
ζ_{ej}^q	$= 1$, if route q^{th} for failure on span e cross span j; 0, otherwise.
h_d	volume of demand d.
ξ_e	unit cost of link e.
c_e	upper bound on the capacity of span e.

- Variables

x_{dp}	working flow variable allocated to path p^{th} of demand d.
w_e	capacity allocated on span e.
$w_e^{B,S}$	capacity allocated on span e for Silver and Bronze demands.
w_e^E	capacity allocated on span e for Economic demands.
w_e^G	capacity allocated on span e for Gold demands.
s_e	spare capacity allocated on span for e.
y_e^q	restoration flow allocated to the qth for restoration of link e.

ILP model

- Objective

$$\text{minimise}: \quad \sum_e \xi_e(w_e + s_e) \tag{4.25}$$

- Constraints

    1) Demand constraints:

$$\sum_{p \in \mathbb{P}^d} x_{dp} = h_d \ , \ \ \forall d \in \mathbb{D}^G \cup \mathbb{D}^{S,B} \cup \mathbb{D}^E \tag{4.26}$$

    2) Working capacity allocated on span e:

$$\sum_{d \in \mathbb{D}^G} \sum_p x_{dp} \delta_{edp} = w_e^G \ , \ \ e = 1, 2, \ldots, E \tag{4.27}$$

$$\sum_{d \in \mathbb{D}^{S,B}} \sum_p x_{dp} \delta_{edp} = w_e^{S,B} \ , \ \ e = 1, 2, \ldots, E \tag{4.28}$$

$$\sum_{d \in \mathbb{D}^E} \sum_p x_{dp} \delta_{edp} = w_e^E \ , \ \ e = 1, 2, \ldots, E \tag{4.29}$$

$$\tag{4.30}$$

    3) protection capacity allocated on span e to support

       all the flows imposed on it:

$$\sum_{q \in \mathbb{Q}_e} y_e^q \zeta_{ej}^q - w_e^E = s_e \tag{4.31}$$

    4) Total flow for span e:

$$\sum_{q \in \mathbb{Q}_e} \zeta_{ej}^q = w_e \tag{4.32}$$

    5) Congestion constraints:

$$w_e^G + w_e^{S,B} + w_e + s_e \leq c_e \ , \ \ e = 1, 2, \ldots, E \tag{4.33}$$

    6) Flow variables are non-negative:

$$x_{dp} \geq 0 \ , \ \ \forall d, p$$

$$w_e \geq 0 \ , \ \ \forall e \tag{4.34}$$

The above model has combinations of four different protection service classes. The test case shows that the most efficient service classes for the design is the combination

of the gold and economy classes. The idea is that the gold restorability can be provided through pre-emption of economy-class services. With high levels of best-efforts restorability, it would give lowest total capacity requirements. This is because this service does not require any reserve spare capacity, and the service would be restored from a failure if there is any capacity available or by pre-emption of economy-class services. Thus, the lowest resource usage in this case does not necessarily equate to being the best, but, rather that this provides an insight into the relationship between classes of services and the allocating of resources.

4.5 Summary

This chapter presents the mathematical formulations for optimal network routing and protection in the most common form: span protection. Basic techniques of network optimisation models known as "*link-path*" and "*link-node*" are also discussed in depth [55, 22, 4, 49].

The "*link-path*" technique introduces less variables into the model than the "*link-node*" model, and thus is preferable. Cost and maximum network congestion are also presented and discussed in details.

Controlling of congestion level should be taken into account in network design to avoid the imbalance of network's load and assuring the continuation of service while maintaining reasonably cost.

Chapter 5

Optimising the Integer Linear Programming Model for Path-Based Protection

Path protection at the optical layer of WDM networks is simple to implement. But in order to do this, each connection requires two disjointed paths: one is the main working path and other is the protection path for the main working path Figure. 5.1(a).

Path protection can be either dedicated or shared. This chapter gives an overview of both schemes and presents them using a link-path formulation. In addition, there are two alternative ILP models proposed for shared backup path protection (SBPP) in optical mesh networks. The first model is a variable-based model (VBM), which has a small number of constraints. The variables of this model are sets of disjointed-primary and joint-backup (DPJB) candidates.

Since there may be a great number of variables involved, the number of candidates is limited by generating only those that have DPJB paths. Thus, the solution of the this model is near optimal value. New entities are introduced into this model that enable
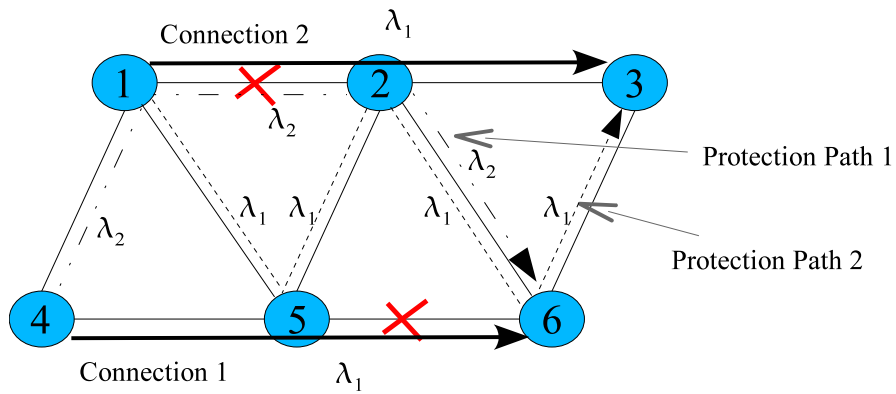
(a) Dedicated path protection.
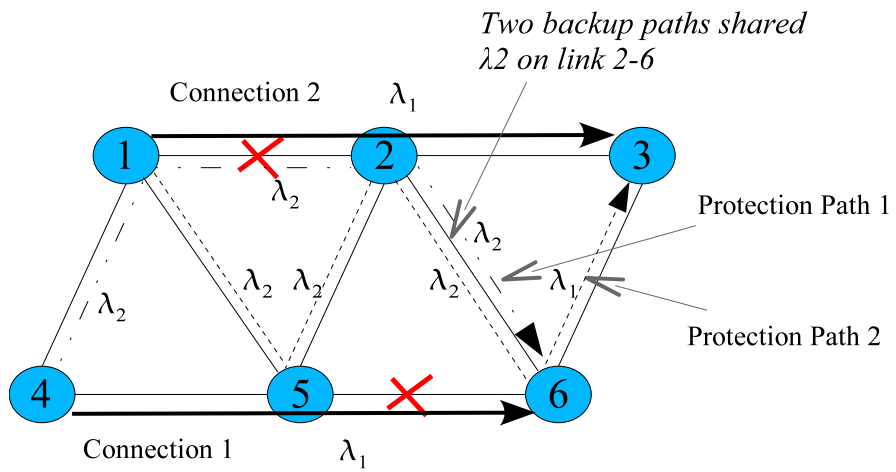
(b) Shared backup path protection.

Figure 5.1: Dedicated and shared backup path protection schemes

us to control the load balancing and congestion levels of the network for optimisation purposes. In contrast, the second ILP model is a constraint-based model (CBM), and has the disjointed path pair candidates as variables. The CBM is an improvement of the joint SBPP model [29] in terms of constraint optimisation, and can provide optimal solutions quicker as the complexity is much less than that of the VBM. For large networks with fewer connection demands, the CBM has a small number of constraints, and can thus be an attractive approach for dynamic routing. The new CBM model is later used in the mixed protection method design.

5.1 Background

Several capacity design models for SBPP networks have been extensively studied in the literature [67, 40, 68, 69]. For the link-path formulation, there are typically three different approaches to the design model known as *non-joint SBPP design, joint SBPP* and *joint SBPP with wavelength assignment* [4, 40, 70].

- In the first approach, the *non-joint SBPP*, the backup paths are allocated based on the given primary paths, and here there is a high probability of not being able to allocate the backup routes for the given primary routes.

- The second approach is the *joint SBPP*, which defines the eligible primary and backup pairs directly, and makes a decision as to which pair is selected for a corresponding demand.

In the *joint SBPP with wavelength assignment*, primary paths, backup paths and the task of assigning the wavelength to the selected paths are formulated together and solved from a single ILP model. In [67, 4], the authors show that capacity design using joint SBPP can have more than 20% capacity reduction compared with the non-joint SBPP. The last approach proposed by Ramamurthy *et al.* [40], combines the non-joint SBPP with the wavelength assignment problem in the model. However, this model contains a larger number

of variables and constraints compared to the others, and therefore it is only applicable to small networks with no more than 10 nodes [40].

This chapter outlines a proposal for utilising DPJB paths to implement an ILP model for SBPP. Introduced here are two implementations of this model. The first ILP model is the VBM, which favours the minimisation of the number of constraints, but has a large number of variables. The variables of this model are sets of DPJB paths for the given connection demands and each set, if selected, holds solutions for a group of corresponding demands. The second model is the CBM, which is an improvement of the joint-SBPP discussed above. This model takes a given set of candidate path pairs as its variables, but has a larger number of constraints compared to the VBM.

It should be noted that in traditional joint-SBPP models, there is one set of constraints generated for working capacity allocation, and another set of constraints for the backup capacity allocation. These two sets are generated independently of each other. However, in many cases, there will be dependencies between some constraints of the two sets, which unnecessarily increase the size of the model. The improvement of CBM is to remove these redundancies, thus reducing the size of the model. For the sake of simplicity, throughout this dissertation, it is assumed that the networks have enough wavelength channels or are fully equipped with wavelength converters. Hence, the wavelength continuity constraint will not be considered.

5.2   Dedicated Backup Path Protection

Dedicated path protection can be modeled in two ways: non-joint optimisation or joint optimisation. In the non-joint case, the working paths are given, and one just has to find the backup path to protect the given working routes. The following model is the uncapacitated joint optimisation for dedicated path protection. In some circumstances such as when the number of wavelength channels is bounded, capacitated optimisation may be required.

Model 5 *Dedicated path protection*

Indices

$\mathbf{D} = \{d_1, d_2, \ldots, d_D\}$ set of demands, and D is the number of demands.

$B^d = \{b_1, b_2, \ldots, b_k\}$ set of distinct candidate primary-backup paths pair between end nodes of demand d.

Constants

$\theta_i^{d,b} = 1$ if the primary route part of the bth eligible path pair for demand d cross span i; and 0, otherwise.

h_d: volume of demand d.

$\xi_j^{d,b} = 1$ if the backup route part of the bth eligible path pair for relation d cross span j, and 0, otherwise.

c_j: cost of link j.

Variables

$\rho_{b,d} = 1$ if the bth eligible path pair is chosen to serve demand d, and 0, otherwise.

w_i: working capacity on span i to support the routing of working paths.

s_j: spare capacity on span j to support the routing of working paths.

- **ILP model**

  – Objective

$$\text{minimise} \sum_{j \in E} c_j(w_j + s_j) \tag{5.1}$$

– Constraints

$$\sum_{d \in D} \sum_{b \in B^d} h_d \theta_i^{r,b} = w_j , \quad \forall j \in E \tag{5.2}$$

$$\sum_{b \in B^d} \rho_{b,d} = 1 , \quad \forall d \in D \tag{5.3}$$

$$\sum_{d \in D} \sum_{b \in B^d} \xi_j^{d,b} \rho_{b,d} h_d \leq s_j , \forall j \in E \tag{5.4}$$

$$w_j \geq 0 , \quad \forall j \in E \tag{5.5}$$

$$s_j \geq 0 , \quad \forall j \in E \tag{5.6}$$

Constraints (Equation 5.2) ensures that the working capacity on each span is sufficient to support the routing of all the working paths that cross it. Constraint (Equation 5.3) indicates that there is one backup route for each working demand or demand bundle. The spare capacity requested to support the working capacity on each span is defined by constraint (Equation 5.4).

5.3   Shared Backup Path Protection

Model 6 *Conventional model (joint SBPP) [67, 4]*

Indices

$\mathbf{D} = \{d_1, d_2, \ldots, d_D\}$ set of demands, and D is the number of demands.
$B^d = \{b_1, b_2, \ldots, b_k\}$ set of distinct candidate primary-backup paths pair between end nodes of demand d.

Constants

$\theta_i^{d,b} = 1$ if the primary route part of the bth eligible path pair for demand d cross span i; and 0, otherwise.

h_d: volume of demand d.

$\xi_j^{d,b} = 1$ if the backup route part of the bth eligible path pair for relation d cross span j, and 0, otherwise.

c_j: cost of link j.

Variables

$\rho_{b,d} = 1$ if the bth eligible path pair is chosen to serve demand d, and 0, otherwise.

w_i: working capacity on span i to support the routing of working paths.

s_j: spare capacity on span j to support the routing of working paths.

- **ILP model**

  - Objective

$$\text{minimise} \sum_{j \in E} c_j(w_j + s_j) \tag{5.7}$$

  - Constraints

$$\sum_{d \in D} \sum_{b \in B^d} h_d \theta_i^{r,b} \rho_{b,d} = w_j , \;\; \forall j \in E \tag{5.8}$$

$$\sum_{b \in B^d} \rho_{b,d} = 1 , \;\; \forall d \in D \tag{5.9}$$

$$\sum_{d \in D} \sum_{b \in B^d} \theta_i^{d,b} \xi_j^{d,b} \rho_{b,d} h_d \leq s_j , \forall i,j \in E | i \neq j \tag{5.10}$$

$$w_j \geq 0 , \;\; \forall j \in E \tag{5.11}$$

$$s_j \geq 0 , \;\; \forall j \in E \tag{5.12}$$

For the above model, the number of variables and constraints are $(\bar{P}D + M) \times (D + M^2)$, where $\bar{P}$ is the average of candidate paths, D is the number of demands and M is the number of network links.

Table 5.1: Number of Variables & Constraints in Conventional Model

Number of Variables	Number of Constraints
$\bar{P}D + M$	$D + M^2$

5.3.1 Developing a Variable Based Model for Shared Backup Path Protection with Disjointed Primary and Joint Backup Path Sets

The ILP models based on link-path formulation require pre-processing of data to generate candidate paths. In path protection routing, for each connection, two disjoint paths must be provided between the source and the destination nodes. The primary path is provisioned to serve the connection under normal operation; while the backup path is reserved in case of failure of the corresponding primary path. There are various well developed techniques for finding disjoint path pairs [71, 72, 55, 73].

The proposed VBM utilises a larger number of candidate path pairs (i.e. larger value of K), which obviously increases the number of variables in the model. However, it is necessary to compensate for this increase by reducing the number of constraints, which in the case of the proposed model will be only the sum of the number of demands (used for the selection constraints) and the number of network links (used for the capacity allocation constraints). After assessing the performance of the VBM, it is possible to further reduce its computational complexity using multi-level optimisation techniques.

Let us first provide some definitions necessary for the VBM model.

Definition 1 *Let $S(P,R)$ be the set of candidate path-pairs, where:*

$P = \{P_1, \ldots, P_D\}$ *is the set of candidate primary paths.*

$R = \{R_1, \ldots, R_D\}$ *is the set of candidate backup paths.*

$P_d = \{p_d^1, p_d^2, \ldots, p_d^K\}$ is the set of K candidate primary paths for connection d, where p_d^K denotes the p^K primary path of connection d.

$R_d = \{r_d^1, r_d^2, \ldots, r_d^K\}$ is the set of K candidate backup paths for connection d, where r_d^K denotes the r^K backup path of connection d, disjoint with p_d^K.

g is the group of demands that have DPJB paths, $g \subseteq D$.

The set of DPJB path-pairs of group demands is denoted as $H = \{H_{d,g,k}^l\}$, where $H_{d,g,k}^l$ is the set of DPJB paths of the kth candidate primary of demand d in group demand g at share level l, with $H_{d,g,k}^l = \{S'(P', R') | S' \subseteq S(P, R)\}$ satisfying the following conditions:

a) $\forall p'_i, p'_j \in P', p'_i \cap p'_j = \emptyset, i \neq j$: primary paths disjoint.

b) $\forall r'_i, r'_j \in R', r'_i \cap r'_j \neq \emptyset, i \neq j$: backup paths joint.

c) $\exists e_i \in E, \sum_{p \in P'} e_i = l$: shared level.

Figure. 5.2 shows a number of candidate paths belonging to the set of DPJB candidates for connections $2-5$, $2-3$ and $8-9$. The backup paths of the three connections have 3 different shared levels; level 1 is at links e_8, e_9 and e_{11}, level 2 is at e_1 and e_6, and level 3 is at e_2. Note that the solid lines indicate primary routes for the connections and they must be disjoint from each other; the dashed lines are the backup routes for these connection and they are common at some arbitrary links. The maximum number of joints between backup paths at one link defines the share level of the corresponding candidate.

5.3.2 Multi Level Optimisation

Model 7 *Proposed VBM for SBPP*

Indices

H: set of DPJB path-pair candidates.

$\mathbf{D} = \{d_1, d_2, \ldots, d_D\}$ Set of demands, and D is the number of demands.

$p = 1, 2, \ldots, n \; p \in H$.

Constants

$\delta_{edb} = \quad$ 1 if link e belongs to path b of demand d; 0, otherwise.

$\sigma_{egp} = \Sigma_{b \in p} \delta_{edb} \quad$ if path-pair b^{th} in S uses link e belongs to set p of group demand $g = \{d_i\}$; 0, otherwise.

h_d: $\quad$ volume of demand d.

ξ_e: $\quad$ unit cost of link e.

W: $\quad$ upper bound on the amount of capacity of link e.

Variables

$x_{dgp} \quad$ flow variable allocated to set p of demand d of group g.

$y_e \quad$ capacity of link e.

- **ILP model**

  – Objective

$$\text{minimise} \qquad \sum_{e \in E} \xi_e y_e \qquad\qquad (5.13)$$

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– Constraints

$$\sum_p x_{dgp} = h_d \ , \ \ d \in D; p \in H; g \subseteq D \tag{5.14}$$

$$\sum_d \sum_p \sum_{egp} x_{dgp} \leq y_e \ , \ \ d \in D; e \in E; p \in H$$

$$x_{dgp} \geq 0 \ , \ \ d \in D; p \in H; g \subseteq D \tag{5.15}$$

Table 5.2: Number of variables & constraints in VBM

Number of Variables	Number of Constraints
$\bar{P}D + M$	$D + M$

The number of variables and constraints that are introduced in the model are $(\bar{P}D + M) \times (D + M)$, and illustrated in the simulation section (Table 5.4).

Routing Cost vs. Network Congestion

Optimisation models for wavelength routing can have objective functions aimed at reducing either the network congestion level (referred to as *CongMin*) or the total wavelength channels used (referred to as *CapMin*) as outlined in one of the published works [74]. The purpose of the *CongMin* scheme is balancing the network load, thus lowering the number of wavelength channels needed and reducing the blocking probability for future connections. However, the total cost (total capacity) used by *CongMin* is usually higher compared to the *CapMin* scheme. In contrast, when the objective function employs the *CapMin* scheme, the total network capacities used may be reduced, and the utilised wavelength channels on some links in the network can reach their upper limit, thus no future demands can be served via those links. By combining the above two schemes into the objective function of the ILP model, it is possible to control and balance the capacity utilisation and congestion level of the network. To do that, it is necessary to introduce some new identities into the model as follows:
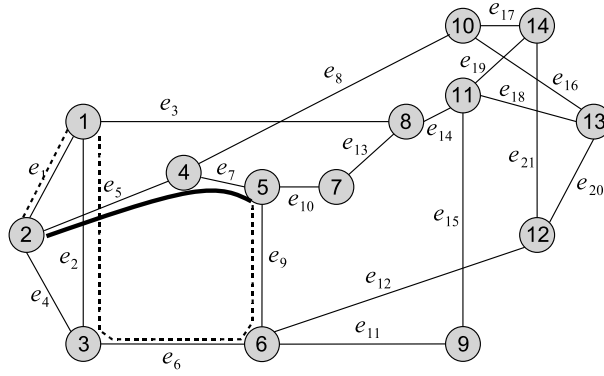
(a) Path candidates for shared level 1.
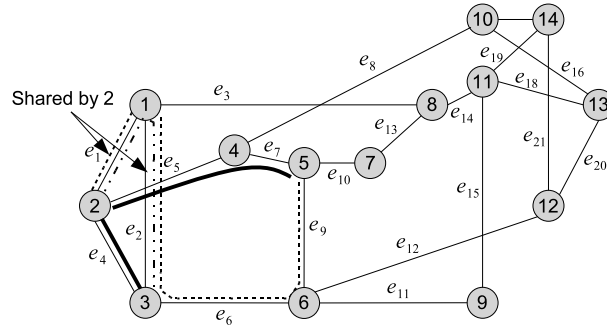
(b) Path candidates for shared level 2.
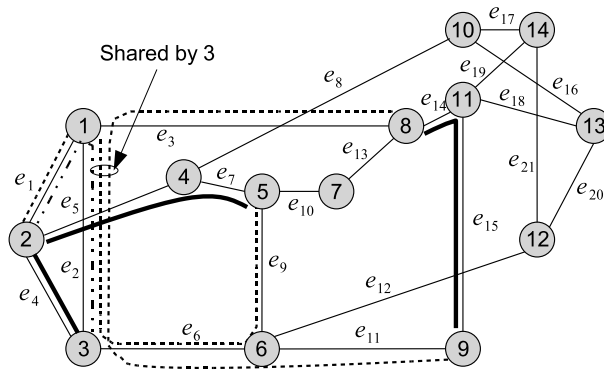
(c) Path candidates for shared level 3.

Figure 5.2: Typical path candidates for connection $2 - 5$

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- Constants

  $f_p = \sum_p \sum_{egp}$ total capacity used by set p,

  $p \in H; g \subseteq D; e \in E.$

- Variables

  α: max congestion of the network.

  Defining $f_{sum} = \sum_p f_p$ and $f_{max} = k\alpha$, where k is the controlling factor, then:

- Objective

$$\text{minimise} \quad f_{sum} + f_{max} \tag{5.16}$$

- Constraints

$$\sum_p x_{dgp} = 1, \quad d \in D; p \in H; g \subseteqq D \tag{5.17}$$

$$\sum_d \sum_p \sum_{egp} x_{dgp} \leq \alpha, \tag{5.18}$$
$$d \in D; \quad e \in E; p \in H; g \subseteqq D$$

$$\alpha \leq W \tag{5.19}$$

$$x_{dgp} \geq 0 , \quad d \in D; p \in H; g \subseteq D \tag{5.20}$$

Effect of Load Balancing on the Solution of VBM model

The introduction of k to control the maximum congestion α, and balancing the network load, may push the congestion at individual links toward α. Thus, it is expected that the cost of the final solution may be larger than the case without f_{max}. In order to reduce the effect of k on the final solution, link congestion control variables are introduced into the model, notated as $\psi_e = -1$. The link congestion controls ψ_e work as slack variables, controlled by the objective function of the model. Defining $\Psi_{sum} = k \sum_e \psi_e$ then it follows that the ILP model becomes:

- Objective

$$\text{minimise} \quad f_{sum} + \Psi_{sum} + f_{max} \tag{5.21}$$

- Constraints

$$\sum_p x_{dgp} = 1, \quad d \in D; p \in H; g \subseteq D \tag{5.22}$$

$$\sum_d \sum_p \sum_{egp} x_{dgp} \leq \alpha + \psi_e,$$

$$d \in D; e \in E; p \in H; g \subseteq D \tag{5.23}$$

$$\alpha \leq W \tag{5.24}$$

$$x_{dgp} \geq 0 \,, \quad d \in D; p \in H; g \subseteq D \tag{5.25}$$

Further improvements in VBM model using multi-level optimisation

The number of variables introduced in VBM increases significantly when dealing with large size networks and large demand sets, as it depends on the actual number of DPJB candidates. This section presents s proposal for a multi-level optimisation technique with the aim of reducing the number of variables and constraints introduced into the model. The proposed model is reduced into a sub-model that has a lower level of sharing between path pair candidates. The next step is to attempt to solve this sub-model. If the sub-model yields a partial solution to some of the demands, then a new sub-model must be created - with the next lower level of sharing, and iterate in this fashion until all demands are satisfied. If a sub-model, at a given share level, does not yield a solution to any of the demands, then it is necessary to reduce the share level and solve it again. Thus, each sub-model contains only a portion of the original model at a different share level, resulting in a significant reduction in the model's complexity compared to the original model. It should be noted that the lowest level of sharing will be equivalent to the dedicated path protection scheme, which is guaranteed to provide a solution, if one exists (ie. if the given demands are within the capacity bounds of the network).

