การจัดเส้นทางเชิงความยาวคลื่นและการปกป้องโครงข่ายระดับชั้นเชิงแสงจากความเสียหายหนึ่งข่ายเชื่อมโยงในโครงข่าย WDM สำหรับทราฟฟิกประเภทมัลติคาสต์

นาย เจริญชัย บวรธรรมรัตน์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต

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WAVELENGTH ROUTING AND OPTICAL NETWORK LAYER PROTECTION APPROACHES AGAINST SINGLE LINK FAILURES FOR MULTICAST TRAFFIC ON WDM NETWORKS

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เจริญชัย บวรธรรมรัตน์, นาย : การจัดเส้นทางเชิงความยาวคลื่นและการปกป้องโครงข่ายระดับชั้นเชิงแสงจากความเสียหายหนึ่งข่ายเชื่อมโยงในโครงข่าย WDM สำหรับทราฟฟิกประเภทมัลติคาสต์. (WAVELENGTH ROUTING AND OPTICAL NETWORK LAYER PROTECTION APPROACHES AGAINST SINGLE LINK FAILURES FOR MULTICAST TRAFFIC ON WDM NETWORKS) อ. ที่ปรึกษา : รองศาสตราจารย์ ดร. ลัญฉกร วุฒิสิทธิกุลกิจ, อ.ที่ปรึกษาร่วม : ดร. ศักดิ์ เสกขุนทด 202 หน้า. ISBN 974-17-4089-1.

วิทยานิพนธ์ฉบับนี้ ศึกษาปัญหาที่สำคัญอย่างยิ่งของโครงข่าย WDM ที่รองรับทราฟฟิกประเภทมัลติคาสต์สองปัญหา สำหรับปัญหาแรกที่ศึกษา คือ ปัญหาการจัดสรรเส้นทางและความยาวคลื่นให้กับทราฟฟิกประเภทมัลติคาสต์ของโครงข่าย WDM โดยมีวัตถุประสงค์ในการศึกษาคือ เพื่อพิจารณาและเปรียบเทียบวิธีการออกแบบโครงข่าย WDM สองวิธีคือ แบบแมช และแบบหลายวงแหวนในด้านของจำนวนเส้นใยแก้วนำแสงที่โครงข่ายต้องการรองรับทราฟฟิก ประสิทธิภาพในการใช้เส้นใยแก้วนำแสง และความซับซ้อนในการจัดการควบคุมโครงข่าย นอกจากนี้ วิทยานิพนธ์นี้ยังมีวัตถุประสงค์เพื่อวิเคราะห์อิทธิพลของจำนวนความยาวคลื่นสูงสุดที่สามารถมัลติเพลกซ์ได้ในเส้นใยแก้วนำแสงหนึ่งเส้น อุปกรณ์แปลงผันความยาวคลื่น รวมทั้งอุปกรณ์ optical power splitter ว่ามีผลอย่างไรต่อจำนวนเส้นใยแก้วนำแสงทั้งหมดที่โครงข่ายต้องการ ดังนั้น เพื่อให้เป็นไปตามวัตถุประสงค์ Integer Linear Programming (ILP) ได้ถูกนำมาใช้เพื่อสร้างแบบจำลองทางคณิตศาสตร์เพื่อหาจำนวนเส้นใยแก้วนำแสงที่โครงข่ายต้องการสำหรับแต่ละวิธีการออกแบบโครงข่าย และมากไปกว่านั้น วิทยานิพนธ์นี้ได้ทำการออกแบบและพัฒนาอัลกอริธึมของการจัดสรรความยาวคลื่น และวิธีการหาค่าขอบเขตล่างของจำนวนเส้นใยแก้วนำแสงที่โครงข่ายต้องการ เพื่อประโยชน์ในการออกแบบโครงข่าย WDM ที่รองรับทราฟฟิกประเภทมัลติคาสต์