Proposition 2 *Consider that, given an undirected graph $G(V,E)$, a finite set of DPJB candidates of demands denoted by H, a set of connection demands $D = d_1, d_2, \ldots, d_m$ and a family $F = H_{g1}, H_{g2}, \ldots, H_{gn}$ of subsets of H, where $g_i \subseteq D$ is group demands and*

H_{g_i} *is the set of DPJB candidates of group* g_i. *Due to the selection constraint, each demand* d_i *can appear in the solution only once. The set H is said to provide sufficient solution to the ILP model if and only if there exists at least a set* $H' \subseteq H$ *and a family* $F' = H'_{g1}, H'_{g2}, \ldots, H'_{gK}, K \leq n$ *such that* $\bigcap_{k \in K} g_k = \emptyset$, *and* $\bigcup_{k \in K} g_k = D$.

Proof: The set of candidates H satisfying the above condition contains the solution for the ILP model. Conversely, assume that there exists a set $H' \subseteq H$ and a family $F' = H'_{g1}, H'_{g2}, \ldots, H'_{gK}, K \leq n$. The demand $d \in D$ must be in one of the following cases:

- $d \in g_i, d \in g_j$, or

- $d \notin g_i, d \in g_j$, or

- $d \in g_i, d \notin g_j$

If the connection demands are in the first case, either the subset H'_{g_i} or H'_{g_j} can be selected by the ILP solver to satisfy the routing demands, thus $\bigcup_{k \in K} g_k = D$, and as each demand can only appear in the solution once, it requires $\bigcap_{k \in K} g_k = \emptyset$. ∎

The algorithm for performing multi shared level optimisation is presented in Appendix A.0.2. In practice, the sets of DPJB candidates in H usually do not satisfy the condition in Pro. 2. Thus, in order to obtain the solution, the K-shortest path pairs need to be included in the candidate paths of the model. This will allow demands that cannot share backup paths to select these path-pairs for dedicated protection.

5.4 Proposed Constraint Based Model for Shared Backup Path Protection

The VBM contains less constraints than the conventional model, but the number of variables in the model will increase greatly when increasing the number of path-pairs or increasing numbers of connection demands. This model can actually obtain the optimal

solution if it be can provided with all the path candidates, but this is impractical to solve as the number of variables in the model turns out to be very large.

In this section, a new alternative constraint-based model (CBM) is presented; one that takes advantage of the information of DPJB candidates and attempts to reduce the number of constraints in the model. In contrast with the VBM model, this model does not take any more variables than the given path pairs, but focuses on managing the constraints of the link failure scenarios. The difference of this model compared to the conventional model is that rather than considering all the spare capacity of the network links in one single equation (Equation 5.23), it divides the network links into two groups: sharable and non-sharable links.

A sharable link is used by more than one backup path to protect different links of the corresponding primary paths. A non-sharable link is also used by more than one backup path but it protects the same link of the corresponding primary paths. The mathematical expression of this is presented in Definition 2. The CBM has three separate constraints. Equation 5.27 is the selection constraint, which allows the solver to select suitable candidates for the final solution. Equation 5.28 combines the working capacity and the non-sharable spare capacity allocation. The constraints for sharable spare capacity allocation are presented in Equation 5.29.

Definition 2 *Let $S = \{s_d^1, s_d^2, ..., s_d^I\}$ be the set of candidate path-pairs, where I is the index set, and $s_d^i = (p_d^i, r_d^i), i \in I, d \in D$; p_d^i is the ith primary path candidate for demand d; and r_d^i is the ith backup path candidate for demand d.*

Let $H_k = \{s_{d_i}^k, H'_{d_j,l} | i \neq j; d_i, d_j \in D; k, l \in I\}$ contain the list of DPJB path pairs between the kth candidate of demand d_i and the lth candidate of demand d_j with

$H'_{d,l} = \{S' | S' \subset S\}$ satisfying the following conditions:

a) $\forall p_{d_j}^l \in S', p_{d_i}^k \bigcap p_{d_j}^l = \emptyset, i \neq j$: primary paths disjoint.

b) $\forall r_{d_j}^l \in S', r_{d_i}^k \bigcap r_{d_j}^l \neq \emptyset, i \neq j$: backup paths joint.

c) $e_i = s_{d_i}^k \bigcap H'_{d_j,l}, e_i \neq \emptyset, e_i \in e, i \in I$: set of shared links of ith candidates.

From the above condition, it is possible to define the set containing all the links that can be shared, denoted by e' as $\bigcap e_i = \{e'|, i \in I, e' \subseteqq e\}$.

Model 8 *Proposed CBM for SBPP*

- **Notations**

  - Indices

    $d = 1, 2, \ldots, D$ demands.

    $b = 1, 2, \ldots, B^d$ candidate path pair between end nodes of demand d.

    $e = 1, 2, \ldots, M$ network links.

    $e' \subseteqq e$: sharable links.

  - Constants

    $\theta_i^{d,b} = 1$ if the primary route part of the bth eligible path pair for demand d crosses span i; and 0, otherwise.

    h_d: volume of demand d.

    $\xi_j^{d,b} = 1$ if the backup route part of the bth eligible path pair for relation d crosses span j, and 0, otherwise.

    c_j: cost of link j.

  - Variables

    $\rho_{b,r} = 1$ if the bth eligible path pair is chosen to serve demand d, and 0, otherwise.

    w_i: working capacity on span i to support the routing of working paths

    s_j: spare capacity on span j to support the routing of working paths.

- **ILP model**

  - Objective

$$\text{minimise} \sum_{j \in E} c_j(w_j + s_j) \tag{5.26}$$

– Constraints

$$\sum_{b \in B^d} \rho_{b,d} = 1, \quad \forall d \in D \tag{5.27}$$

$$\sum_{d \in D} \sum_{b \in B^d} (h_d \theta_j^{r,b}) + \xi_i^{d,b} = w_j + s_i,$$

$$\forall j \in e, \forall i \in \{e \setminus e'\} \tag{5.28}$$

$$\sum_{d \in D} \sum_{b \in B^d} (\theta_i^{d,b} \xi_j^{d,b} \rho_{b,d} h_d) \leq s_j, \forall i, j \in e' | i \neq j \tag{5.29}$$

$$w_j \geq 0, \quad \forall j \in E$$

$$s_j \geq 0, \quad \forall j \in E$$

Table 5.3: Nunmber of variables & constraints in CBM

Number of Variables	Number of Constraints
$\bar{P}D + M$	$D + MS$

The number of variables and constraints that are introduced in the model are $(\bar{P}D + M) \times (D + MS)$, where $\bar{P}$ is the average of candidate paths, D is the number of demands and M is the number of network links, and S is the number of links that can be shared among candidates.

5.5 Model Comparison

This section presents a comparison between the ILP models introduced in this paper based on a few key factors, including the number of constraints & variables and the amount of data pre-processing involved.

Number of constraints and variables:
The VBM model is only concerned with the total cost of candidates instead of all the link failure scenarios, this allows the model to have a smaller number of constraints. However, it contains a very large number of variables because an enormous combination of

sets of DPJB can be generated from the pre-processing stage. This limitation of the VBM makes it less favourable compared to other models, therefore, a better criteria for selecting candidates, or other techniques, may need to be employed to reduce the number of variables. Figure. 5.4 illustrates the change in the number of variables of the VBM versus the number of connection demands.

The CBM has the same number of variables as the conventional model, but the number of constraints are less, and gradually increasing with the number of demands. For example, with the NFSNET network, the number of constraints in the CBM model was gradually increased from 183 to 466 while this value varied from 443 to 466 in the conventional model. This is because the shared and the non-shared links are considered separately rather than combining them together in the ILP formulation and this is also the trade off with the CBM compared to the conventional model.

Data pre-processing:

Pre-processing of path candidates is recognized as a convenient way for controlling the properties of allowable paths such that the designer can select path candidates within the limited number of hops or maximum allowable path costs [75]. Theoretically, the VBM offers more control to the designer compared to other models via the pre-processing of data to generate DPJB candidates. This allows us to evaluate the cost of candidates, hop lengths, share limits,or to determine which candidates are allowed to be shared before introducing them into model. However, the number of candidates becomes significantly larger with the increase of path-pairs, or the amount of traffic demands, which makes VBM unsuitable for large size networks.

Model 8, when compared to the conventional model, only requires an extra simple process for finding all the links that can be shared between candidates. In the case of low traffic demands this figure is usually less than the total number of network links, hence this model usually has smaller constraints. This becomes particularly obvious when dealing with large size networks with moderate demands.

5.6   Simulation and Discussion

In this section, a number of random traffic patterns over different network topologies using the conventional model are considered, the VBM, and the CBM. The size and the quality of solutions of the models are then analyzed and compared.

The simulated networks are denoted by NSFNET-14 (National Science Foundation Network), EON (European Optical Network), and a random network: N25-L54 (25 nodes, 54 links network). The number of connection demands are generated randomly, ranging from 5 to 30, with the volume of each demand also set randomly between 1 and 5. The simulation results and size of models versus the number of connection demands are represented in Table 5.4 for the NFSNET, EON and the arbitrary N25L54 network. The first two columns of the tables show the number of connection demands and volume of demands respectively for each simulation, and the other columns contain the size of each model (given as *number of constraints × number of variables*) and routing results.

In Figure. 5.4, a comparison of the number of constraints of each model as a function of the total volume of demands is provided, and, in Table 5.6, the number of variables are compared as a function of the total number of connection demands.
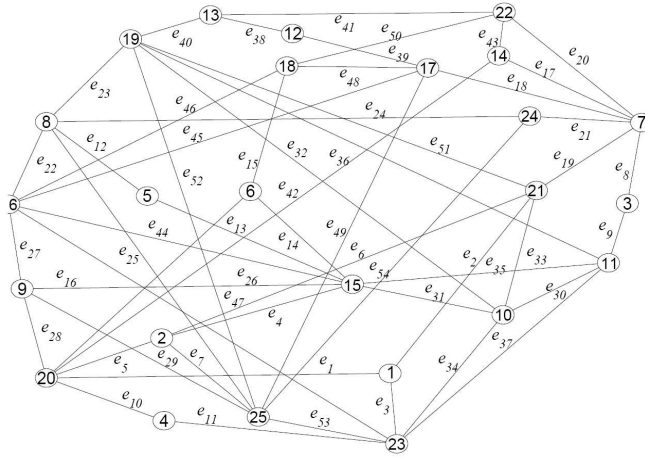
(a) N25L54
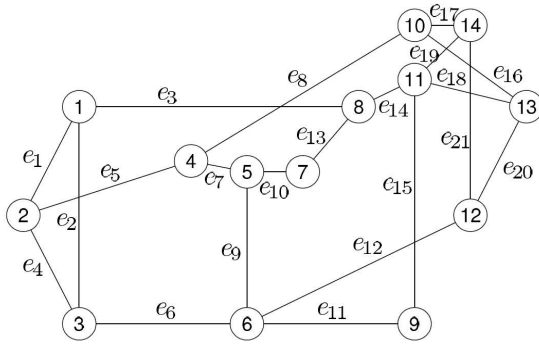
(b) NSFNET
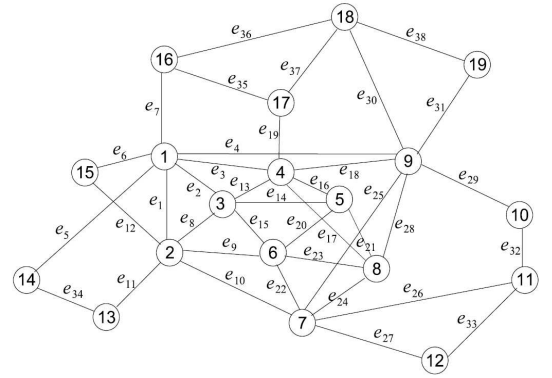
(c) EON

Figure 5.3: Simulation networks
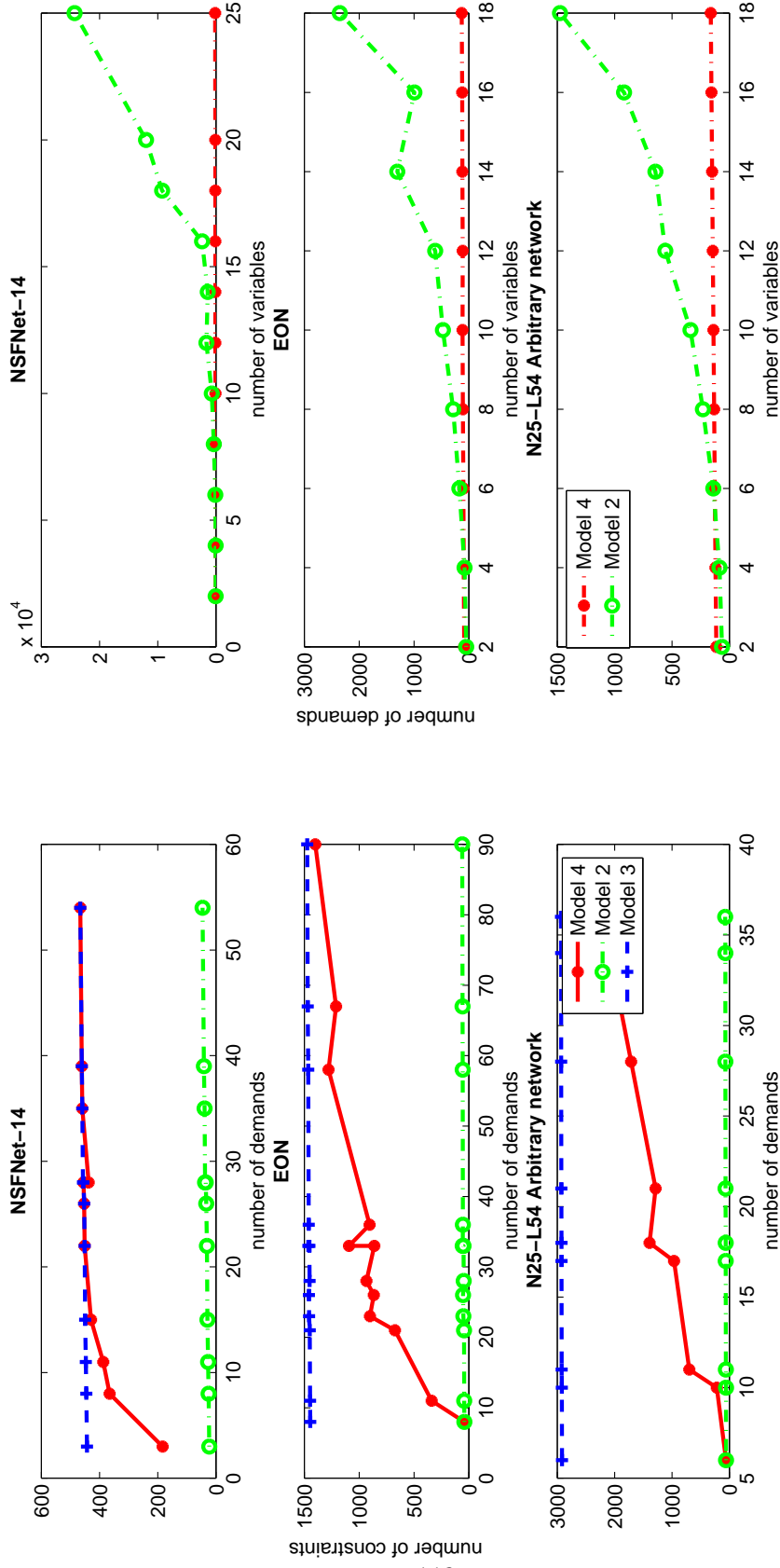
(a) Comparing the number of constraints between models

(b) Comparing the number of variables between models

Figure 5.4: Simulation results

The solutions obtained from the conventional model and CBM are very close with differences of less than 3%. This may be caused by the tolerance of the solver itself, and it is possible to narrow that down to less than 1% if the number of candidate path-pairs is increased, eg. from 3 to 4, or if the tolerance of the solver is improved. However, for the VBM, the differences may be up to 20%, and are proportional to the increase in the number of demands.

It is interesting to compare the size of the CBM and the conventional model. The total number of variables of the two models is actually the same, but the number of constraints in CBM is usually less, and this increases with the increase of total volume demands to its upper limit, which is the number of constraints of the conventional model. For instance for the NSFNET case as shown in Figure. 5.4a, the number of constraints in Model 8 is 183 and gradually increases with the increase of the volume of demands while this was approximately 450 in Model 6. The difference in size between these models becomes very obvious when the size of the network is particularly large as illustrated in Figure. 5.4a with N25-L54 model. The difference between the number of constraints in the two models can be up to 50 times more (56 constraints under CBM and constraints 2918 under the conventional model with the same number of connection demand). This suggests that it is possible to obtain the results from the CBM faster, which is the main advantage of this model; there are a few fluctuation segments in Figure. 5.4. These are caused by the variation in the number of links that can be shared among candidates.

With static routing, the number of demands is usually large. Hence, the size of the CBM could end up being the same as in the conventional model. In contrast, however, dynamic routing only has a small number of demands to be routed at any time, giving CBM an advantage over other models in this context.

Table 5.6 shows a comparison between the original heuristic model and its alias model using the multi-level optimisation technique. Recall that, in the integer programming, the number of variables is the main contribution to the complexity of the model and proportional to 2^N, where N is the number of variables. In Table 5.6, for the multilevel

optimisation and at column 6, the number of variables has the format: $844 + 25$, meaning that 2 consecutive optimisation processes have been done: the first model has 844 variables and the second model has 25 variables. If a comparison of the complexity of the multilevel optimisation is performed - which is for example $(2^{844} + 2^{25})$ with 2^{1710} of the full optimisation process, the computation complexity is greatly reduced. With the multi-level optimisation, the number of variables of the ILP model is significantly reduced after each iteration. In this simulation, the number of variables is reduced by about half in the first iteration and by only 2% in the second. The total capacity allocated for the demands, resulting from the multi level optimisation, is close to that of the full model. In addition, the simulation results show that it is possible to control the congestion of individual network links as well as the maximum congestion of the network by adding control entities. However, this is a heuristic technique to solve integer programming problems. The consistency and maximum deviation of this result from the optimal solution require further verification for different scenarios and network topologies.

5.7 Summary

This chapter presented two new ILP models for SBPP at the optical layer of mesh networks. The first proposed model was a VBM (variable-based model). This model has a small number of constraints but a larger number of variables, which are sets of DPJB candidates created from the pre-processing stage. It has been shown through simulation that the multi-level optimisation technique reduces the number of variables in the VBM significantly. However, this model is still only suitable for small networks and a small number of traffic demands. The VBM can be further developed to produce optimal solutions by balancing its number of constraints and variables.

The CBM proposed in this thesis uses the DPJB path pairs as candidates in order to reduce the number of constraints in the model. The proposed ILP model has the same number of variables as the reference model, but has a lower number of constraints. In

the worst case, when the traffic demand is large, the size of these two models will be the same. The CBM has an advantage when dealing with large size networks and reasonable traffic demands, which suggests that the model is a good candidate for dynamic routing.

Table 5.4: NSFNET Simulation Results

No of demands	Total volume of demands	CBM size	CBM Capacity	VBM size	VBM Capacity	Conventional model size	Conventional model Capacity
NSFNET							
2	3	183×50	18	24×35	18	443×50	18
4	8	365×58	33	25×49	33	445×58	33
6	11	387×66	53	27×100	54	447×66	52
8	15	429×74	66	29×349	74	449×74	66
10	22	451×82	78	31×699	92	451×82	78
12	26	453×90	98	33×1617	118	453×90	98
14	28	455×98	102	35×1405	123	455×98	102
16	28	437×106	121	37×2383	134	457×106	122
18	35	459×114	133	39×9241	130	459×114	133
20	39	461×112	144	41×11989	161	461×112	145
25	54	466×142	186	46×24275	203	466×142	186
EON							
2	8	40×84	39	40×47	39	1446×84	39
4	11	338×92	62	42×79	65	1448×92	62
6	21	673×100	114	44×174	119	1450×100	113
12	23	902×112	119	50×612	124	1456×112	119
14	26	866×118	106	52×1304	116	1458×118	106
8	28	934×108	113	46×287	130	1452×108	113
10	33	862×116	166	48×472	172	1454×116	162
18	33	1092×130	156	56×2353	173	1462×130	156
16	36	905×121	151	54×991	158	1460×121	151
N25-L54							
2	6	56×114	45	56×63	45	2918×114	45
4	10	217×120	58	58×86	59	2920×120	58
6	11	696×126	49	60×139	52	2922×126	49
8	17	963×132	79	62×230	78	2924×132	78
10	18	1389×138	85	64×339	86	2926×138	85
12	21	1285×144	84	66×558	87	2928×144	83
14	28	1711×150	102	68×644	106	2930×150	102
16	34	2084×156	132	70×918	144	2932×156	128
18	36	1980×162	137	72×1476	153	2934×162	136

Table 5.5: Comparison between Full and Multi-level optimisations

Description	No of demands	Load balancing	Limited candidates	Link congestion control	Number of variables	Total capacity	Max. congestion
Full optimisation	8	no	no	yes	226	43	5
		yes	no	no	227	46	4
		yes	no	yes	248	44	4
Multi-Level optimisation		no	yes	yes	97+8	42	6
		yes	yes	no	98+69	44	4
		yes	yes	yes	119+90	44	4
Full optimisation	36	no	no	yes	1710	123	9
		yes	no	no	1690	137	8
		yes	no	yes	1711	123	8
Multi-Level optimisation		no	yes	yes	844 + 25	122	9
		yes	yes	no	824 + 46	123	8
		yes	yes	yes	845 + 26	124	8
Full optimisation	39	no	no	yes	7802	186	18
		yes	no	no	7803	187	14
		yes	no	yes	7824	181	14
Multi-Level optimisation		no	yes	yes	4226+543	179	17
		yes	yes	no	4227+435	184	14
		yes	yes	yes	4248+59	177	14

Table 5.6: Comparison between Full and Multi-level optimisation for NFSNET

Description	No of demands	Load balancing	Limited candidates	Link congestion control	No of variables	**Total capacity**	**Max. congestion**
Full optimisation	8	no	no	yes	226	43	5
		yes	no	no	227	46	4
		yes	no	yes	248	44	4
Multi-Level optimisation		no	yes	yes	97+8	42	6
		yes	yes	no	98+69	44	4
		yes	yes	yes	119+90	44	4
Full optimisation	36	no	no	yes	1710	123	9
		yes	no	no	1690	137	8
		yes	no	yes	1711	123	8
Multi-Level optimisation		no	yes	yes	844 + 25	122	9
		yes	yes	no	824 + 46	123	8
		yes	yes	yes	845 + 26	124	8

Chapter 6

p-Cycles Modeling Using a Network's Fundamental Cycles

This chapter addresses the issues related to the design of network survivability with p-cycles and propose a novel ILP formulation for capacity design based on a network's fundamental cycles and the straddling links. Concepts of visible and hidden straddling links, which are essential components of the model, are also introduced. The proposed model caters for the case of joint optimisation of a p-cycle network that can be solved without enumerating p-cycle candidates. In addition, the complexity of the proposed model is much less than any conventional model dealing with large size networks and suitable for the design of networks having multiple quality of protection (MQoP) service classes using mixed protection techniques.

6.1   Introduction and Motivation

The introduction of p-cycles in 1998 by W. D. Grover et al. [33] has advanced network protection to a new level and fills the gap between the mesh and ring networks in terms of resource efficiency and recovery time. p-cycles can be seen as the most efficient pre-

configured protection for networks with the restoration speed like ring networks, and capacity efficiency like mesh networks. This is because the network is of mesh type, but the protection scheme is implemented based on the virtual ring structures. In addition, p-cycle takes advantage of the straddling link to achieve further resource utilisation.

Figure. 6.1 is an example of a p-cycle. Here, the thick solid lines contain spare channels to protect the working channels passing through them, and the dashed lines indicate straddling spans which have no spare capacity but can protect twice the number of working channels passing through them. Although, a p-cycle is an advanced pre-configured protection scheme, its capacity allocation model (known as *pure ILP model*) [76] employs all possible p-cycle candidates. The number of p-cycle candidates increases exponentially with the network size, and also with the complexity of the ILP model.

There are cycles known as "non-simple p-cycle". The non-simple p-cycle contains extra straddling links compared to the simple p-cycle. In order to reduce the complexity, pure ILP model usually does not include the non-simple p-cycle, and in this case, the result obtained from this model is not always optimum as all the possible solutions are not considered.

This study aims to support the design of networks that provide MQoP service classes [47] and applying mixed protection techniques in one model [20]. For this purpose, various protection techniques are integrated into one ILP formulation, giving due consideration to the advantages and disadvantages of each technique in terms of resource usage and recovery time after failure, etc. It is important to note, that in practical situations, network demands do not all have the same requirements. For instance, one group of demands may require protection, but others may not need it, or, one group may need fast recovery time while for others this may not be critical and delays of a couple of seconds may be acceptable. By considering MQoP class demands, network resources can be allocated much more efficiently. However, conventional protection scheme designs take many different implementation approaches and nearly all of them contain a very large number of variables; for example, the *pure ILP model* for p-cycles. This makes the process of integrating

these into one model a very difficult task, potentially yielding a highly complex model. In this chapter, the complexity problem of the *pure ILP model* is solved by proposing a new ILP formulation using the network's fundamental cycles. Thus, it is proved that the formulation presented in this paper can achieve the optimal solution. It is also important to note that, in reducing the model complexity, there is no guarantee of a shorter time frame resulting in a satisfactory solution when compared with other models. However, it does guarantee to improve on the worst case scenarios within the conventional model. It is not the purpose of this study to compare the run-times of various models.

6.2 Related Works and Preliminary Theory on p-Cycle Modeling
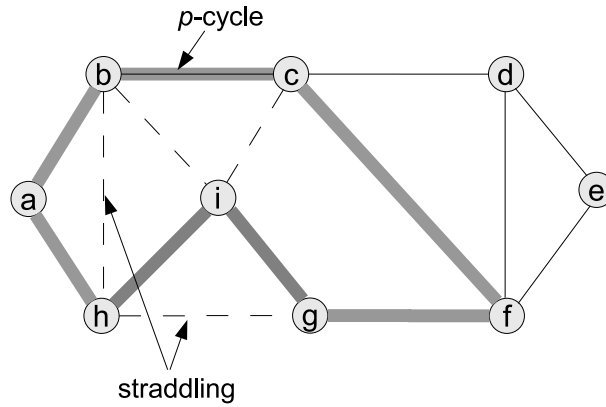
Figure 6.1: Typical p-cycle on an arbitrary network

This section presents some major developments in p-cycle design, and define a number of important terms that are used in the proposed model.

The research on p-cycle design can be categorised into three main areas:

- **Application** - In this category, authors try to implement p-cycles in networks with different design scenarios such as multi-failures [77], node protection [78, 36], path protection [78, 79], wavelength converter placement [35, 80, 81], etc.

- **Capacity design & modeling** - Research in this category concentrates on resource allocation, p-cycle placement and model formulation [82, 34, 83, 84, 37].

- **Evaluation** - Here the focus is on evaluating the reliability of networks with p-cycles [36, 85].

In the first category, researchers attempt to discover all the potential benefits of the p-cycle for network survivability. An investigation into the network's survivability with p-cycles under multiple failures is performed by Schupke [77], and his report shows that the main factors which contribute to the restorability of the network are the number of p-cycles allocated and the number of protected working capacities. Increasing the number of cycles, and minimizing the maximum working capacity coverage of selected p-cycles will increase the restorability of the network [83]. In general, p-cycles are also known as 'span-protecting' p-cycles, and can partially protect the network against node failures [78, 86]. Please note, throughout this chapter, the term p-cycle(s) alone implies the 'span-protecting' p-cycle(s). A variation of p-cycles called 'encircling' p-cycles is proposed by Stamatelakis et al [87]. Although the encircling p-cycles can protect a network from node failures, the p-cycle capacity is high when there are larger numbers of transiting traffic [36]. 'Path segment-protecting p-cycles' or 'flow-p-cycles' is another concept introduced by Shen et al. [78]. In this context, flow-p-cycles can be more efficient than p-cycles and can protect the network against both link and node failures. According to [78, 36], 'flow-p-cycles' have a limitation as they do not have the "*simplicity of failure detection and protection switching by the node adjacent to the failure*", thus switching nodes are required [36]. In the study of p-cycle configuration with partial wavelength converter by Tianjian Li et al. [81], both joint and non-joint optimisation cases[1] show promising results by taking into account the full advantages of wavelength converter sharing.

Due to the larger number of variables involved in the *pure ILP model*, it takes a sig-

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[1] In joint optimisation, the working channels are found at the same time as the spare channels. In non-joint optimisation, the working channels are assigned in advance.

nificant amount of computation time in network design to obtain the optimal solution. Therefore, to reduce the computational complexity, several methods of preselecting a reduced number of candidate p-cycles is proposed. A cycle generation algorithm is used to find a good set of candidates based on a combination of high efficiency cycles and short cycles so that working capacities can be efficiently protected by the candidate cycles [84]. Heuristic algorithms for finding the optimal p-cycles to protect a given working capacity distribution is introduced in [34], where two pre-selection criteria known as topological score (TS) and priori efficiency (AE) of p-cycles are used to obtain the set of candidates. The work in [76] involves the identification of primary p-cycles using the straddling link algorithm (SLA), followed by a search for better cycle candidates using various algorithms to produce the final set of candidates with highest efficiency. The maximum deviation of the results from the *pure ILP model* can be up to 14% and vary with network topology. The complexity of this model is greatly reduced compared to the *pure ILP model*, e.g. 270 vs. 7321 for USA network.

Dominic A. Schupke [83] introduces a different approach to formulate a non-joint optimisation without enumeration of candidates before optimisation. However, the proposed model is very complex, and the author suggests a *four-step* heuristic which makes the calculation tractable and achieves a near-optimal solution.

Except for the use of heuristic programs to search for suitable p-cycles to protect the working capacities, all ILP formulations for p-cycle network design require a set of candidates. By using network fundamental cycles and establishing the set of possible straddling links constructed from those fundamental cycles, the formulation of the p-cycle network design is less complex then the conventional models, but still able to achieve the optimum solutions. The number of input variables is significantly reduced, since the number of the network's fundamental cycles is much less than the number of p-cycle candidates.

6.2.1 Necessity of Obtaining all Cycle Candidates for Optimal Solutions

Conceptually, a p-cycle in a network G can be considered as a logical cycle c embedded on G. The p-cycle provides one pre-configured protection path against any failure of on-cycle links and two protection paths against failures of straddling links. Fig. 6.2(a) shows an example in which p-cycle c contains 5 on-cycle links and 1 straddling link l. In the 'pure' ILP model, all cycles in a network have to be included in the set of candidates.

<div align="center">(a)   (b)   (c)</div>
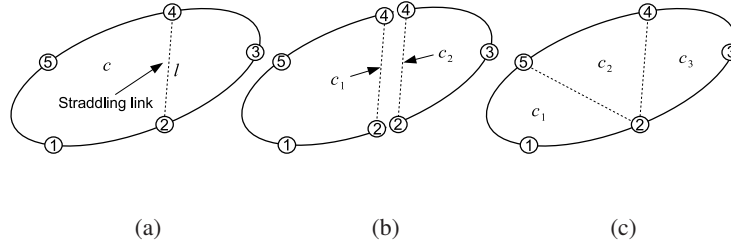
Figure 6.2: Constructing p-cycles

In fact, p-cycle c can be constructed by merging two smaller cycles c_1 and c_2 and then removing the common link l as in Fig. 6.2(b). Generally, any cycle in the network can be constructed from a number of *fundamental cycles* which contain no straddling links. Fig. 6.2.1 shows an example in which a cycle is constructed by merging three fundamental cycles c_1, c_2 and c_3. Therefore, in principle, the set of all fundamental cycles in the network is sufficient for obtaining optimal solutions in survivable network p-cycles design.

6.2.2 Preliminary Theory

In this part, the preliminary theory relating to the proposed model is discussed. Mathematical and technical concepts used in this chapter are defined and explained.

- A network physical topology is represented as an undirected graph $G(V, E)$, where V is a set of network nodes and E is a set of network spans. The term 'span' implies

Hidden straddling link

e_{12} is not on cycles c_4 and c_6

Visible straddling link

e_3 is common between c_1 and c_5
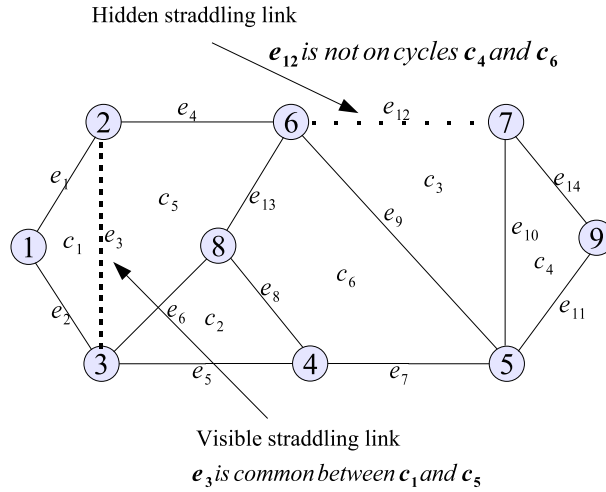
Figure 6.3: Typical planar network 9N14S

the direct physical connection between two end nodes and 'link' refers to the direct logical connection between two end nodes.

- A cycle in an undirected graph is fundamental if it contains no straddling link. Figure. 6.3 shows an arbitrary network with 9 nodes and 14 spans, which has the following set of fundamental cycles: c_1={1 2 3}, c_2={3 4 8}, c_3={5 6 7}, c_4={5 7 9}, c_5={2 3 8 6}, c_6={4 5 6 8}, c_7={2 3 4 5 6} (c_7 contains no straddling link, thus it is valid).

- A straddling link is called a *visible straddling link* if it can be created by merging two different fundamental cycles, and is the only common link that exists between them. Figure. 6.3 shows a typical *visible straddling link* e_3, which is the common link between two fundamental cycles c_1, c_5.

- A straddling link is called a *hidden straddling link* if it can be created by merging two or more fundamental cycles together, but it is not part of any of those cycles. Note that, the number of fundamental cycles that are used to generate the *hidden straddling links* yields the trade off between resource efficiency and minimum restoration time in case of failure. Longer recovery paths may result if the hidden straddling link is formed by many fundamental cycles. Figure. 6.3 shows a

typical *hidden straddling link* e_{12}, which is formed by the two fundamental cycles c_4 and c_6.

- A non-shareable set Λ: The purpose of finding the non-shareable set Λ is to prevent the construction of the encircling p-cycle(s) at every single node on the selected p-cycle. There must be two non-straddling spans at each node of the cycle that can carry the spare capacity. Each Λ contains groups of straddling links. Each group in the set consists of straddling links that have at least one common fundamental cycle component. However, if merging these fundamental cycles into a subgraph causes the straddling links to disappear, the group is non-shareable. For example, in Figure. 6.3, straddling link e_6 is formed by cycles c_2 and c_5, straddling link e_8 is formed by cycles c_2 and c_6, and straddling link e_{13} is formed by cycles c_5 and c_6. When cycle c_2 is shared between straddling links, the relevant straddling links will vanish, i.e. the sharing of cycles will create a new subgraph $\{2\ 3\ 4\ 5\ 6\ 8\}$ with no straddling links. Therefore, this group is non-shareable.

6.2.3 Non-Shareable Cycles Between Straddling Spans
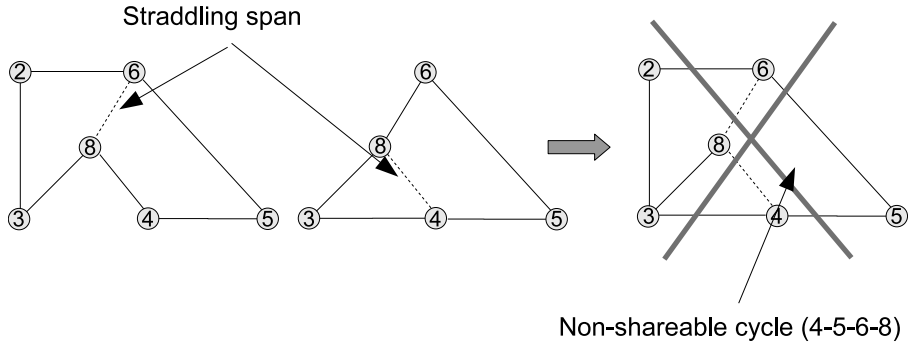
Figure 6.4: Illustration of a non-shareable cycle

The non-shareable set contains a number of subsets $\lambda_i, \{i = 1, 2..., n\}$ corresponding to the straddling span indices. In each subset λ_i, there may be more than one non-shareable group of straddling spans. For example, λ_4 of the straddling span index 4 has the follow-

ing non-shareable groups: $g_1 = \{2-3-8-4-5-6\}$ and $g_2 = \{3-4-5-6-8\}$. It becomes invalid cycle if the two groups join together as shown in Figure. 6.4. For a given graph with K straddling spans (K is an arbitrary number), there will be K subsets containing the non-shareable groups. The number of straddling spans is very much dependant on the graph topology, and is proportional to the network nodal degree.

Table 6.1: Straddling Link Details

Straddling index	Cycles	Physical span
Visible straddling span		
1	1-7	e_3
2	1-5	e_3
3	3-7	e_9
4	2-5	e_6
5	5-6	e_{13}
6	2-6	e_8
7	3-6	e_9
8	3-4	e_{10}
Hidden straddling span		
9	5-6	e_5

6.2.4 Finding a Network's Fundamental Cycles

Fundamental cycles play an important role in the proposed model as all the construction of straddling spans is based on the relation between these cycles, and these cycles are later used to obtain the *p*-cycles from the ILP solution.

The algorithm for finding the fundamental cycles is given in Algorithm 4, which is a simple process of looking for all the simple cycles that are passing though the source nodes of the network tree. The branches of the spanning tree for the given network are

more concentrated on the left hand side of the tree starting from the second level. The fundamental cycle can be found if a link exists between two branches of a tree with at least one branch containing just the neighbor node of the source node. Figure. 6.5 is a typical example of a tree generated from the network shown in Figure. 6.3 with the source at node 2. The simple cycles crossing the source node are $\{2\ 1\ 3\}$, $\{2\ 3\ 8\ 6\}$ and $\{2\ 3\ 4\ 5\ 6\}$.

Algorithm 3 : Finding Fundamental Cycles

Input : An undirected graph $G(V,E)$.

Output: set of fundamental cycles.

   for $i = 1$ to N **do**

      $cycles \Leftarrow cycles \cup \mathbf{get\_cycle}(\mathrm{Net},i)$

      $E \Leftarrow \{E \setminus i\}$

   end for
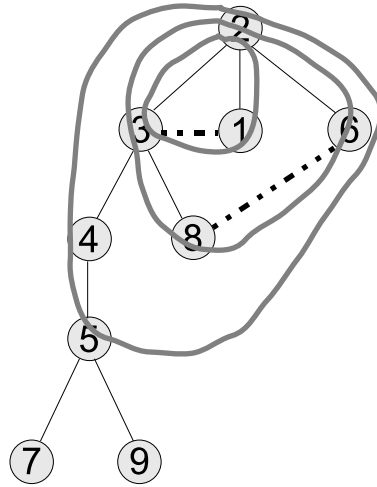
Figure 6.5: A tree with the source at node 2 of network 9N14S(Figure. 6.3)

- Analysis of algorithm: For each value of i in the algorithm, the inner instructions **get_cycle** is executed **T(i)** time. The number of execution times is therefore

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function **get_cycle**(Net,*source*) return *Cycles*

neighbors $\Leftarrow$ neighbors of *source*

N_neighbor $\Leftarrow$ length of *neighbors*

if *N_neighbor* < 2 **then**

   return

end if

for $i = 1$ to *N_neighbor* $- 1$ **do**

   for $j = i + 1$ to *N_neighbor* **do**

     if $e = \{neighbors(i), neighbors(j)\} \subset E$ **then**

       $cycle \Leftarrow \{source, neighbors(i), neighbors(j)\}$

       $Cycles \Leftarrow Cycles \cup cycle$

     else

       push *queue.node* $\Leftarrow$ *neighbor(i)*

       push *queue.branch* $\Leftarrow$ *neighbor(i)*

     end if

     $Cycles \Leftarrow Cycles \cup ($**processNode**(Net,*queue*,

     $source, neighbors(j)))$

   end for

end for

function **processNode**(Net, *queue*, *source*, *neighbors*(j)) return *Cycles*

---

while *queue.node* $\neq \emptyset$ **do**

  pop *node* $\Leftarrow$ *queue*(*end*).*node*

  pop *branch* $\Leftarrow$ *queue*(*end*).*branch*

  *S*1 $\Leftarrow$ neighbors of *node*

  *V*1 $\Leftarrow$ {*branch*, *source*, *neighbors*(j)}

  *S*1 $\Leftarrow$ {*S*1 \ *V*1}

  if *S*1 $\neq \emptyset$ **then**

    N $\Leftarrow$ length of *S*1

    for *k* = 1 to *N* **do**

      *S*2 $\Leftarrow$ neighbors of node *S*1(*k*)

      *S*2 $\Leftarrow$ {{*S*2 $\cap$ {*branch*, *source*}} \ *node*}

      if *S*2 = $\emptyset$ **then**

        continue

      end if

      if *e* = {*S*1(*k*), *neighbors*(j)} $\subset$ *E* **then**

        cycle $\Leftarrow$ {*S*1(*k*), *neighbors*(j)}, *branch*(1 : *end* − 1)

        Cycles $\Leftarrow$ *Cycles* $\cup$ *cycle*

      else

        push *queue.node* $\Leftarrow$ *S*1(*k*)

        push *queue.branch* $\Leftarrow$ {*branchS*1(*k*)}

      end if

    end for

  end if

end while

$\sum_{i=1}^{n} \mathbf{T(i)} = s$ times. For the control of the outer loop, the inner loop is initialised n times, therefore n is added to the execution time of the algorithm. The total time taken by the above algorithm is now $\Theta(n+s)$.

6.3 Proposed Integer Linear Programming Formulation for p-Cycle Networks

6.3.1 Non-Joint Optimisation Model

This section proposes the non-joint optimisation model. Recall that all the fundamental cycles and straddling link details for the given network, have been pre-processed.

Model 9 *Non-joint ILP model for p-cycle network design*

- **Notation**

  - *Network notation*

    $E = \{e_1, e_2, \ldots, e_M\}$ *Set of M network spans.*

    $V = \{v_1, v_2, \ldots, v_N\}$ *Set of N network nodes.*

  - *Indices*

    $C = \{c_1, c_2, \ldots, c_J\}$ *Set of network fundamental cycles.*

    $S = \{s_1, s_2, \ldots, s_K\}$ *Set of visible straddling links.*

    $I = \{i_1, i_2, \ldots, i_L\}$ *Set of hidden straddling links.*

    $\Lambda = \{\lambda_1, \lambda_2, \ldots \lambda_n\}$ *Set of non-sharable straddling links.*

  - *Constants*

    $\delta_{c,j} = 1$ *if cycle c includes span j, 0 otherwise.*

    $\xi_{s,c}^{j} = 1$ *if visible straddling link s at span j can be created by cycle c,*
    0 otherwise.

    $\pi_{i,c}^{j} = 1$ *if hidden straddling link i at span j can be created by cycle c,*
    0 otherwise.

    $\upsilon_{i,j} = 2$ *is the number of useful paths provided by hidden straddling link i*
    to restore span j.

    w_j: *is the number of working channels on span j.*

    α_j: *is the cost per channel on span j.*

  - *Variables*

y_j: is the capacity on span j that can support the cycle that crosses it.

n_c: is the number of unit capacity copies of the cycle c in the design.

$m_{i,c}$: is the number of unit capacity copies of the hidden straddling i using cycle c in the design.

$u_{i,c}$: is the number of unit capacity copies of the visible straddling i using cycle c in the design.

- **ILP model**

  - *Objective*

$$minimise : \quad \sum_{j \in E} \alpha_j (y_j - 2\xi_{i,c}^j),$$

$$i \in S; c \in C \tag{6.1}$$

  - *Constraints*

    1. *Spare capacity on span j is sufficient to support all cycles that cross it.*

$$\sum_{c \in C} \delta_{c,j} n_c = y_j, \qquad \forall j \in E \tag{6.2}$$

    2. *The number of unit cycle n_c is sufficient to create straddling links.*

$$\sum_{i \in S} \xi_{i,c}^k u_{i,c} - n_c \le 0, \tag{6.3}$$

$$\sum_{j \in I} \pi_{j,c}^k m_{j,c} - n_c \le 0, \tag{6.4}$$

$$\forall c \in C; k \in E$$

    3. *The number of useful paths for each span j (provided by selected hidden straddling links) plus capacity of selected cycles that support 100 % restorability.*

$$\sum_{i \in I} v_{i,j} m_{i,c} + y_j \le w_j, \qquad \forall j \in E; c \in C \tag{6.5}$$

4. *The total number of useful paths provided by the visible straddling i at span j must be less than or equal to the total number of spare capacities provided by the corresponding span.*

$$\sum_{i \in S} 2\xi_{i,c}^{j} u_{i,c} - y_j \leq 0, \qquad\qquad \forall j \in E; c \in C \qquad (6.6)$$

5. *The constraint for non-shareable straddling links i, j ensures that the identical cycle of the straddling links in the group will not become the common cycle between them.*

$$\left(\sum_{i \in S} \xi_{i,c}^{m} u_{i,c} + \sum_{j \in I} \pi_{j,c}^{n} m_{j,c} \right) - n_c \leq 0,$$

$$\forall \{\xi_{i,c}^{m} \pi_{k,c}\} \subseteq \Lambda;$$

$$\forall c \in C; m, n \in E \qquad (6.7)$$

The number of variables and constraints that are introduced in the model are shown in Table 6.2, where $\bar{v}$ is the average number of cycles forming a straddling link.

Table 6.2: Number of Variables & Constraints

Number of Variables	Number of Constraints
$|C| + |S| + |I| + M$	$\bar{v}(|S| + |I|) + 3M$

6.3.2 Joint Optimisation Model

In this section, it is assumed that all the fundamental cycles and available straddling links of the network under consideration have been pre-processed or given. In addition, the network is assumed to have sufficient wavelength channels or wavelength converters to support the routing of connection demands. Thus, wavelength continuity is not an issue in this context.

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Joint optimisation models usually provide better solutions than the non-joint optimisation models. In the following section, the joint optimisation model is introduced. However, this model can be easily converted to the non-joint model by just a few simple modifications to the existing model.

Model 10 *Joint ILP model for p-cycle network design*

Notation:

$E = \{e_1, e_2, \ldots, e_M\}$ *Set of M network spans.*

$V = \{v_1, v_2, \ldots, v_N\}$ *Set of N network nodes.*

$\mathbf{C} = \{c_1, c_2, \ldots, c_C\}$ *Set of C fundamental cycles.*

$\mathbf{S} = \{s_1, s_2, \ldots, s_S\}$ *Set of S visible straddling links.*

$\mathbf{I} = \{i_1, i_2, \ldots, i_I\}$ *Set of I hidden straddling links.*

$\Lambda = \{\lambda_1, \lambda_2, \ldots \lambda_n\}$ *Set of non-sharable straddling links.*

$\mathbf{D} = \{d_1, d_2, \ldots, d_D\}$ *Set of D demands.*

$\mathbf{P} = \{p_1^i, p_2^j, \ldots, p_P^k\}$ *Set of path candidates between end nodes of demands; $d \in$*
         D.

Constants:

$$
\delta_{x,j} = \begin{cases} 1, & \text{\textit{if cycle x includes span j;}} \\ & j \in E; x \in \mathbf{C} \\ 0, & \text{\textit{otherwise.}} \end{cases}
$$

$$
\xi_{s,c}^{j} = \begin{cases} 1, & \text{\textit{if }} c = \{x, y | x \cap y = j; x, y \in \mathbf{C}\}; \\ & j \in E; c \subset \mathbf{C}; s \in \mathbf{S} \\ 0, & \text{\textit{otherwise.}} \\ & \text{\textit{s is the straddling link formed by}} \\ & \text{\textit{cycles }} x, y. \end{cases}
$$

$$\pi_{i,\theta}^{j} = \begin{cases} 1, & \textit{if } s \bigcap E(\theta) = \emptyset \textit{ and} \\ & V(s) \subseteq V(\theta); \\ & j \in E; \theta \subseteq \mathbf{C}; i \in \mathbf{I} \\ 0, & \textit{otherwise.} \\ & \textit{i is the straddling link formed by} \\ & \textit{set of cycles } \theta. \end{cases}$$

$$\tau_{i,j}^{d} = \begin{cases} 1, & \textit{if candidate path } i^{th} \textit{ of demand } d \in \mathbf{D} \\ & \textit{crosses span } j; \\ 0, & \textit{otherwise.} \end{cases}$$

$$\chi_{i,j} = \begin{cases} 1, & \textit{if the p-cycle passes through node } i \\ & \textit{span } j; i \in V; j \in E \\ 0, & \textit{otherwise.} \end{cases}$$

$$\varphi_{i,s} = \begin{cases} 1, & \textit{if the visible straddling } s \textit{ passes through} \\ & \textit{node } i; i \in V; s \in \mathbf{S} \\ 0, & \textit{otherwise.} \end{cases}$$

$$\omega_{i,j} = \begin{cases} 1, & \textit{if the spare capacity used span } j \textit{ and passes} \\ & \textit{through node } i; i \in V; j \in E \\ 0, & \textit{otherwise.} \end{cases}$$

$\upsilon_{s,j} = 2$:   *the number of useful paths provided by hidden straddling link s to restore span $j \in E$; $s \in \mathbf{S}$.*

α_j: *the cost per channel on span $j \in E$.*

h_d: *volume of demand d; $d \in \mathbf{D}$.*

ϕ_j: *maximum capacity provided by span $j \in E$.*

Variables:

y_j: *the capacity on span j that can support the cycle that cross it; $j \in E$.*

n_x: *the number of unit capacity copies of the cycle x in the design; $x \in \mathbf{C}$.*

$m_{i,x}$:   *the number of unit capacity copies of the hidden straddling i using cycle x in the design; $i \in \mathbf{I}; x \in \mathbf{C}$.*

$u_{i,x}$:   *the number of unit capacity copies of the visible straddling i using cycle x in the design; $i \in \mathbf{S}; x \in \mathbf{C}$.*

w_j: *the working capacity on span j to support the routing of working paths; $j \in E$.*

p_i^d: *the number of unit capacity copies of the ith path candidate chosen to serve demand d; $i \in \mathbf{P}; d \in \mathbf{D}$.*

z^i: *the number of unit p-cycles passing through node i; $i \in V$.*

ILP model

- *Objective*

$$minimise : \quad \sum_{j \in E} \alpha_j (y_j + w_j) - \sum_{i \in S} \sum_{j \in E} 2\xi_{i,c}^j u_{i,x},$$

$$x \in c; c \subset \mathbf{C} \tag{6.8}$$

- *Constraints*

  1. *Capacity on each span is sufficient to support all cycles that cross it.*

$$\sum_{x \in \mathbf{C}} \delta_{x,j} n_x = y_j, \qquad\qquad \forall j \in E \tag{6.9}$$

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2. *Number of cycles must be sufficient to support the chosen straddling links.*

$$\sum_{i \in \mathbf{S}} \xi_{i,c}^k u_{i,x} - n_x \leq 0, \qquad\qquad\qquad\qquad (6.10a)$$

$$\sum_{j \in \mathbf{I}} \pi_{j,c}^k m_{j,x} - n_x \leq 0, \qquad\qquad\qquad\qquad (6.10b)$$

$$\forall c \subset \mathbf{C}; x \in c; k \in E$$

3. *The working capacity allocated to each span.*

$$\sum_{i \in \mathbf{P}} \sum_{d \in \mathbf{D}} p_i^d \tau_{i,j}^d = w_j, \quad \forall j \in E \qquad\qquad (6.11)$$

4. *Spare capacity allocated on links must be sufficient to support 100% restorability.*

$$\sum_{i \in I} v_{i,j} m_{i,x} + y_j \geq w_j, \qquad\qquad \forall j \in E; x \in \mathbf{C} \qquad (6.12)$$

5. *The total amount of useful capacity provided by the ith visible straddling link at span j must be less than or equal to the total amount of capacity of that span formed by the corresponding cycles.*

$$\sum_{i \in \mathbf{S}} 2\xi_{i,c}^j u_{i,x} - y_j \leq 0, \qquad\qquad \forall j \in E; x \in c; c \subset \mathbf{C} \qquad (6.13)$$

6. *The common cycle cannot be shared between straddling links.*

$$\left(\sum_{i \in \mathbf{S}} \xi_{i,c}^k u_{i,x} + \sum_{j \in \mathbf{I}} \pi_{j,c}^l m_{j,x} \right) - n_x \leq 0,$$

$$\forall \{\xi_{i,c}^k \pi_{k,c}^l\} \subseteq \Lambda;$$

$$x \in c; c \subset \mathbf{C}; k, l \in E \qquad\qquad (6.14)$$

7. *Path selection constraint: each demand connection requires to be assigned to one candidate path.*

$$\sum_{i \in \mathbf{P}} p_i^d = h_d, \quad \forall d \in \mathbf{D} \qquad\qquad (6.15)$$

8. *The total capacity assigned for each span (working plus spare capacity) must be less than or equal to the maximum capacity that can be provided by the corresponding span*

$$\sum_{i \in \mathbf{S}} -2\xi_{i,c}^{j} u_{i,x} + y_j + w_j \leq \phi_j,$$

$$\forall j \in E; x \in \mathbf{C}; c \subset \mathbf{C} \qquad (6.16)$$

9. *The number of selected visible straddling spans s through node i must be less than or equal to the number of p-cycles passing through it.*

$$\sum_{i \in V} \varphi_{i,s} u_{s,x} - \sum_{i \in V} \chi^i < 0,$$

$$\forall s \in \mathbf{S}; x \in \mathbf{C}; \qquad (6.17)$$

10. *The total number of links through a node v must be equal to the total number of useful paths provided by the visible straddling links plus twice the number of p-cycles through that node. In other words, at every p-cycle node, there are always two links that are not straddling links.*

$$\sum_{s \in \mathbf{S}} 2\varphi_{i,s} u_{s,x} + 2\sum_{i \in V} \chi^i - \sum_{i \in V} y_j \omega_{i,j} = 0,$$

$$\forall i \in V; j \in E; x \in \mathbf{C} \qquad (6.18)$$

The objective of the above model given by Equation 6.8 has a constant number 2 (after the minus sign). This is because as in the model, when merging 2 cycles to create a straddling link (the visible straddling link), the total number of links is equal to the sum of the number of links on these cycles. As there is no working capacity required for the straddling link, 2 is subtracted from the total for each chosen straddling link.

Equation 7.14 guarantees that each network span has enough spare capacity to support all the working channels through it. The total spare capacity required for each span is equal to the total number of virtual fundamental cycles selected which pass through the corresponding span. This needs to be considered for each $j = \{1, 2, ..., M | j \in E\}$.

In Equation 6.10a and Equation 6.10b, for each chosen straddling link i or j (i and j belong to two different sets: visible and hidden), the fundamental cycles for which the straddling link is formed must also be selected. The straddling link i, j represents the logical link(s), which is different from the physical connection, span represented as $k = 1, 2, ..., M$. Each physical link can have various straddling links formed by different sets of fundamental cycles.

Equation 6.11 describes the working capacity allocated to each span of the network. This is equal to the sum of all the candidate path with index $i = 1, 2, ..., P$ and demand $d = 1, 2, ..., D$ passing through span j for every $j = \{1, 2, ..., M | j \in E\}$.

Equation 6.12 guarantees that the resources allocated on each span must be equal to or greater than the sum of the total working capacity and the total spare capacity required to protect the network from failure. This is crucial as the useful paths provided by the hidden straddling links are not yet included in y_j.

According to Equation 6.13, the total amount of useful capacity provided by the visible straddling link(s) at span j must be less than or equal to the total amount of cycles that cross it. It can be seen that each straddling link provides two useful capacities, and there must be at least two cycles crossing the corresponding span. The straddling links do not need any spare resource, but they cannot be removed directly from the model.

Equation 6.14 is used mainly for preventing the selection of node-encircling p-cycle(s). If node protection is desired, this constraint will be removed from the model. The total number of cycles c will be equal to the total number of those selected straddling links.

Equation 6.15 indicates that the total number of paths selected for each demand must satisfy the volume demands.

Equation 6.16 ensures that the total capacity allocated for each span always less than or equal to the maximum capacity assigned for each span.

In Equation 6.17 as each individual visible straddling link is formed by two fundamental cycles crossing the corresponding span, this ensures that the number of selected straddling links is always less than the total number of cycles crossing it.

Equation 6.18 prevents the over selecting of straddling links compared to the number of selected p-cycle(s). This is based on the characteristic of p-cycle. At every node v on the p-cycle, there are always two links with assigned spare capacity.
The number of variables and constraints that are introduced in the model are shown in Table 6.3, where $\bar{v}$ is the average of number of cycles forming a straddling link.

Table 6.3: Number of Variables & Constraints

Number of Variables	Number of Constraints
$C + S + I + 2M + kD + N$	$\bar{v}(2S + 2I) + C + D + 5M + N$

6.4 Obtaining p-Cycles from the Solution

The solution of the ILP model contains only the unique capacity of cycles, the relevant straddling spans, and the spare capacity allocated on each span of the network. Thus, to obtain a complete solution, which is the set of p-cycles required to protect all the working channels, it is necessary to translate the solution obtained from the model. This can be done in two different ways: one is based on the details given from the ILP results, where the set cover theorem can be used to search for the matching patterns, eg. the number of selected fundamental cycles, straddling spans, total cost etc... Another technique is to generate p-cycle candidates from a set of cycles and the straddling spans selected by the ILP; then formulating an ILP to select the set of p-cycles that satisfies the solution obtained previously. This technique is preferable as most of the data used for the formulation can be reused from the previous model, and the number of candidates that can be generated from the set of selected cycles is small and does not effect the complexity of the

ILP model. The ILP formulation for obtaining the required set of *p*-cycles is presented in Model 11.

Model 11 *ILP model for p-cycle selection*

<u>*Notation:*</u>

$\mathbf{Z} = \{z_1, z_2, \dots, z_Z\}$ *Set of p-cycle candidates obtained from the previous solution.*

<u>*Constants:*</u>

$$\lambda_c^z = \begin{cases} 1, & \textit{if candidate z includes cycle c;} \\ & z \in \mathbf{P}; c \in \mathbf{C}; \\ 0, & \textit{otherwise.} \end{cases}$$

<u>*Variables:*</u>

n_z: *the number of unit capacity copies of the p-cycle z in the design; $z \in \mathbf{Z}$.*

m_c: *the number of unit capacity copies of cycle c in the design used by the p-cycles; $c \in \mathbf{C}$.*

k_c: *the number of unit capacity copies of cycle c in the design not used by the p-cycles; $c \in \mathbf{C}$.*

ILP model

- *Objective*

$$\textit{minimise :} \qquad \sum_{z \in \mathbf{Z}} n_z + \sum_{c \in \mathbf{C}} k_c \tag{6.19}$$

- *Constraints*

  1. *The number of fundamental cycles must be sufficient to construct the candidate p-cycles.*

$$\sum_{z \in \mathbf{z}} n_z \lambda_c^z - m_c = 0,$$

$$\forall c \in \mathbf{C} \tag{6.20}$$

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2. The number of fundamental cycles must be equal to those obtained from the Model 10.

$$\sum_{c\in\mathbf{C}}(m_c+k_c)-v_c=0,$$

$$\forall c\in\mathbf{C} \qquad\qquad (6.21)$$

3. Integer constraints:

$$n_z,m_c,k_c\in\mathbb{N} \qquad\qquad (6.22)$$

6.5   Simulation

This section presents the simulation and evaluates the performance of the proposed model with the network shown in Figure. 6.3. The proposed model is then compared with a conventional ILP model, which uses all candidate cycles. The model comparisons are based on the worst case scenario, as the number of input variables is the main factor contributing to the model's complexity. This is due to the time nondeterministic characteristics of the ILP.

1. Simulation results of the of 9N14S network

   The simulation has shown that the optimum p-cycles required to protect the network can be obtained by using the network's fundamental cycles. Table 6.4 shows the routing optimisation results from the proposed model, where (a) gives the working channels that need to be protected, and are in indexing order; (b) gives the spare channels that are required for each span to guarantee 100% protection of the working channels, and (d) is the total of network spare channels. (f), (g) are the total straddling links required. The details of fundamental cycles that make the corresponding p-cycles are shown in (j) with the following format [*cycles indices*$\times$*volume*] (e.g., $[1\ 5\ 6]\times 2$ implies that there are 2 p-cycles, which are formed by fundamental cycles c_1, c_5, and c_6). The size of the model is 291×81 (291 constraints and 81 variables as shown in (h)). The number of fundamental cycles required to achieve

the optimal solution is shows in (i). In this case 3 units of cycle are indexed 1, 1 unit of cycle indexed 2, 0 unit of cycle indexed 3, and so on.

Table 6.4: Simulation Results for the 9N14S Network

a) Working capacity on each link	[3 2 4 3 5 3 1 1 1 0 0 0 0 0]
b) Spare capacity on each link	[3 3 0 3 1 2 2 3 2 0 0 0 1 0]
c) Total link capacity	[6 5 4 6 6 5 3 4 3 0 0 0 1 0]
d) Total Spare capacity requested	20
e) Total Network capacity	43
f) Number of visible straddling links used	[6]
g) Number of hidden straddling link used	[2]
h) Model size	(291×81)
i) Cycles used	[3 1 0 0 3 2 0]
j) **The network p-cycles are**	
	[1 2 5]
	[1 5 6] $\times$ 2

2. Model comparison In order to achieve the optimal solution, the pure ILP model needs to use a complete set of possible eligible cycles in the network [76]. Thus the complexity of the model greatly increases with the size of the network. Although the complexity of the model proposed in this chapter is dependent on the network size, the complexity increases at a much slower rate than compared to that of the pure ILP model.

Figure. 6.6 shows the comparison of the number of variables between the pure ILP and the proposed model over a number of well known test networks. The difference in the number of variables between the two models becomes significant when the size of the network increases. The size of the first four networks is relatively small as there are not many candidate p-cycles existing in these networks. However, when the size of the networks is increased, the number of candidate p-cycles increases significantly. This is however not the case in the new proposed model, where the number of fundamental cycles only increases slightly with the size of the network.

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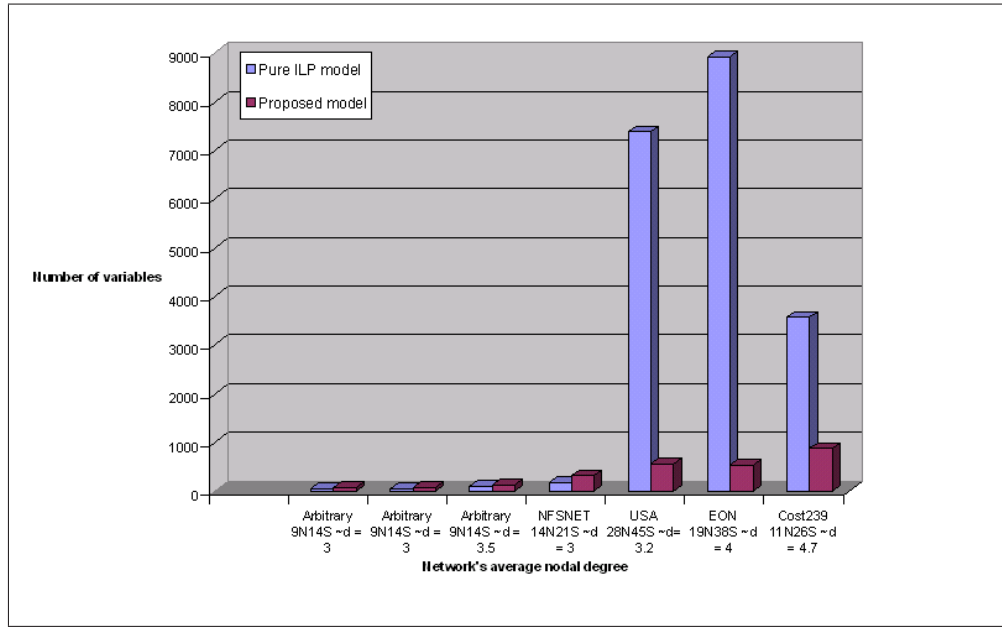
Figure 6.6: Models comparison

Additionally, none of the ILP formulations can include the *extra straddling relation-ships with non-simple p-cycles* without increasing the number of candidates by including the non-simple *p*-cycles.

Therefore, when compared to other conventional ILP models, regardless of how the candidates are generated, the proposed model always outperforms them with the truly op-timal solution because the formulation is built from the network's fundamental entities (the fundamental cycles and straddling links construction information). In some cases, the complexity of the proposed model when used for small non-planar networks, may be higher than the pure ILP model. This is because a large number of hidden strad-dling links may exist. The NFSNet network in Figure. 6.6 represents the case of a small non-planar network. Furthermore, through a larger number of simulations performed on different network topologies, it was found that when some extra links are added to the existing network, this can significantly increase the model's variables. For example, be-tween the Net-9N14S and Net-9N15S there is no difference, but between Net-9N15S and Net-9N16S the difference is 51 units by adding just a single link. Figure. 6.6 shows the

comparison between the total number of all cycles, and the total number of fundamental cycles existing in randomly generated networks with different average nodal degrees. The difference between the two candidates becomes significant with the increase of network nodes and average nodal degree.
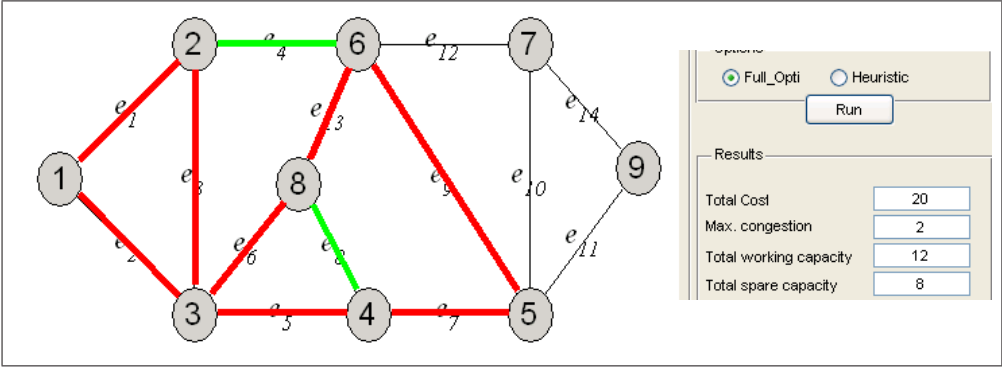
Figure 6.7: *p*-cycles allocation result with non-simple *p*-cycles
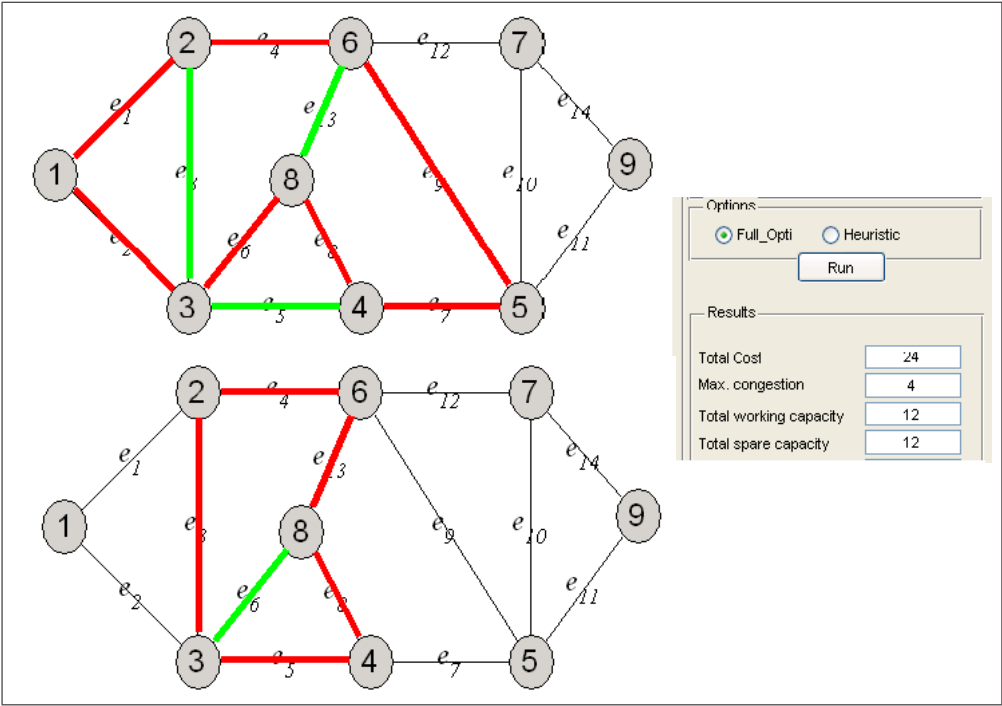
Figure 6.8: *p*-cycles allocation result without using non-simple *p*-cycles

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Figure. 6.7 and Figure. 6.8 are snapshots of the simulation program with different demands. In these, the red cycles are the p-cycles and the green lines are the straddling links. Figure. 6.7 shows the result of the p-cycles allocated to protect the network using the "non-simple p-cycle". In this, there is only one non-simple p-cycle required, which is the p-cycle: $c_1 \bigcup (c_2 \bigcup c_6)$. The total cost of the capacity usage is 20, the maximum congestion is 2, and the total capacity redundancy is 8.

For the same traffic demands and working capacity on each span, Figure. 6.8 shows the allocation of p-cycles. In this case, the "non-simple p-cycle" cannot be constructed. There are two p-cycles allocated to protect the network: $c_2 \bigcup c_5$ and $c_1 \bigcup (c_5 \bigcup c_6)$. The total cost of the capacity in this case is 24, the maximum congestion is 4, and the total capacity redundancy is 12.

In the proposed model it is clear that "non-simple p-cycles" can give better results, than the conventional model without significantly increasing the number of variables.

6.6 Summary

This chapter examines the network design with p-cycles and proposed a new ILP formulation for the p-cycle network design using the set of network fundamental cycles and the straddling links formed by the fundamental cycles. The fundamental cycle of the network is defined as a cycle that contains no straddling link.

The proposed model can obtain the optimal solution by getting all the *extra straddling relationships with non-simple p-cycles* if available, which has never been formulated before. The reduced complexity of the proposed model has the advantage over the pure ILP model when dealing with large size networks. In planar networks, the number of constraints is small due to a smaller number of relations between cycles, and thus a smaller number of hidden straddling links that can be formed by the fundamental cycles. This implies that, the proposed model is highly suitable for designing shared risk link group p-cycles protection networks or backbone networks where the cross spans are limited.

Chapter 7

Network Survivability with Multiple Quality of Service Classes

This chapter presents a new network design and optimisation model with mixed protection techniques and supporting multiple quality of protection (QoP) service classes. By integrating mixed methods of protection and service classes, the proposed model minimises both the cost of working and the spare capacity of routing from a given set of demand. Maximised resource usage with minimum design cost are achieved for network design or network upgrades using suitable set of network span candidates. In addition, this study provides an insight into the relation between the physical and logical topologies, and the advanced step of studying joint topology design and optimisation with mixed protection schemes and multiple QoP classes.

7.1   Related Works and Background Theories

A variety of protection and restoration methods have been studied and implemented for the mesh topology, such as automatic protection switching (APS), dedicated path protection, shared backup path protection (SBPP), *p*-cycles... [28, 32, 41, 88, 89, 34]. These

protection techniques have variations in terms of complexity, spare capacity usage and restoration speed. Thus, from the network designer's perspective, each method has its own advantages and disadvantages. For example, a network employing 1 + 1 APS can achieve a restoration time of less than 60 ms, but must use more than 100% capacity redundancy. In contrast, with SBPP, the restoration time after a failure can be as large as 200ms and but the tradeoff is that in some cases, the total redundancies can be as low as 21%.

Studies of capacity-design for transport networks assume that all the service classes must be restorable against failures of network components. However, in reality, they can be categorised into four different policies for the treatment of different demands in a mesh-restorable network [4], which is called multiple Quality of Protection (QoP) service-classes.

Following are the definition of the service classes, ordered from high grade to low grade based on the complexity of implementation at the optical layer and the level of protection they can provide:

1. Gold class: Lightpaths that are guaranteed to be protected by the optical layer.

2. Silver class: Lightpaths that are protected by best effort, being working channels that should be restored, if possible, following the full restoration of any of the higher service classes.

3. Bronze class: Lightpaths that are not protected, being working channels that do not receive any restoration effort, but are not subject to pre-emption.

4. Economy class: Low priority lightpaths that utilise protection bandwidth under normal conditions, which are channels that do not receive any protection, and are pre-empted when other lightpaths need to be protected.

The study of Clouquer *et al* [47] shows a significant reduction in the spare capacity requirements as not all services need restoration. Thus, design and optimisation of the

mesh-restorable network with mixed-service classes will allow the network to enhance the operation and provide more customer options. However, this study was based on span protection in conjunction with this type of protection scheme only, which requires high level of resource redundancy.
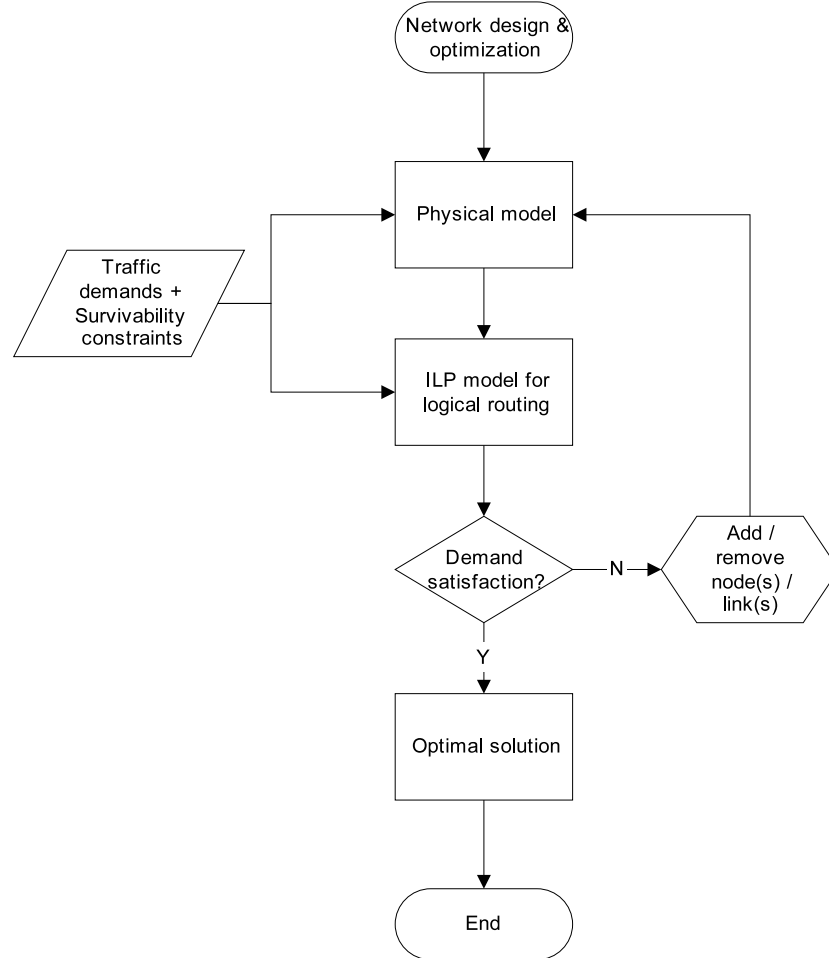
Figure 7.1: Typical network design flow

With regards to the physical network design of mesh-restorable networks, most studies are based on the assumption that node positions are known in advance, and the number of OXCs in the **N** nodes have unbounded switching capacity. Therefore, the physical topology design is reduced to forecasting the demand and deciding on a topology between OXCs, how to connect client sub-networks through OXCs, and placement of other

resources such as amplifiers, converters, and power splitters. In practice, if the physical topology must be designed from scratch, many providers take a cautious approach by initially building a skeleton network and then adding new resources, if necessary, depending on the actual user demands as a way to minimise the additional capacity [12].

These physical topology design problems have been studied in [43], for a given number of label switching routers (LSRs) and a set of lightpaths to be setup among pairs of OXCs, with the objectives being minimising number of OXCs and minimising the number of wavelengths used. This was a combination of physical and logical topology design problem, where the routing and wavelength assignment for the lightpaths was also determined. Y. Xin [43] has shown that the physical topology design problem can be formulated as an integer programming (IP) problem. An iterative approach was developed for this problem, whereby a genetic algorithm (GA) was used to generate feasible physical topologies, and heuristic techniques were employed for RWA on a given physical topology, which generated the fitness reference value for GA solutions.

Some other physical topology design studies have focused on various aspects, such as placement of converters, connectivity, nodal degrees, and average hope distance [15, 43, 4, 46]. The economic attractiveness of mesh-restorable networks depends on the extent to which and how the capacity is shared for restoration, and is dependent on topology. The next step in this research is to introduce the graph physical topology into the optimisation problem as a variable [4, 12].

Glenstrup [23] has researched the optimisation of the link cost based on different protection scenarios and is treated as green-field network planning. In this work, the author has also proposed a way of minimising the node cost by grouping the wavelengths that share a common sub-path and employing multi-granular switch component, thereby effectively reducing both switch ports and link costs. The physical topology design problem is quite complex because of the interdependencies between physical and logical architectures, such as the links, OXCs capacities, location of optical devices (amplifier, converters) all are dependent on the routing of lightpaths and the wavelengths assignment

strategy, and vice versa.

Growing demand, economic changes and the need to optimise the networks have lead to a new approach of topology evolution, this is single span addition to existing networks. For a given network with N nodes and S existing spans, the number of single spans that can be considered for addition is described as follows:

$$Y = \frac{N(N-1)}{2} - S \qquad (7.1)$$

As an example, a degree 2.5 network with 100 nodes would typically have 125 spans; there would be about 48,025 single span addition possibilities for testing. The consideration is which one of those will be the most suitable candidate. Two heuristic algorithms namely Partial Express Flows and Frequency & Remoteness Metrics are used to identify the new span additions based on the considerations of routing & topology in the existing network. More details about these heuristic algorithms can be found in Chapter 2 and [4].

The studies of Grover et al. in [47] have shown that there would always be benefit in spare capacity allocation when designing networks to support multiple QoP service classes. In other words, more resource efficiency will be gained if there are economic classes present, as the restoration paths of the protected demand can be partially or completely provided via pre-emption of the economic class services. The non-protected and best-effort classes, however, will not have any effect or make any contribution on saving of the spare resources.

In this chapter, the study of the ILP formulation for the network design, optimisation and integrating mix-protection schemes (dedicated path protection, SBPP and *p*-cycle) into optical transport layer to respond to different quality of service demands with optimum resources usage is presented. As each protection scheme has different recovery time and capacity usage, the selection of these protection techniques is based on their restoration time and the requirement of resources. In addition, for simplicity purpose, the Silver and Bronze classes of demand are removed from the model. The ILP formulation is implemented with two types of service classes known as gold and economic classes, and focus on the joint capacity optimisation and design with mixed protection schemes. This

is because with the Silver class, the connections can be restored only if the resources are available and with the Bronze class, the connections do not require protection. Thus, the capacity usage for these demand classes mainly affects the working capacity. The mixed-protection schemes introduced in the formulation will be under the Gold class demand. The networks physical topology can also be considered, together with the logical routing allocation of resources, in the same model.

7.2 Integer Linear Programming Formulation for Network Survivability with Multiple Quality of Service Classes

This section presents an Integer Linear Programming optimisation model. This model is based on the previous study of the SBPP design in [90] and *p*-cycle optimisation [91]. The optimisation models in theses studies were particularly designed for this purpose. They have a minimum number of constraints and variables, and therefore, they will not cause significant increases in the complexity of the model for joint protection schemes. The model complexity mentioned here is not the practical running time of the model. They are two different aspects that cannot be compared. In addition, ILP is known as a non-polynomial time algorithm, and large models do not always have greater running times and vice versa.

Figure. 7.2 presents the general view of the network design for the joint optimisation model. Given a set of traffic demands, a trial physical network with N nodes with a set of M span candidates will be generated and formulated into the ILP model. In the ILP formulation, demands will be presented as the percentage of the service classes and assigned according to the quality of protection requested. In the proposed model, each variable representing the physical span has the value of '1' if the link is considered a candidate. For new network design, all the new spans must be assigned with the value of '1' and for all the existing spans in the upgrading network, the the corresponding variables must be assigned with '0'. The unused physical span(s) will take the '0' value in the
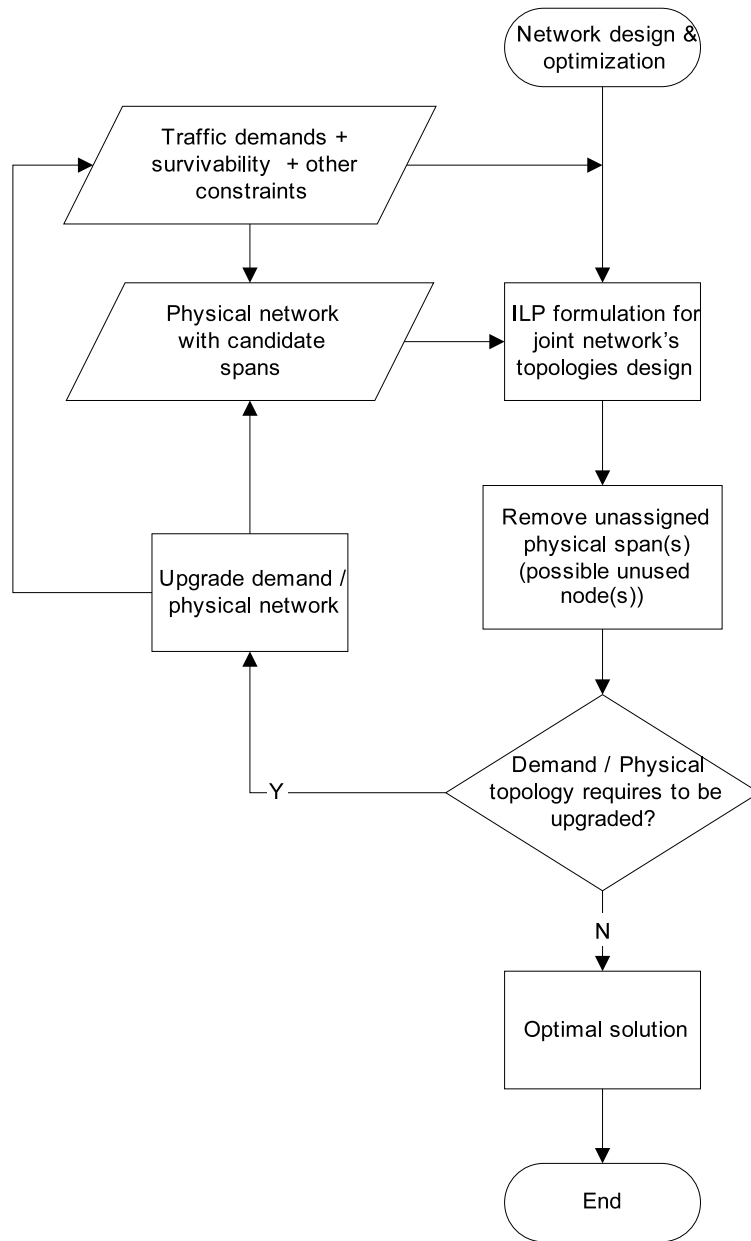
Figure 7.2: Typical network design flow

solution and will be removed from the physical network.

The final solution is the protected physical network with all the capacities allocated for routing demands with various QoP service classes.

Model 12 *ILP model*

Set

M: *Set of restoration methods, indexed by m.*

E: *Set of network spans, indexed by i or j.*

V: *Set of network nodes, indexed by v.*

D: *Set of demand relation, indexed by r.*

P_r*:*   *Set of candidate path pairs for the relation r, indexed by p.*

E′:   *Set of sharable span of the backup paths, indexed by i or j. $E' \subseteq E$.*

C: *Set of network fundamental cycles, indexed by c.*

S: *Set of visible straddling links, indexed by s.*

H: *Set of hidden straddling links, indexed by h.*

G_r*:*   *Set of shortest path candidates between two end nodes of relation r, indexed by g.*

Λ: *Set of non-sharable straddling links.*

Constants

c_j*:*   *cost of a unit capacity of span j.*

F_j*:*   *cost for establishment of physical span j.*

        (Note that, F_j have negative value if their present the profits given by the establishment of physical span j).

K: *is an arbitrary large positive constant.*

        This value must larger than any expected accumulation of capacity required on any span j.

$h^{m,r}$:   *volume of demand for relation r, method m.*

$\tau_{g,j}^{m,r}$ $= 1$ *if span j is on path g of relation r; 0 otherwise.*

$\theta_{p,i}^{r}$: $= 1$ *if the primary route of the pth eligible path pair for demand relation r*

          cross span i; 0 otherwise.

$\phi_{p,j}^{r}$ $= 1$ *if the backup route of the pth eligible path pair for relation r*

          cross span j; 0 otherwise.

$\delta_{c,i}$ $= 1$ *if span i is on cycle c; 0 otherwise.*

$\xi_{\alpha,s}^{j}$ $= 1$ *if $\alpha = \{x,y | x \cap y = j, x,y \in C\}$;*

          0 otherwise. $j \in E, \alpha \subset C, s \in S$,

          s is the sth straddling link formed by cycles $\{x,y\}$.

$\pi_{\alpha,h}^{j}$ $= 1$ *if the set of cycles α do not cross span j,*

          0 otherwise. $\alpha \subseteq C, V(j) \in V(\alpha)$.

h: *is the hth hidden straddling link formed by the set of cycles α.*

χ_{v} $= 1$ *if the p-cycle passes through node v;*

          0 otherwise.

γ_{j}:   *max capacity provided by span j.*

$\vartheta_{h,j}$ $= 2$, *is the number of useful paths provided*

          by the hidden straddling link h to restore

          span j.

$\varphi_{v,s} =$ $= 1$ *if the visible straddling s passes through*

          node i; 0 otherwise. $v \in V, s \in S$.

$\omega_{v,j} =$ $= 1$ *if the spare capacity used span j passing*

          through node v; 0 otherwise. $v \in V, j \in E$.

ω_{i} $= 1$ *if the physical span i is considered as a*

          physical candidate; 0 otherwise.

Variables

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$\rho_p^{r,m}$:   *number of unit capacity copies of the pth*

             eligible path to serve demand relation r.

w_j: *working capacity on span j.*

b_j: *spare capacity on span j.*

w_j^m: *working capacity on span j for method m.*

b_j^m: *spare capacity on span j for method m.*

n_c: *number of unit capacity copies of the cycle c.*

$m_{h,c}$:   *number of unit capacity copies of the hidden*

             straddling link h using cycle c.

$u_{s,c}$:   *number of unit capacity copies of the visible*

             straddling link s using cycle c.

$d^{m,r}$:   *number of demand units for relation r,*

             method m.

- **ILP model**

  - *Objective:*

$$\text{minimise} \sum_{j \in E} c_j(w_j + b_j) - \sum_{s \in S} \sum_{j \in E} 2\xi_{c,s}^j u_s + \sum_{j \in E} F_j \omega_j \qquad (7.2)$$

  - *Subject to constraints:*

    1. *For every span, the total working capacity must be equal to the sum of working capacities for all protection methods:*

$$\sum_{m \in M} w_i^m = w_i \; , \forall i \in E \qquad (7.3)$$

    2. *For every span, the total spare capacity must be equal to the sum of spare capacities for all protection methods:*

$$\sum_{m \in M} b_j^m - w_j^1 = b_j \; , \forall j \in E \qquad (7.4)$$

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3. *The total demand must be equal to the sum of all demand relations assigned to all protection methods:*

$$\sum_{m \in M} d^{m,r} = \sum_{m \in M} h^{m,r} \qquad (7.5)$$

4. *Working capacity assigned for APS scheme:*

$$\sum_{r \in D} \sum_{p \in P_r} d^{2,r} \theta_{p,i}^r \rho_p^{r,2} = w_i^2 \ , \ \ \forall i \in E \qquad (7.6)$$

5. *Spare capacity required for APS scheme:*

$$\sum_{r \in D} \sum_{p \in P_r} d^{2,r} \phi_{p,j}^r \rho_p^{r,2} = b_j^2 \ , \ \ \forall j \in E \qquad (7.7)$$

6. *Working capacity assigned for SBPP scheme:*

$$\sum_{r \in D} \sum_{p \in P_r} d^{3,r} \theta_{p,i}^r \rho_p^{r,3} = w_i^3 \ , \ \ \forall i \in E \qquad (7.8)$$

7. *Spare capacity required for SBPP scheme:*

$$\sum_{r \in D} \sum_{p \in P_r} \theta_{p,i}^r \phi_{p,j}^r \rho_p^{r,3} d^{3,r} \leq b_j^3 \ , \forall i,j \in E | i \neq j \qquad (7.9)$$

8. *One backup route assigned to each working demand of SBPP:*

$$\sum_{p \in P_r} \rho_p^{r,3} = 1 \ , \ \ \forall d \in D \qquad (7.10)$$

9. *Capacity of each span must be sufficient to support all cycles that cross it:*

$$\sum_{c \in \mathbf{C}} \delta_{c,j} n_c = b_j^4, \qquad\qquad \forall j \in E \qquad (7.11)$$

10. *Number of cycles must be sufficient to support the chosen straddling links.*

$$\sum_{s \in \mathbf{S}} \xi_{\alpha,s}^j u_{s,c} - n_c \leq 0, \qquad (7.12)$$

$$\sum_{h \in \mathbf{H}} \pi_{\alpha,h}^j m_{h,c} - n_c \leq 0, \qquad (7.13)$$

$$\forall c \in \alpha; \alpha \subset C; j \in E$$

11. *Working capacity allocated to each span must be protected by p-cycles:*

$$\sum_{g \in \mathbf{G}} \sum_{r \in \mathbf{D}} \rho_g^{r,4} \tau_{g,j}^{4,r} = w_j^4, \quad \forall j \in E \tag{7.14}$$

12. *Spare capacity allocated to each span must be sufficient to support 100% restorability:*

$$\sum_{h \in H} \vartheta_{h,j} m_{h,c} + b_j^4 \geq w_j^4, \qquad \forall j \in E; c \in C \tag{7.15}$$

13. *The total number of useful capacity units provided by the sth visible straddling link at span j must be less than or equal to the total number of spare capacities of that span formed by the corresponding cycles.*

$$\sum_{s \in \mathbf{S}} 2\xi_{\alpha,s}^j u_{s,c} - b_j^4 \leq 0, \qquad \forall j \in E; c \in \alpha; \alpha \subset C \tag{7.16}$$

14. *The constraint for non-shareable straddling links. This is for preventing the selection of node-encircling p-cycle(s). If node protection is desired, this constraint will be removed from the model. If it exists two straddling links have the same fundamental cycle c, but cannot be shared. The total number of cycles c will be equal to the total number of those selected straddling links.*

$$\left(\sum_{s \in \mathbf{S}} \xi_{\alpha,s}^i u_{s,c} + \sum_{h \in H} \pi_{\alpha,h}^j m_{h,c} \right) - n_c \leq 0,$$
$$\forall \{\xi_{\alpha,s}^j \pi_{\alpha,h}^j\} \subseteq \Lambda;$$
$$c \in \alpha; \alpha \subset C; i, j \in E, i \neq j \tag{7.17}$$

15. *Path selection constraint: each demand connection requires to be assigned to one candidate path.*

$$\sum_{p \in \mathbf{P}} \rho_p^{r,m} + \sum_{g \in \mathbf{G}} \rho_g^{r,m} = h^{m,r}, \quad \forall r \in D \tag{7.18}$$

16. *Total capacity assigned for each span (working plus spare capacity) must be less than or equal to the maximum capacity that can be provided by*

the corresponding span.

$$\sum_{s \in \mathbf{S}} -2\xi_{\alpha,c}^j u_{s,c} + b_j + w_j \le \gamma_j,$$

$$\forall j \in E; c \in \alpha; \alpha \subset C \qquad (7.19)$$

17. *Number of selected visible straddling span s through node i must be less than or equal to the number of p-cycles passing through it.*

$$\sum_{s \in S} \varphi_{v,s} u_{s,c} - \sum_{s \in S} \chi_v \le 0,$$

$$\forall v \in \mathbf{V}; c \in C; \qquad (7.20)$$

18. *Total number of links through a node v must equal to the total of useful paths provided by the visible straddling links plus twice the number of p-cycles through that node. Therefore, at every p-cycle node, there are always two spans that are not straddling spans.*

$$\sum_{\forall v \in \mathbf{V}} (2\varphi_{v,s} u_{s,c} + 2\chi^v - b_j^4 \omega_{v,j}) = 0,$$

$$s \in S; j \in E; c \in C \qquad (7.21)$$

19. *Working capacity assigned for pre-emptible demand.*

$$\sum_{r \in D} \sum_{p \in P_r} d^{1,r} \theta_{p,i}^r \rho_p^{r,1} = w_i^1 , \quad \forall i \in E \qquad (7.22)$$

20. *Physical span e must be selected if either a primary path or backup path is crossing it:*

$$\sum_{\forall i \in E} (w_i + b_i - K\omega_i) \le 0 \qquad (7.23)$$

The objective function of the above model Eqn. 7.2 has a constant number 2 in its second term. This is because, as in the model, when merging 2 cycles to create a straddling link

(the visible straddling link), the total number of links is equal to the sum of the number of links on these cycles. As there is no working capacity required for the straddling link, thus 2 is subtracted from the total for each chosen straddling link.

Note that in this model, there is no consideration of the self-selected method protection as in [20]. This is because in the self-selected model, the connections will be automatically assigned differently with each protection method. However, this may not be practical as each connection's demand can randomly request any method of protections, and is therefore uncontrollable by the network manager. Reader can refer to [20] for more information about the self-selected protection method.

7.3   Simulation & Discussion

This section presents the test and analytical results of the proposed model over the following networks: NFSNet-N14-S21, NFSNet-N14-S18, N9S14, N9S16, N9S17. The NFSNet-N14-S18 network is a variation of the NFSNet-N14-S21 network. The N9S16, N9S17 networks are variations of the N9S14 network. Firstly, it is necessary to compare the capacity utilisation of networks with mixed protection schemes and their capacity efficiency when integrated with multiple QoP service classes. Secondly, the effects of the proposed model over the physical networks, when used as a joint optimisation model to design new or upgrade existing networks will be shown.

The use of pre-emptible connections in multiple QoS always gives better capacity efficiency compared to the network without multiple QoS. Figure. 7.4 shows the test results for the routing of demands at various ratios of service classes over the NFSNet-N14-S18 and the NFSNet-N14-S21 networks. The demand ratio in each test case is presented as the percentage of classes and requires protection techniques. The mix of service classes and protection schemes are denoted by (a:b:c:d), where a, b, c and d are the percentages of demand relations: pre-emptible (economic class), dedicated protection (gold class), SBPP (gold class) and p-cycles (gold class) respectively.   In Figure. 7.4, there are two
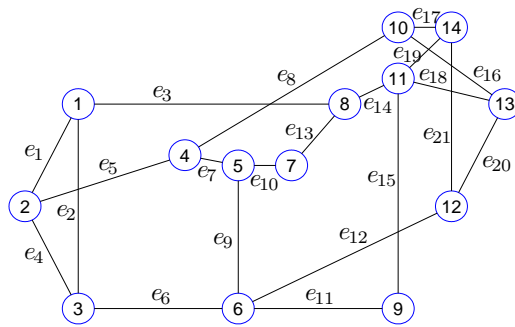
(a) NFSNET network.
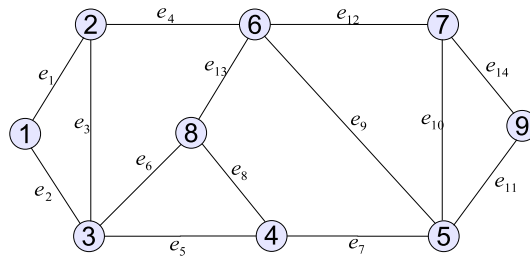
(b) An arbitrary network.

Figure 7.3: NFSNET and an arbitrary N9S14 network.

Capacity effects on various demand ratios on:
NSFNET_N14_S18 and NSFNET_N14_S21
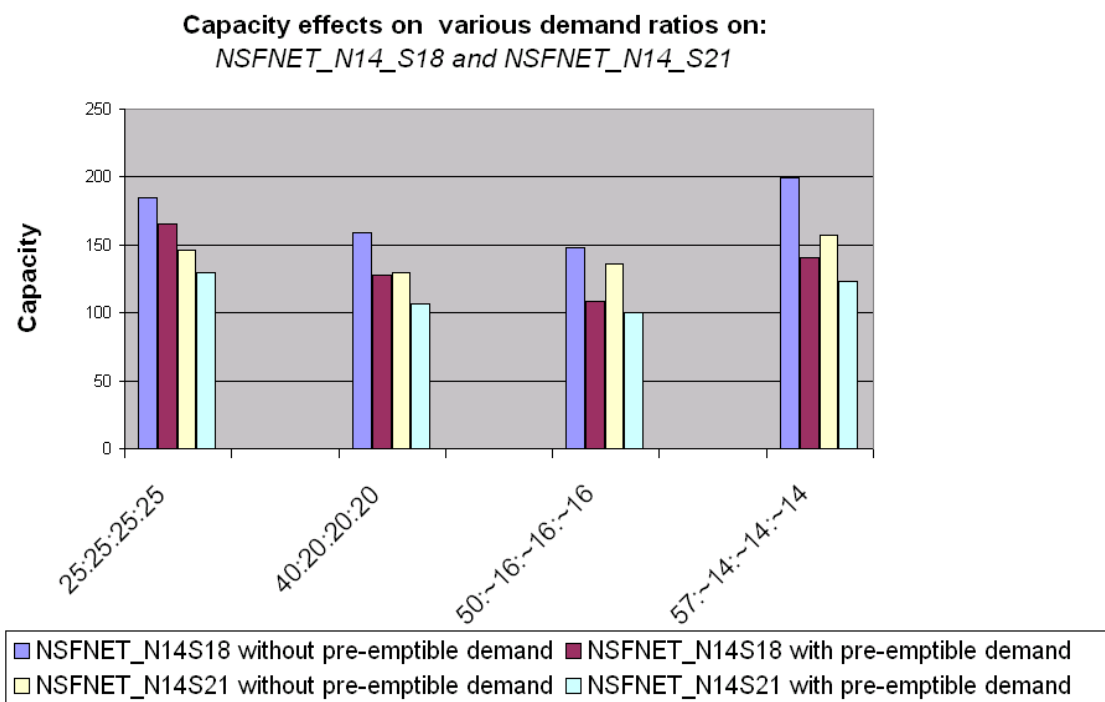
Figure 7.4: Effects of capacity utilisation at various demand ratios on NFSNET-N14-S18 and NFSNET-N14-S21

Table 7.1: Simulated Results

Demand mixed	Description	N9S14	Networks N9S16	N9S17
25:25:25:25	Number of physical link required	14/14 (55)	13/16 (51)	13/17 (46)
	Total capacity allocation	55	51	46
	Links used	1,2,3,4,5,6,7,8,9,10, 11,12,13,14	1,3,4,5,6,7,8,9,10, 11,12,13,14,15,16	1,2,3,4,5,6,7,8,9,10, 11,13,14,15,16,17
40:20:20:20	Number of physical link required	12/14 (48)	12/16 (44)	12/17 (42)
	Total capacity allocation	48	44	42
	Links used	1,3,4,5,6,7,8,9,10, 11,12,14	1,4,5,6,7,8,9,10, 11,12,13,14,	2,3,4,6,7,8,9,10, 11,13,14,16
50:16:16:16	Number of physical link required	13/14 (53)	13/16 (50)	15/17 (44)
	Total capacity allocation	53	50	44
	Links used	1,2,3,4,6,7,8,9,10, 11,12,13,14	2,3,4,5,7,8,9,10, 11,12,13,14,15	1,2,3,4,5,7,8,9,10, 11,12,13,14,15,16,
57:14:14:14	Number of physical link required	13/14 (61)	13/16 (59)	14/17 (56)
	Total capacity allocation	61	59	56
	Links used	1,2,3,4,5,6,7,9,10, 11,12,13,14	1,2,4,5,6,7,8,10, 11,12,14,15,16	1,2,3,4,6,7,8,9, 11,12,13,14,15,17
50:11:16:22	Number of physical link required	13/14 (91)	15/16 (85)	15/17 (79)
	Total capacity allocation	91	85	79
	Links used	1,2,3,4,5,6,7,8,9,10, 11,12,13,	1,2,3,4,5,6,7,8,9,10, 11,12,13,14,15	1,2,3,4,5,6,7,8,9,10, 11,12,14,15,16,
57:14:19:10	Number of physical link required	14/14 (99)	15/16 (95)	16/17 (88)
	Total capacity allocation	99	95	88
	Links used	1,2,3,4,5,6,7,8,9,10, 11,12,13,14	1,2,4,5,6,7,8,9,10, 11,12,13,14,15,16	1,2,3,4,5,6,7,8,9,10, 11,12,13,14,15,16
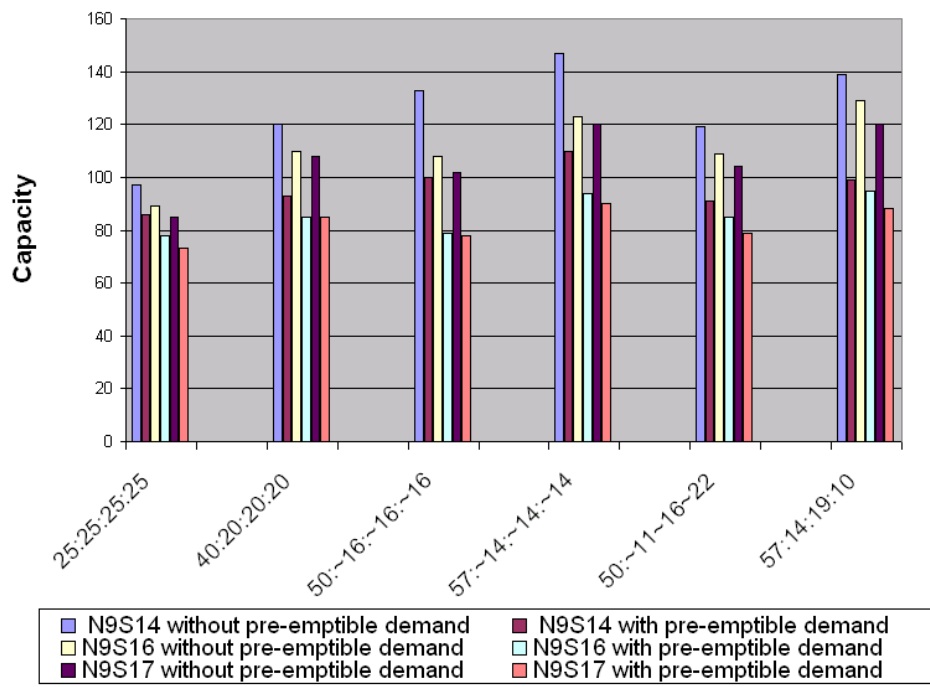
Figure 7.5: Effects of capacity utilisation on different network sizes at various demand ratios

test scenarios: without pre-emptible and with pre-emptible connections. In the first scenario, without the pre-emptible connection, the total capacity usage can be increased from 10% to 20% compared to the second scenario which considers pre-emptible demands in the optimisation. Although, the results vary with different physical networks and different sets of demands, there is always capacity saving by considering the pre-emptible connections in the model. Figure. 7.5 shows the test results for routing of various demands over different arbitrary networks.
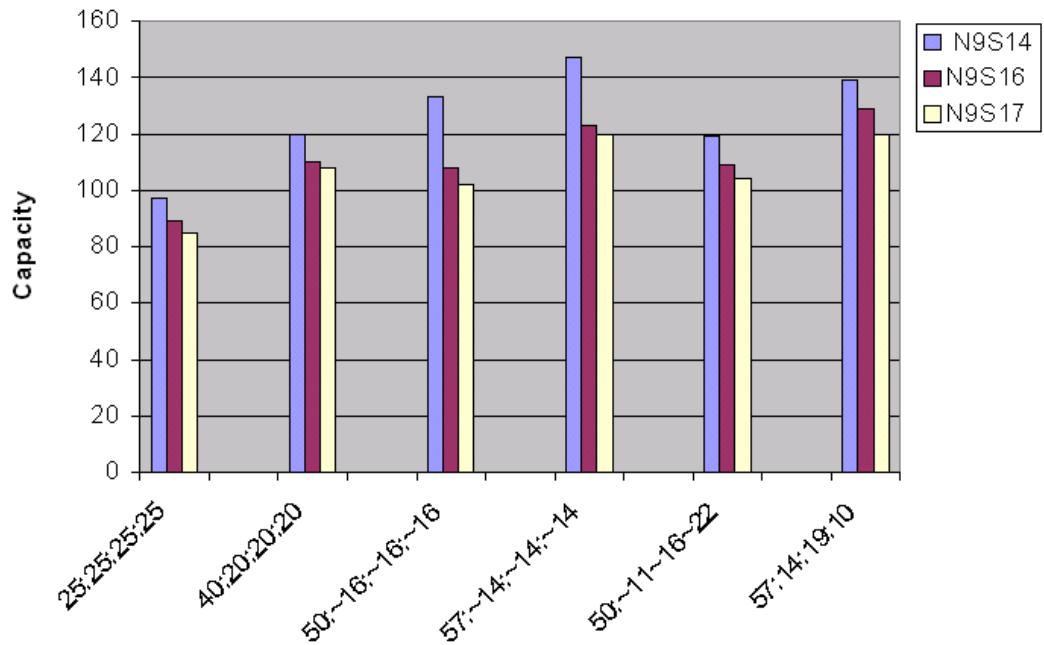
Figure 7.6: Capacity effects on different network size

The network topologies are also an important factor that affect the results, as shown in Figure. 7.4 when the two networks are assigned the same demand in each scenario. The total capacities allocated on the NFSNet-N14-S21 are always less than when assigned over NFSNet-N14-S18 networks. Similar results can be seen on Figure. 7.5 and Figure. 7.6 and also in Table 7.1. This is because, for larger networks, there are more possible routes for each connection than can be chosen by the model. Thus in most cases, for the same

demand, it is possible to have better capacity efficiency in larger networks which have a higher number of physical links.

The joint design of physical and logical routing in the same model gives better resource utilisation than when designed them separately. This is because, in principle, there would be a way of routing demands over certain sets of physical spans that would minimise design costs.

For a given set of demands, the design or upgrade of an existing network is done by assigning the unit cost for each corresponding physical link in the objective function (Eq. 1). For network spans, the value of ω_i in the last constraint (Eq. 20) must be equal to 1 if the corresponding span is to be selected by the model or it must equal to 0 for all other network spans. Table 7.1 shows the details of selected physical links chosen by the model.

7.4 Summary

This study is an advanced step in network design and optimisation, and introduce further research on network design with multiple QoP service classes and the mixed protection schemes conducted by W.D. Grover *etal*. in [47], [20]. The proposed model for network design and optimisation with multiple QoP service classes is integrated with mixed protection techniques in order to improve the resource efficiency by satisfying the demand of recovery times after failures have occurred. The proposed model shows the advantages of using mixed protection schemes and is able to serve various classes of demand while optimising resources. In addition, this study provides an insight into the relationship between the physical and logical topologies, and forms a basic tool for studying "joint topologies" design and optimisation using mixed protection schemes and multiple QoP classes.

Chapter 8

Case study: Optical Network Design

This chapter presents a case study involving the analysis and design of a metropolitan optical network. The design results compare the resource usage of ring and mesh networks. The mesh network was designed using Model 12 - introduced in Chapter 7 - and the SONET/SDH ring network follows on from the work found in [5]. This case study was adopted from [5], which was designed mainly for the multi-service metro optical SONET/SDH network of the downtown metro area of a large U.S. city. In this chapter, the focus is on the capacity planning and physical topology design of an optical network; factors such as network operating costs and return on investment are excluded from this study.

8.1   Optical Network Design Strategies

The design process of an optical network is often based on some common key business considerations. According to [5], some of these key considerations that influence the network design are as follows:

- *Low capital expense* (CAPEX): Refers to the investment on network resources and infrastructure. The cost of a network is proportional to its complexity.

- *Low operating cost* (OPEX): Refers to the expense of network management and other operational costs.

- *Minimizing the cost of ownership* (TCO): This can be seen as the lifespan of the network before any major upgrade takes place, and is the sum of CAPEX and OPEX.

- *Quick return from investment* (ROI).

Network design aims to reduce the TCO. This can be done in two ways, these could be by either minimising the CAPEX (disregarding both the consideration of minimizing the network operation and management cost) or optimising of CAPEX and OPEX. In this chapter, we focus on minimizing the CAPEX model over both ring and mesh networks. Optical network design requires detailed analysis in order to achieve end-to-end solutions. For example, the following parameters have a strong influence on the final design results [5], and must be adhered to by the network designer:

- Customer service: This parameter covers the services that the network can provide to the consumer, such as transmission of voice, video and data over the network. This has a significant influence on the technology selected to be used in the implementation of the network.

- Capacity planning: Provides for the network capacity requirement based on the demographic and population models of the area; the area's customers could range from medium to large business or small business to residential users. The required bandwidth and port density are subsequently calculated from the classification of predicted network traffic and applications for specific services received from customers.

- Quality of service classes: Each service level represents a contract that exists between a network provider and its customers. The service classes can mean the latent

percentage available. These factors in turn are involved in the consideration of the network elements and redundant of network capacity.

- Fiber plan: One of the main elements of capital expenditure. The type and number of fibers in each span of the network define the type and number of ports required. Fiber plans are also dependent on the method of network routing and protection mechanisms.

- Technology selection: there are various technologies available such as: multi-service SONET/SDH, ATM, Gigabit Ethernet and pure IP services. The selected technology is considered on the basis of the core services available and customer service model required.

8.2 Design of a Multi-Service Metro Optical Network: a Case Study

The aim of the case study included in this thesis is to explore the design process of an optical network for a metropolitan area with the following requirements:

"A service provider has just been granted right of way to and the irrevocable right to use (IRU) of 30 miles (48km) of two-strand fiber in the downtown metropolitan area of Washington, D.C.. It is the intention of this new, competitive local exchange carrier to offer data, voice, and broadband video services to the market. The network operator (service provider) has access to adequate technical, financial, and human resources.

The service provider has performed a user survey and has determined that there is a potential market for up to 10,000 business customers in the downtown area. Of these customers, 8,000 can be classified as small businesses with up to 10 employees, and 1,800 of these customers can be classified as medium-size business with up to 100 employees. There is also potential for up to 200 large business customers having up to 500 employees on average. Customer applications include voice, VPN and pure Internet access.

There are 300 customers (the 200 large business and at least 100 medium-size business)
that need connectivity with their out-of-state branches and headquarters. There are also
about 5,000 potential residential and small home office customers that need voice and
broadband Internet access. There are 250 buildings that need to be lit up by the service
provider to provide service to all potential customers. The service provider intends to
provide 99.99% availability with highly competitive pricing to capture a market share.

The service provider has performed a site survey of the downtown area and has de-
cided on several fiber routing options with diverse ingress from various buildings. The
service provider intends to light up the first seven buildings in a pilot run. Each of these
seven buildings are multi-tenant units (MTU), housing up to 35 small business and 5
medium-size business in each building. The pilot run will provide voice and Internet ac-
cess services to the seven buildings" [5].

8.3   Case Study Solutions

Optical network design covers a variety of tasks such as: capacity planning, cable and
delay analysis, technology analysis, and logical and physical topology design. Table 8.1
provides a summary of customer requirements. In practice, requirement documents must
be established data (not predictions) that detail customer requirements.

8.3.1   Capacity Planning for the Multi-Service SONET/SDH

Capacity planning for the Multi-service SONET/SDH network requires an estimation
of bandwidth to be used by the network. It is assumed that 64kbps per user for non-
normalized voice bandwidth, and 128kbps of non-normalized data bandwidth. The nor-
malized bandwidth is obtained using a ratio of 1:10 oversubscription. Dupont Circle is
chosen to be the service provider data center and network operation center (Figure. 8.1).
The site was chosen because the location of the Dupont Circle node can be a matching

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(a)

(b)

Figure 8.1: Fiber routing plan

Table 8.1: Network requirements (source: Optical network design and implementation [5]

Unit	Number	Factor	User count
Residential	5000	1	5000
Small business	8000	10	80000
Medium business	1800	100	180000
Large business	200	500	100000

Requirement	Specification
Building	250
Network availability	99.999%
End-to end latency	25ms
QoS	4 classes of protection service
Services	Voice, VPN, and IP internet access

node for the core ring, which includes the Adams Morgan, California Street, and Florida Avenue buildings. The remaining nodes form an access ring covering 34th Street, 30th Street, and the 35th Street. Based on the survey, Table 8.5 shows the total normalized bandwidth required for the 7 buildings. In the worst case scenario, if the symmetrical link is taken into account, the bidirectional traffic matrix plan must be constructed as presented in Table 8.3. The bandwidth calculation is as follows:

Firstly, assuming the traffic flow is unidirectional, in a clockwise direction. For the ring **Dupont Circle - 24th St - 30th st - 35th St**, the bandwidth between 30th St - 35th St is 16.3Mbps added from 24th St node with 16.3Mbps from the 30th St node, giving a total of 32.6Mbps.

Secondly, with the bidirectional case, the bandwidth on the span 30th St - 35th St is equal 32.6Mbps +16.3Mbps (added by node 35th St), which rises to 48.9Mps. The same technique is used to calculate other network's spans.

Table 8.3 shows the bidirectional traffic matrix of the network based on the survey data of just 7 out of 300 buildings. It is not required to have information about the distribution for the remaining buildings. Therefore, it is assumed that the core ring can have multiple nodes, and each of them is a matching node that interfaces with the collector

Table 8.2: Normalized Bandwidth Calculation

Location	Small business	Medium business	Small business voice bandwidth	Small business data bandwidth	Medium business voice bandwidth	Medium business data bandwidth	Bandwidth requirement
35th St	350	500	22.4Mbps	32Mbps	44.8Mbps	64Mbps	163.2Mbps
30th St	350	500	22.4Mbps	32Mbps	44.8Mbps	64Mbps	163.2Mbps
24th St	350	500	22.4Mbps	32Mbps	44.8Mbps	64Mbps	163.2Mbps
Dupont Circle St	350	500	22.4Mbps	32Mbps	44.8Mbps	64Mbps	163.2Mbps
California St	350	500	22.4Mbps	32Mbps	44.8Mbps	64Mbps	163.2Mbps
Florida Avenue	350	500	22.4Mbps	32Mbps	44.8Mbps	64Mbps	163.2Mbps
Adam Morgan	350	500	22.4Mbps	32Mbps	44.8Mbps	64Mbps	163.2Mbps
Total							**1142Mbps**
Total normalized bandwidth (1:10) oversubscription							**1142Mbps**

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Table 8.3: Bidirectional Traffic Matrix

Destination	35th St	30th St	24th St	Dupont Circle St	California St	Florida Avenue	Adam Morgan
35th St		48.9Mbps					
30th St			48.9Mbps				
24th St				48.9Mbps			
Dupont Circle St	48.9Mbps				48.9Mbps		
California St				48.9Mbps		48.9Mbps	
Florida Avenue							48.9Mbps
Adam Morgan					48.9Mbps		

rings having an even bandwidth distribution. The upgrade bidirectional traffic matrix is shown in Table 8.4.

The total normalized bandwidth is the sum of the normalized voice and data bandwidths of each individual in the entire network. The details of these bandwidths are shown in Table 8.5. In addition, an estimate of the network growth of 15% and 25% per annum is presented in Table 8.6.

The traffic matrix shows that for the access ring, the bandwidth required at each span is 48.9Mbps, and for the core ring, each span requies an bandwidth of 7.008Gbps. Thus the OC-3/STM-1 (155.52Mbps) and the OC-192/STM-64 (9.953Gbps) could be used for the access and core rings respectively.

8.3.2   Fiber Plant

Fiber plant needs to establish the optical transmitter power and the receiver sensitivity for a selected fiber. The fiber plant consists of two components, they are the inside and outside plants. Described in [5], inside the fiber cable there are two fusion splice points that form the connection with either the ingress or egress conduits of the building. The termination of a fiber that enters or exits the building is known as the 'fiber patch panel.' This is attached to the Optical-electronics-optical (OEO) equipment. The cable extends from the building exit conduit on two sides of the building, for example, the East and West run conduits. There are also two splice points that connect the building to the East and West runs. From an end-to-end between two active OENs, there are eight splice points, two are within the inside plant, and two splice points on the outside plant at each side of the premise.

The fiber loss estimation is shown in Table 8.7 was based on the operation of the system over 5 km SMF cable between buildings, and assumes that there are two patch panels in the path and eight fusion splices.

Table 8.4: Upgrade Bidirectional Traffic matrix

Destination	35th St	30th St	24th St	Dupont Circle St	California St	Florida Avenue	Adam Morgan
35th St		48.9Mbps					
30th St			48.9Mbps				
24th St				48.9Mbps			
Dupont Circle St	7.008Gbps						
California St				7.008Gbps		7.008Gbps	
Florida Avenue					7.008Gbps		7.008Gbps
Adam Morgan					7.008Gbps		

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Table 8.5: Normalized Bandwidth Calculation

Location	User count	Voice Bandwidth per user	Voice bandwidth	Normalized voice bandwidth(1:10)
Residential	5000	64kbps	320Mbps	32Mbps
Small business	80000	64kbs	5.12Gbps	512Mbps
Medium business	180000	64kbps	11.52Gbps	1.152Gbps
Large business	100000	64kbps	6.4Gbps	640Mbps

Location	User count	Internet bandwidth per user	Internet bandwidth	Normalized internet bandwidth
Residential	5000	128kbps	640Mbps	64Mbps
Small business	80000	128kbps	10.24Gbps	1.024Gbps
Medium business	180000	128kbps	23.04Gbps	2.304Gbps
Large business	100000	128kbps	12.8Gbps	1.28Gbps
Total Normalized bandwidth				**7.008Gbps**

Table 8.6: Total Normalized Bandwidth

Compounded grow	15 %	25 %
Year 1	8.509Gbps	8.760Gbps
Year 2	9.268Gbps	10.950Gbps
Year 3	10.658Gbps	13.687Gbps
Year 4	12.257Gbps	17.10Gbps

Table 8.7: Total Normalized Bandwidth (source: Optical network design and implementation [5])

Component	dB Loss
SMF 1550 nm cable (5 km * 0.25dB/km)	1.25
FC connectors (4 * 0.5 dB/connector)	2.00
Fusion splices (8 * 0.1 dB/splice)	0.80
Patch panels (2 * 2 dB/panel)	4.00
Optical safety margin	3.00
Total Span Loss	11.05

8.3.3 Delay Analysis

Network delays are generally caused by three specific issues within a network service: serialization delays, propagation delays and network element delays. Serialization delay is mainly affected by the frame sizes and transmission rates provided, whereas propagation delay occurs due to the finite speed of light and the laws of physics. The nominal velocity of light (NVP) that propagates is defined as the ratio of speed of light (C=300,000 km/sec) and the refractive index of the medium. The refractive index of SMF is 1.5, thus giving the NVP $= (300,000km/sec)/1.5 = 200,000km/sec)$, and the propagation delay of the SMF in one millisecond per kilometer is 0.005. Finally, network element delay refers to the time taken for the signal to enter a network element and exit to its destination and is equal to 0.45 ms specified by ITU-T [5].

Thus, the normal total delay is:
Total delay = Serialization delay + Propagation delay + NE processing delay. (Where NE processing delay refers to network element delays)

In ring networks,the network designer aims to limit the number of end-to-end rings to three. Thus the traffic demand can be routed from a collector ring node and terminated at another collector node. For a maximum of 16 nodes per ring, the signal would traverse a maximum distance of 8 * 3 = 24 nodes. It is assumed that the signal would not traverse more than 15 km over a single ring (each ring has a maximum of 30 km circumference). Therefore, the maximum distance the signal can reach is 15 km * 3 = 45km. Refer to [5], the slowest speed the network service can provide to the customers is via the DS1 interface (Appendix C) with a maximum transfer unit of 1500 bytes/frame. The requirement here is that the network delay must satisfy the following equation:

Total delay ¡ serialization delay + Propagation delay + NE processing delay
or

Total delay ¡ [(1500 * 8 bit/byte)/Bandwidth of lowest speed service interface)] + [Fiber length (km) * 0.005 km/s] +[Total number of NEs on the path * 0.45 ms]

Substituting the values given above into the equation: Total delay ¡ [(1500 * 8)/1,536,000] + [45 * 0.005] + [24 * 0.45]= 18.825 ms

The above total delay satisfies the 25 ms delay of the design specification.

8.3.4 Ring Network Design

The network was designed according to the requirements determined in previous sections and the ONS 15454 multi-service provision platform was selected for implementation. The network consists of a 2-ring topology, and has been designed according to the traffic matrix given in Table 8.4 with the OC-192/STM-64 being implemented for the core ring, and the OC-3/STM-1 being used for the collector ring. Figure. 8.2 shows the logical design of the Multiservice metro optical SONET/SDH network.

The network protection mechanism can be chosen from either two-fiber or four-fiber BLSR/MSSPRING. In the case of the two-fiber option, the BLSR/MSSPRING would provide (OC-N/2)∗(Number of spans) of bandwidth for full optimisation for add and drop traffic at the adjacent nodes of the network. For the core ring, the required bandwidth is 4.976Gbps∗4 spans = 19.9Gbps, and for the tributary ring, the required bandwidth is 77.6Mbps∗4 spans = 310.4Mbps.

Should the four-fiber option be selected, the number of bandwidths would be double those in the two-fiber case. Therefore, four-fiber protection systems are used for rings spanning large geographic areas, or where critical traffic being carried. Other rings can still be implemented with the two-fiber BLSR/MS-SPRING. For example, in this case, the tributary ring would use two-fiber BLSR/MS-SPRING = 310.4Mbps and the core ring uses = 39.8Gbps.

The deployment of the pilot tributary ring, however, cannot represent the full solution for the entire network. Indeed, this is currently a sample test case of an attached access ring. The required network should consist of 2-ring topology with two OC-192/STM-64. The required bandwidth is be = 39.8Gbps for the case of two-fiber BLSR/MSSPRING,

and $= 79.6$Gbps for the four-fiber protection systems.

The net bandwidth required for the two-fiber BLSR/MSSPRING and four-fiber BLSR/MSSPRING are $= 39.8$G$bps + 39.8$G$bps = 79.6$Gbps and $= 79.6$G$bps + 39.8$G$bps = 119.4$Gbps respectively Figure. 8.2.
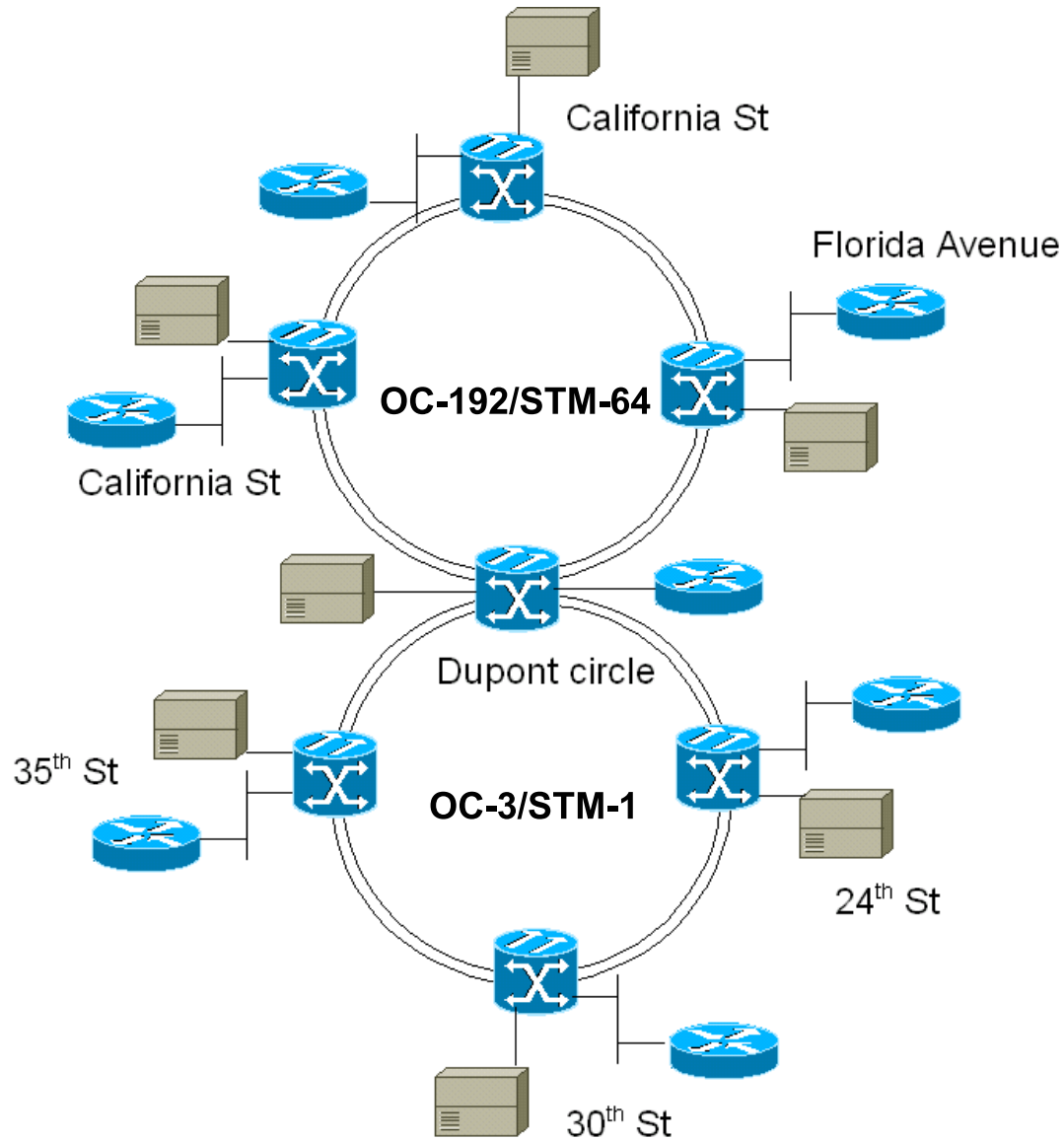
Figure 8.2: Logical design of Multiservice SONET/SDH network.eps

8.3.5 Mesh Network Design to Support Multiple Quality of Service classes

Logical Design

The traffic matrix in mesh topology requires more details in the consideration, calculation and design compared to that of ring topology. It does not need to involve the traffic at the intermediate nodes. Therefore, the network demands are equal to the total number of connections between the source and destination nodes. It is assumed that each node distributes traffic evenly to all other remaining network nodes and has the same bandwidth requirement. From the given case study, the optimisation of a possible network was run with an average nodal degree of $\widetilde{d} \approx 3.7$ as shown in Figure. 8.3. It should be noted that, the higher the network's nodal degree - combined with a larger number of path candidates - could give a better result, but may have significantly larger running time.

The network connections are calculated as follows: the total user count given is about 365,000, which gives an average of 53,000 users per node ($365,000(usercount) \div 7(nodes) \approx 53,000(user/node)$) (see Table 8.5 for more details). Each user is assigned an equivalent bandwidth of 19.397kps.

The demand distribution from each source node to every destination node in the network is approximately $53,000 \div 6 \approx 8,835$. In addition, these connections are further divided into smaller portions according to the service classes required, eg, in this test case, the demand is divided as follows: 40% for Economic class, 20% for Dedicated protection, 20% for SBPP, and 20% for p-cycle protection Table 8.8. Thus, at each source node, there are about $21,000$ connections using economy class, and for dedicated SBPP p-cycles, each technique has $11,000$ connections flowing into various destination nodes. Figure. 8.4 shows the bidirectional flow of traffic on the network under consideration.

The above network's data is formulated into the ILP using Model 12 introduced in Chapter 7. From the routing results, two physical spans have been removed from the original network Figure. 8.3, and eleven spans are used for carrying both working and the
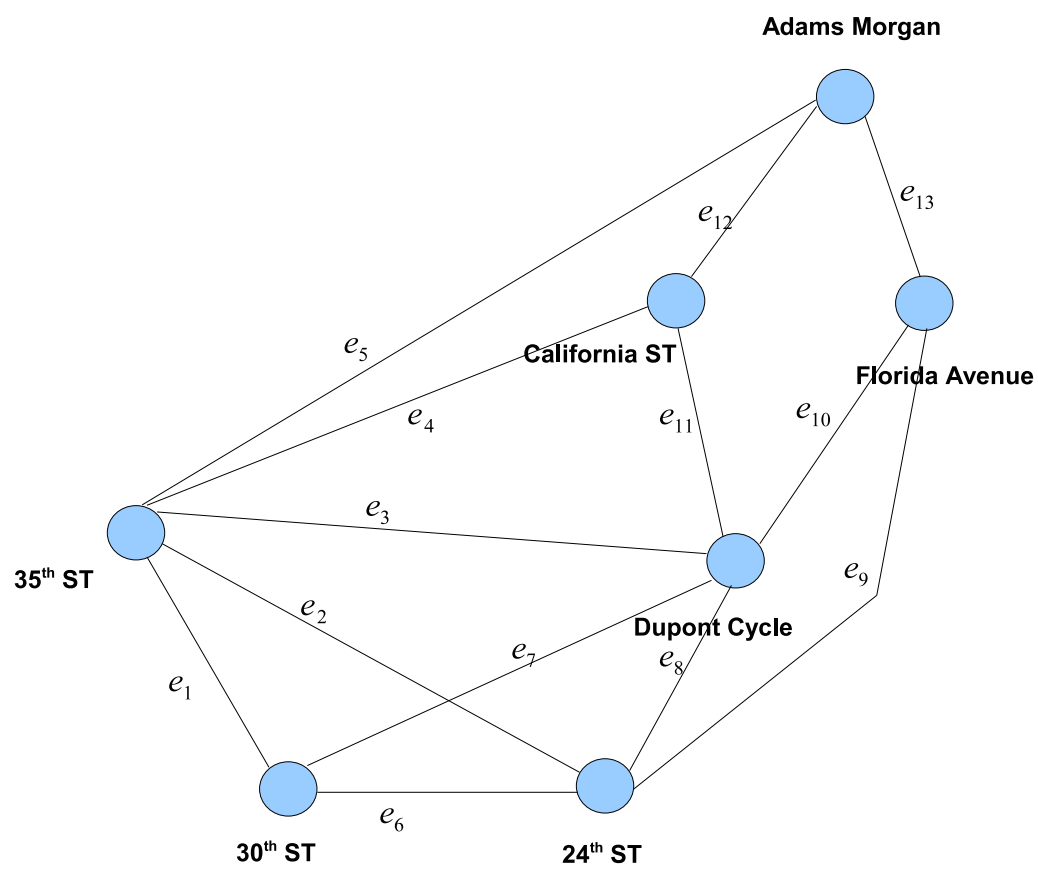
Figure 8.3: Network Under optimisation
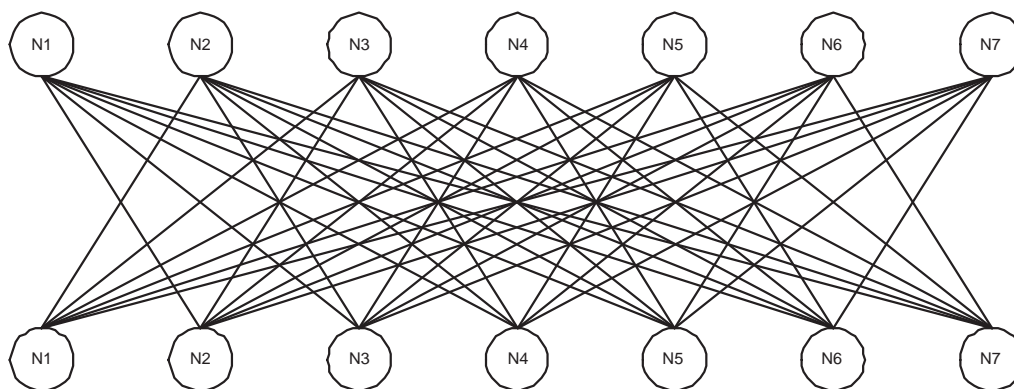
Figure 8.4: Connection Flow between Network Nodes

Table 8.8: Distribution of Demand from Single Source Node over Various QoP Service Classes

% of demand distributed from source node to destination nodes			
Economic class	Dedicated protection	SBPP	p-cycle
40	20	20	20

redundance capacity for network protection purposes. Figure. 8.5 shows the optimised network with the shortest path candidates factor k=2. In this figure, at each span, there are three distinct values: e_i represents the span index, the middle number (in blue) is the routed capacity (unit=1000), and the last number (in red) is the bandwidth required at the corresponding span to guarantee normal service of the network as planned.

Table 8.9: Network Capacity Allocation

Link index	Requires bandwidth (Gbps)						
	35th ST	30th ST	24th ST	Dupont Cycle	California ST	Florida Ave	Adam Morgan
1	2.754	2.754	-	-	-	-	-
2	1.377	-	-	1.377	-	-	-
3	1.667	-	-	-	1.667	-	-
4	1.415	-	-	-	-	-	1.415
5	-	1.629	1.629	-	-	-	-
6	-	1.415	-	1.415	-	-	-
7	-	-	1.222	1.222	-	-	-
8	-	-	-	1.512	-	1.512	-
9	-	-	-	1.086	1.086	-	-
10	-	-	-	-	1.066	-	1.066
11	-	-	-	-	-	0.543	0.543
Total	7.214	5.800	2.854	6.616	3.824	2.061	3.031

Table 8.9 shows the bandwidth required to be installed for each physical span of the network. The maximum bandwidth is 7.2Gps at 35th St and the minimum is 2.06Gbps at Florida Avenue. The bandwidth allocated for each span here includes the network protection bandwidth. Various OC-X cards can be used to achieve the design bandwidth,
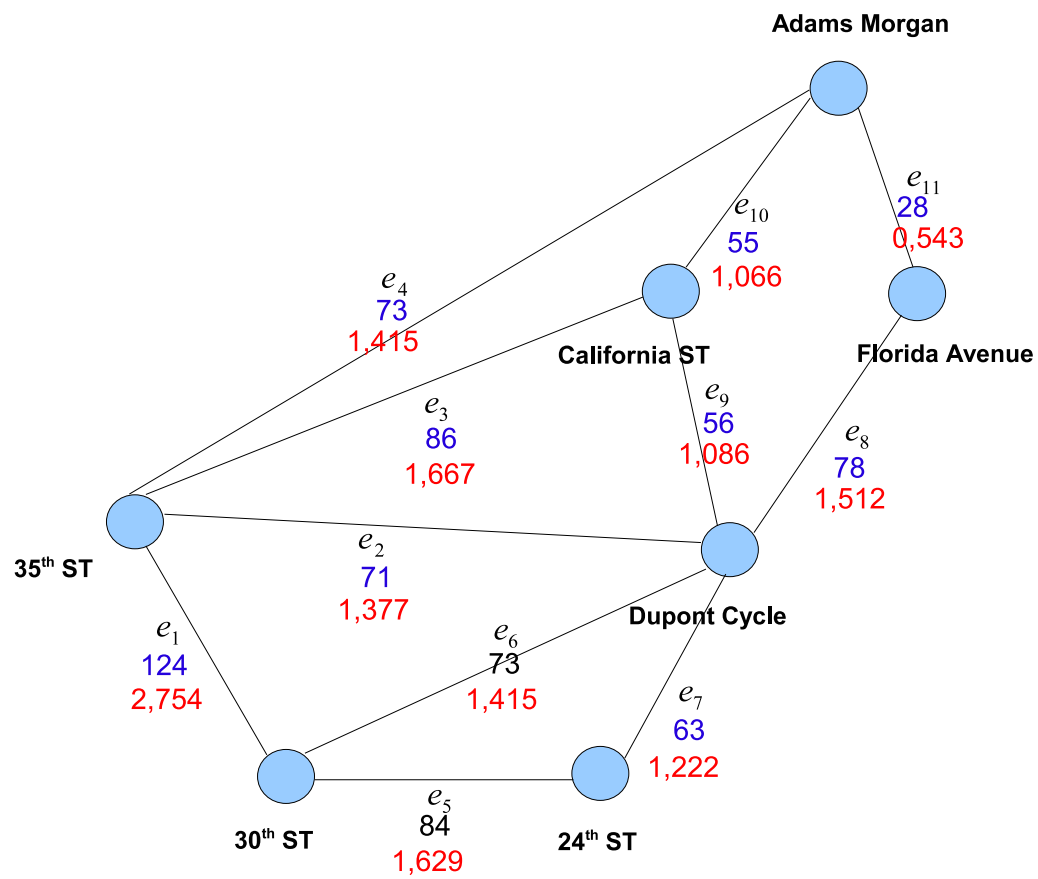
Figure 8.5: Network optimised with KSP=2

such as OC-192/STM64 for the nodes at 35th St, Dupont Cycle, 30th St; a combination of OC-48/STM16, OC-12/STM4 can be used for other remaining nodes.

8.4   Discussion

From the design results, the maximum bandwidth required by the ring network is approximately 79.6 Gbps in the case of two-fiber BLSR/MSSPRING and 119.4 Gbps for four-fiber protection. In contrast, the capacity allocated for the mesh network is only 31.216 Gbps, which is just 39.2% of the two-fiber BLSR/MSSPRING case, and 26.14% of the four-fiber BLSR/MSSPRIN case.

In a ring network, every node that belongs to a ring must be installed with the same OC-X card. However, this is not the case for mesh networks, where a variety of OC-X cards can be installed at each node. This is because the bandwidth requirements can be different at individual nodes within the mesh network.

Depending on the geological condition of the area, the total geographical ground length required to be dug for fiber installation may exceed that of the ring network. However, the signal that traverses between two end nodes can still be kept well within the 24 nodes as planned. In practice, shared-risk link groups would be a better choice for deploying the fiber cable network, thereby reducing fiber installation costs.

Optical ring networks are restricted by fiber length and the number of nodes allowed to be attached to it [92]. The purpose of this is to minimise protection switching delay, and avoiding transmission impairment within the ring. However, the ring protection allows protection switching to be invoked within 50ms as no complex signaling is required. The advantage of using pre-configured protection such as Dedicated or p-cycle is that the demand under these schemes can be recovered in approximately 50ms. The demand protected by SBPP takes a much longer time to recover after a failure.

The schedule for upgrading an existing network usually takes place every few years, sometimes as often as every 5 years. During that time, the ring network may experience

bandwidth problems due to fast growing communication demands, resulting in the slowing of service speeds. In contrast with the ring network, a mesh network can be easily upgraded; extra capacity can be added to the corresponding nodes/ spans to satisfy the growing demand without causing any disruption of network services.

8.5 Summary

The case study presented in this chapter shows an analysis and the design of a metropolitan optical network providing service to about 350,000 users. Two types of networks, known as ring and mesh topologies were considered with focus on capacity allocation, logical and physical design. This chapter also covered a variety of designing tasks such as analysis, capacity planning, cable and delay analysis, logical and physical topology design.

The mesh type network is designed based on Model 12 introduced in Chapter 7, while the SONET/SDH ring network was designed by following the guidelines in [5]. Both ring and mesh networks required different design methods. The results showed that the mesh network supporting multiple QoP service classes had significant resource efficiency. The maximum bandwidth required for the mesh network was 31.216 Gbps compared to 79.6 Gbps for the two-fiber BLSR/MSSPRING and 119.4 Gbps for four-fiber BLSR/MSSPRING protection. In this topology, only the demands being protected by p-cycles can be recovered as quickly as in the ring network (the average recovery time of ring is approximate 50ms), some other demands protected by non pre-configured protection schemes such as SBPP would take up to 250ms to recover from failure.

In [92], the authors stated that the design of the ring networks is cheaper than the mesh networks due to the low cost of OADMs. However, this is no longer the case. By providing 100 times the bandwidth of traditional equipment and facilitating easier operation and maintenance, the network with OXC systems and integrated with WDM technologies would dramatically reduce capital and operational expenses, and also increase network manageability.

This study proves the efficiency of using multiple QoP service classes in network design and analysis. Model 12 is an excellent design tool that can be used in analysis of the interaction between network topologies which have a variety of quality of services classes of traffic demands.

Chapter 9

Closing Discussion

Communications networking is one of the most important elements of communications and data transfer infrastructure in the 21th century. A wide range of services and applications rely heavily on these networks from the most basic functions, such as voice communication and email to more complicated services such as security, social virtual networking and many multimedia applications. Huge amounts of data are transmitted and received over various networks in every second of the day, around the globe. A transport network therefore must be protected and able to cope with failures such as cable cuts, faulty network elements etc.. A communications network is also required to provide intelligent services; such as fast recovery from failures and high routing efficiency. Therefore, the design of reliable networks has become a topic studied intensely by researchers, service providers and enterprizes in recent years, all with the aim of providing highly reliable networks. This trend is almost certain to continue in the future.

The aim of this thesis has been to study the optical transport mesh network design issues involving survivability and routing efficiency. This thesis provides an in depth examination of network design concepts and presents novel ideas and models for network topology design. The works in this study cover both the simple forms of network protection schemes known as span protection, path protection through to the more complicated forms such as shared backup path protection, p-cycle and, finally, the mixed-protection

scheme model to service multiple quality of demand service classes. The proposed models provide joint design and optimisation of both working and backup paths of demand, and particularly, network physical topology design is also implemented in the model formulation. Therefore, a complete solution of physical network design, or the upgrading of existing networks with protected routing can be achieved. From the results obtained from the calculations and models this thesis presents, it has been found that the joint network topology design of the proposed model provides the best resource efficiency for designing a protected mesh network.

This thesis initially presented an overview of communication networks, transport networks, key enabling technologies and design issues regarding network protection and network routing. A review of relevant set theory, graph theory and integer linear programming methods for the developed the mathematical formulations of the corresponding network design models and operations research were also presented in Chapter 2.

Chapter 3 presented a new approach to establishing the physical survivability of networks. The proposed algorithm has proven to be comparable, by many orders of magnitude, to the *biconnected* technique when dealing with larger networks, whilst providing all the distinct fundamental cycles of the network, if required, with a small change in the Algorithm 1. The proposed technique is capable of identifying network protection problems such as node-bridges and link-bridges.

Chapter 4 showed the mathematical formulations used for optimising network routing and protection in the most common form - span protection. The basic techniques of network optimisation modeling, known as "*link-path*" and "*link-node*" were also discussed in depth. In this chapter, the routing cost and maximum network congestion were discussed in the context of being applied to network modeling. Control of congestion level is found to be of great importance, and should be taken into account in network design to avoid the unbalancing of a network's load and assuring the continuatity of service while still maintaining a reasonable routing cost.

Chapter 5 proposed two new ILP models for SBPP at the optical layer of mesh net-

works. The first proposed model is a VBM and has a small number of constraints, but a large number of variables, which are the sets of DPJB candidates created in the pre-processing stage. From the results, by applying the multi-level optimisation technique, this helps to reduce the number of variables in the VBM significantly; however, this model is still only suitable for small networks and a small number of traffic demands. The VBM can be further developed to produce optimal solutions by balancing the number of constraints and variables.

The second model was called CBM model. The CBM uses the DPJB path pairs as candidates in order to reduce the number of constraints in the model. The proposed CBM model has the same quantity of variables as the conventional model, but has less constraints. The CBM has advantage over the conventional model when dealing with large size networks.

Chapter 6 gave a comprehensive review of related works on network design using *p*-cycles and proposed a new ILP formulation. The new model is formulated using the fundamental set of network cycles and the straddling links formed by these fundamental cycles. The network fundamental cycle is defined as a cycle that contains no straddling link. The proposed model can obtain the optimal solution by obtaining all the *extra straddling relationships with non-simple p-cycles*, which is something that no other previously proposed model has been capable of. The reduced complexity of the proposed model provides a great advantage over the pure ILP model when dealing with large networks. The proposed model is suitable for designing shared risk link group *p*-cycle protection networks, or backbone networks where the cross spans are usually limited.

Chapter 7 introduced a novel ILP model for network design and optimisation with multiple QoP services classes. The model is integrated with mixed protection techniques in order to improve the resource efficiency while still satisfying demand requests. The proposed model proves the advantages of using mixed protection schemes to serve various classes of demands in optimisation of routing. In addition, this study is a step forward in network design and optimisation, as it provides an insight into the relation between the physical and logical topologies, and is an excellent tool for the study of network topology

design and optimisation with mixed protection schemes to serve multiple QoP service classes.

Chapter 8 considers the analysis and design of two types of optical networks known as ring and mesh topologies. This is done through a simple case study of metropolitan network design. This chapter focuses on the capacity planning, logical and physical design of the optical networks. The mesh type network is designed based on Model 12, introduced in previous chapters, and the SONET/SDH ring network is designed following the traditional technique [5]. The comparison between both topologies shows that the mesh network with support for multiple QoP service classes provides a significant increase in resource efficiency over the ring network. The maximum bandwidth required for the mesh network is 7.2Gbps, compared to 19Gbps for the two-fiber BLSR/MSSPRING or 40Gbps for four-fiber protection. This study proves the efficiency of using multiple QoP service classes in network design and analysis. Model 12 is an excellent design tool that can be used in analysis of the interaction between network topologies that have a variety of quality protection services of traffic demands.

9.1   Future Works

The new proposed model Model 12 provides the best efficiency in mesh network design when compared to ring networks. In practice, the physical layers are built in such a way that two or more spans can be placed together, and thus logically distinct spans share common-mode failure structures and are called shared-risk span groups, which are recognized generally as shared-risk link groups (SRLGs). SRLGs provide better economical ways to design and deploy optical communication networks. However, when a failure occurs, all wavelength channels are assumed to fail together in a span. Network protection schemes see them as a single total amount of capacity that must be restored. The span SRLGs require a vastly different design to maintain survivability. The proposed model can be implemented to support the SRLG network by additional constrain for each related protection scheme in the model. More study on the failures that affect SRLG networks

under mixed protection schemes and the relationship between resource requirements and allocation in various scenarios is required.

9.2   List of Publications

1. Hoang N. Nguyen, Daryoush Habibi, Senior Member, IEEE, Quoc V. Phung, Kung-meng Lo, " A Shared Backup Path Protection Scheme for Optical Mesh Networks", Asia-Pacific Conference on Communications (APCC2005), pp. 309-313, Novemeber 2005.

2. Nguyen H., Lachowicz, S. and Eshraghian, K, (2003), "Adaptive beam control for intelligent reconfigurable holographic optical switch", 7th World Multiconference on Systemics, Cybernetics and Informatics (SCI2003), Orlando, Florida, U.S.A., July 27-30, pp. 202-207.

3. Nguyen H., Rothermel, A., Lachowicz, S. and Eshraghian, K, (2003), "Simplified Color Transformations for Analog Processing in CMOS Imagers", 7th World Multiconference on Systemics, Cybernetics and Informatics (SCI2003), Orlando, Florida, U.S.A., July 27-30, pp 208-213.

4. Daryoush Habibi, Hoang N. Nguyen, Quoc V. Phung, and Kung-meng Lo, "Establishing Physical Survivability of Large Networks using Properties of Two Connected Graphs", Tencon 2005.

5. Hoang N. Nguyen, Daryoush Habibi, Senior Member, IEEE, Viet Q. Phung, Kung-meng Lo, Stefan Lachowicz, Senior Member, IEEE, "Finding the Optimum Solution in p-Cycle Protection using Fundamental Cycles", IEEE Transactions on Communications (under review).

6. Hoang N. Nguyen, Daryoush Habibi, Senior Member, IEEE, Viet Q. Phung, Kung-meng Lo, Stefan Lachowicz, Senior Member, IEEE, "Networks Protection: A Mix-protection Schemes for Multiple QoP Service Classes", IEEE Transactions on Communications (under review).

7. Hoang N. Nguyen, Daryoush Habibi, Senior Member, IEEE, Viet Q. Phung, Kung-meng Lo, Alexander Rassau, "A Compact ILP Model for Shared Path Protectionin WDM Mesh Networks", IEEE Transactions on Communications (under review).

8. Hoang N. Nguyen, Daryoush Habibi, , Viet Q. Phung, Stefan Lachowicz "Joint optimisation in Capacity Design of Networks with p-Cycle Using the Fundamental Cycle Set", Globecom 2006 (accepted).

9. Kung-meng Lo, Daryoush Habibi, Quoc V. Phung, H.N. Nguyen and Byungkyu Kang, "Dynamic p-cycles Selection in Optical WDM Mesh Networks", the International Conference on Networks(ICON2005) , December 2005.

10. Quoc V. Phung, Daryoush Habibi, H.N. Nguyen and Kung-meng Lo, "K-pairs of Disjoint Paths Algorithm for Protection in WDM Networks", Asia-Pacific Conference on Communications (APCC2005), pp. 183-187, October 2005.

11. Kung-meng Lo, Daryoush Habibi, Quoc V. Phung and H.N. Nguyen, " Dynamic Wavelength Routing in All-Optical Mesh Networks", Asia-Pacific Conference on Communications (APCC2005), pp. 178-182, Novemeber 2005.

12. Quoc V. Phung, Daryoush Habibi, Hoang N. Nguyen and Kung-meng Lo, "Capacity utilisation versus Congestion Levels in Wavelength Routing for Large Scale WDM Networks", Asia-Pacific Conference on Communications (APCC2005), pp. 822-826, Novemeber 2005.

13. Daryoush Habibi, Viet Q. Phung, Hoang N. Nguyen and Kung-meng Lo, "A Tractable Wavelength Routing Solution in Optical Networks", Australian Telecommunication Networks and Applications Conference (ATNAC 2004), pp. 183-187, December 2004.

14. Viet Q. Phung, Daryoush Habibi, H.N. Nguyen and Kung-meng Lo, "An Efficient Approach to Optimal Wavelength Routing in Optical WDM Networks", the 12th IEEE International Conference on Networks (ICON2004), pp. 600-604, Novemeber 2004.

Appendix A

Algorithms

A.0.1 Finding K disjoint path pairs

Algorithm 4 : K disjoint-path pairs

Input : An indirected graph $G(V, E)$, a pair of source and destination nodes (s, d), and the number of shortest disjoint-path pairs required.

Output: A set of K-shortest disjoint-path pairs.

1: Take a shortest path between the source s and destination d, using one of the shortest path algorithms, eg. modified Dijkstra or BFS [55, 75]. Denote this as p.

2: Define the direction of each link traversed in p from s toward d as positive.

3: Remove all directed links on the shortest path p and replace them with reverse direction and negative weight of each such link (eg. by multiplying the original link's cost with -1).

4: Find K least cost paths from s to d in the modified graph using the algorithm in [93]. Denote these as the set of paths $S = \{s_1, s_2 \ldots, s_K\}$.

5: For each pair of paths (p, s_i), remove any link of the original graph traversed by both p and s_i. These are called *interlacing links*. Identify all path segments by the link removal from path p and s_i. Such path-pairs form the K-disjoint path pairs $(Ppairs) = \{(w_1, r_1), (w_2, r_2), \ldots, (w_K, r_K)\}$.

A.0.2 Multilevel optimization algorithm

Algorithm 5 : Multilevel optimization

Input : An undirected graph $G(V,E)$; a set H containing disjoint-joint path-pair candidates for a given set of demands D; a set K of k-shortest disjoint path pair candidates of demands D; and l, the maximum allowable number of shared dependencies on spare capacity between backup paths.

Output: Routing paths for demands D.

Set the final solution $S_f \leftarrow \emptyset$, current solution $S_c \leftarrow \emptyset$.

while $l > 1$ **do**

    Create a new set of candidate $KH^l = K \bigcup H^l$;

    Solve the SBPP at level l with the new candidates using Model 7;

    Obtain the model's solution $S_c = \{K'_{di}\} \bigcup \{H^l_{dgk}\}$

    $\forall d_i \in dg$ from the solution set S_c, update all demands;

    if $l > 2$ **then** $D = D \backslash di$;

    endif

    $\forall H^l_{dgk} \in S$, $\{S_f\} = \{S_f\} \bigcup \{S_c \backslash K'\}$;

    $l \leftarrow l - 1$;

end while

A.0.3 Finding DPJB candidate paths

Algorithm 6 Finding DPJB candidate paths

Input : An undirected graph $G(V,E)$; the set $T = \{t_1, t_2, \ldots, t_D\}$ of connection demands D over the network, where t_i denotes the connection between node pair $\{s_i, d_i\}$ required for each demand d; a set of candidate disjoint path-pairs $S = (P, R)$ as given in Definition 1.

Output: The set of Joint-Disjoint path pairs H of demand D at different share levels.

  1: Finding primary disjoint path of K shortest path-pair for each demand $d \in D$:

  init. $i \leftarrow 1$

  for every p_d^i **do**

    $dP_d^i \leftarrow \{p_d^i\}$

  end for

  while $i < D$ **do**

    for $j = 1 \rightarrow K$ **do**

      for $t = i+1 \rightarrow D$ **do**

        for $s = 1 \rightarrow K$ **do**

          if $p_i^j \bigcap p_t^s = \emptyset \wedge b_i^j \bigcap b_t^s \neq \emptyset$

            $dP_i^j \leftarrow dP_i^j + \{p_t^s\}$

          end if

        end for

      end for

    end for

    $i \leftarrow i+1$

  end while

  2: Generate H

  $\alpha \leftarrow Share factor$

  for $d = 1 \rightarrow D$ **do**

    for $i = 1 \rightarrow K$ **do**

      for $j = 2 \rightarrow \alpha$ **do**

        $N \leftarrow C_{\{dP_d^i\}}^j$

        if $\forall n \in N, \exists e \in E, \sum_b e_b = i$ **then**

          $H_{\{d\},i}^j \leftarrow \{n\}$

        end if

      end for

    end for

  end for

Appendix B

Network configurations

1. NSFNET (Table B.1)

Table B.1: The NSFNET Physical Configuration

Link index	end nodes	capacity	cost
1	1 - 2	12	1
2	1 - 3	12	1
3	1 - 8	12	1
4	2 - 3	12	1
5	2 - 4	12	1
6	3 - 6	12	1
7	4 - 5	12	1
8	4 - 10	12	1
9	5 - 6	12	1
10	5 - 7	12	1
11	6 - 9	12	1
12	6 - 12	12	1
13	7 - 8	12	1
14	8 - 11	12	1
15	9 - 11	12	1
16	10 - 13	12	1
17	10 - 14	12	1
18	11 - 13	12	1
19	11 - 14	12	1
20	12 - 13	12	1
21	12 - 14	12	1

2. EU network(Table B.2)

Table **B.2**: The EON Physical Configuration

Link index	end nodes	capacity	cost
1	1 - 2	12	1
2	1 - 3	12	1
3	1 - 25	12	1
4	1 - 9	12	1
5	1 - 14	12	1
6	1 - 15	12	1
7	1 - 16	12	1
8	2 - 3	12	1
9	2 - 6	12	1
10	2 - 7	12	1
11	2 - 13	12	1
12	2 - 15	12	1
13	3 - 4	12	1
14	3 - 5	12	1
15	3 - 6	12	1
16	4 - 5	12	1
17	4 - 8	12	1
18	4 - 9	12	1
19	4 - 17	12	1
20	5 - 6	12	1
21	5 - 8	12	1
22	6 - 7	12	1
23	6 - 8	12	1
24	7 - 8	12	1
25	7 - 9	12	1
26	7 - 11	12	1
27	7 - 12	12	1
28	8 - 9	12	1
29	9 - 10	12	1
30	9 - 18	12	1
31	9 - 19	12	1
32	10 - 11	12	1
33	11 - 12	12	1
34	13 - 14	12	1

3. N25-L54 Network (Table B.3)

Link index	end nodes	capacity	cost
35	16 - 17	12	1
36	16 - 18	12	1

Table B.3: The N25-L54 Physical Configuration

Link index	end nodes	capacity	cost
1	1 - 20	12	1
2	1 - 21	12	1
3	1 - 23	12	1
4	2 - 15	12	1
5	2 - 20	12	1
6	2 - 21	12	1
7	2 - 25	12	1
8	3 - 7	12	1
9	3 - 11	12	1
10	4 - 20	12	1
11	4 - 23	12	1
12	5 - 8	12	1
13	5 - 15	12	1
14	6 - 15	12	1
15	6 - 18	12	1
16	6 - 20	12	1
17	7 - 14	12	1
18	7 - 17	12	1
19	7 - 21	12	1
20	7 - 22	12	1
21	7 - 24	12	1
22	8 - 16	12	1
23	8 - 19	12	1
24	8 - 24	12	1
25	8 - 25	12	1
26	9 - 15	12	1
27	9 - 16	12	1
28	9 - 20	12	1
29	9 - 25	12	1

Link index	end nodes	capacity	cost
30	10 - 11	12	1
31	10 - 15	12	1
32	10 - 19	12	1
33	10 - 21	12	1
34	10 - 23	12	1
35	11 - 15	12	1
36	11 - 19	12	1
37	11 - 23	12	1
38	12 - 13	12	1
39	12 - 17	12	1
40	13 - 19	12	1
41	13 - 22	12	1
42	14 - 20	12	1
43	14 - 22	12	1
44	15 - 16	12	1
45	16 - 17	12	1
46	16 - 18	12	1
47	16 - 23	12	1
48	17 - 18	12	1
49	17 - 25	12	1
50	18 - 22	12	1
51	19 - 21	12	1
51	19 - 25	12	1
53	23 - 25	12	1
54	24 - 25	12	1

Appendix C

Network technical notes

- **TCC2** - Control the main processing functions of the ONSCC2s. The TCC2 provides the following functions: timing, control and switching functions which include system initialization, provisioning, alarm reporting, maintenance, diagnostic, IP address detection and resolution, timing, SONET/SDH DCC termination, and system fault detection.

- **OC-192/STM64 1-Port card (OC192IR/STM64)** - The port operates at 9.95328Gbps over unamplified distances up to 40km with SMF-28 fiber (with the 1550nm wavelength range) limited by loss and/or dispersion.

- **OC3IR/STM1 SH card (OC3IR/STM1)** - The card provides 8 intermediate or short range 1310nm OC-3/STM-1 port. The port operates at 155.52Mbps.

- **MS-SPRING** - MS-SPRING function is to provide the switching of ring or span between nodes. The traffic can be transmitted in both direction, and the protection traffic can also be used to serve extra demand. There are two type of MS-SPRING known as 2-fiber MS-SPRING and 4-fiber MS-SPRING. They are physically different as the name implies, and also the way of assigning working/protection bandwidth in the optical fibers.

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