สำหรับปัญหาที่สองที่วิทยานิพนธ์นี้ศึกษา คือ ปัญหาการปกป้องโครงข่ายจากความเสียหายหนึ่งข่ายเชื่อมโยงในโครงข่าย WDM ที่รองรับทราฟฟิกประเภทมัลติคาสต์ ในการจัดการแก้ไขปัญหาดังกล่าว วิทยานิพนธ์พิจารณาและวิเคราะห์ระบบปกป้องโครงข่าย 2 ระบบ สำหรับระบบปกป้องโครงข่ายระบบแรกคือ ระบบปกป้องแบบมัลติคาสต์ (multicast protection system) โดยวิทยานิพนธ์นี้นำเสนอวิธีการปกป้องโครงข่ายที่เกี่ยวข้องกับระบบแรกนี้ทั้งหมด 6 วิธี และสำหรับระบบปกป้องระบบที่สองคือ ระบบปกป้องแบบพอยท์ทูพอยท์ (point-to-point protection system) ซึ่งสำหรับระบบนี้ วิทยานิพนธ์จะศึกษาวิธีการปกป้องทั้งหมด 5 วิธี และจากการนำเสนอ วิทยานิพนธ์นี้มีวัตถุประสงค์หลักคือ เพื่อวิเคราะห์ความซับซ้อนของกระบวนการปกป้องโครงข่าย และจำนวนเส้นใยแก้วที่โครงข่ายต้องการในแต่ละวิธีการปกป้องโครงข่าย รวมทั้งยังมีวัตถุประสงค์หลักอีกประการหนึ่งคือ เพื่อนำเสนอการวิเคราะห์เชิงเปรียบเทียบระหว่างวิธีการปกป้องโครงข่ายที่วิทยานิพนธ์ศึกษา ดังนั้น เพื่อให้เป็นไปตามวัตถุประสงค์ วิทยานิพนธ์นี้จึงออกแบบแบบจำลองทางคณิตศาสตร์เพื่อหาจำนวนเส้นใยแก้วนำแสงต่ำสุดที่แต่ละวิธีการปกป้องโครงข่ายต้องการ รวมทั้งนำเสนออัลกอริธึมในการจัดสรรความยาวคลื่น และฮิวริสติกอัลกอริธึมที่ประยุกต์จากแบบจำลองทางคณิตศาสตร์ที่ใช้ในการคำนวณหาจำนวนเส้นใยแก้วนำแสงที่แต่ละวิธีการปกป้องโครงข่ายต้องการ

จากการศึกษาและวิเคราะห์ผลเฉลยของปัญหาการปกป้องโครงข่าย สามารถสรุปได้ว่า โดยทั่วไปแล้ว โครงข่ายที่ใช้ระบบปกป้องแบบมัลติคาสต์จะใช้จำนวนเส้นใยแก้วนำแสงรองรับทราฟฟิกน้อยกว่าโครงข่ายที่ใช้ระบบปกป้องแบบพอยท์ทูพอยท์ แต่อย่างไรก็ตาม สำหรับโครงข่ายที่รองรับทราฟฟิกทั้งแบบมัลติคาสต์ และยูนิคาสต์พร้อมๆ กัน ระบบปกป้องแบบพอยท์ทูพอยท์จะให้ข้อดีกับโครงข่ายในแง่ของการที่โครงข่ายสามารถมีระบบควบคุมการปกป้องโครงข่ายเพียงระบบเดียวได้ โดยระบบนี้ใช้ได้ทั้งทราฟฟิกประเภทมัลติคาสต์และยูนิคาสต์ แต่ในทางตรงกันข้าม สำหรับโครงข่ายที่ใช้ระบบปกป้องแบบมัลติคาสต์ โครงข่ายจะต้องมีระบบควบคุมการปกป้องโครงข่ายแยกต่างหากที่ออกแบบมาเฉพาะกับทราฟฟิกประเภทมัลติคาสต์ และนอกจากนี้ จากผลเฉลยยังสามารถสรุปได้ว่า อัลกอริธึมที่อาศัยแบบจำลองทางคณิตศาสตร์มีประสิทธิภาพสูงในการประมาณจำนวนเส้นใยแก้วนำแสงต่ำสุดที่แต่ละวิธีการปกป้องโครงข่ายต้องการ

ภาควิชา วิศวกรรมไฟฟ้า ลายมือชื่อนิสิต..

สาขาวิชา วิศวกรรมไฟฟ้า ลายมือชื่ออาจารย์ที่ปรึกษา..

ปีการศึกษา 2546 ลายมือชื่ออาจารย์ที่ปรึกษาร่วม................................

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KEY WORD: MULTICAST ROUTING AND WAVELENGTH ASSIGNMENT/ WDM NETWORK/ LIGHT-TREE / PROTECTION APPROACH / NETWORK OPTIMIZATION
CHAROENCHAI BOWORNTUMMARAT : THESIS TITLE (WAVELENGTH ROUTING AND OPTICAL NETWORK LAYER PROTECTION APPROACHES AGAINST SINGLE LINK FAILURES FOR MULTICAST TRAFFIC ON WDM NETWORKS) THESIS ADVISOR: Associate. Prof. LUNCHAKORN WUTTISITTIKULKIJ, Ph.D., THESIS COADVISOR : SAK SEGKHOONTHOD, Ph.D., 202 pp. ISBN 974-17-4089-1.

As optical wavelength division multiplexing (WDM) networks are now widely recognized as the core of next generation broadband networks and multicasting is also increasingly becoming important in modern communication networks, this thesis investigates two significant problems of optical WDM networks on which multicast traffic is supported.

As the first research problem, the multicast routing and wavelength assignment (MC-RWA) problem that refers to the problem of routing multicast traffic and assigning wavelengths to it on WDM networks is systemically analyzed. For the MC-RWA problem, mesh and multi-ring design approaches are intensively studied. Key aspects that are taken into consideration and comparison of those two design approaches include fiber requirements, fiber utilization, and complexity of network operation and management. Moreover, the influences of the maximal wavelengths multiplexed per fiber, splitting degree of optical power splitters, and wavelength conversion on fiber requirements are investigated in this thesis. Integer linear programming (ILP) formulations are derived and used as a solution technique to obtain the fiber requirement of each studied design approach. Finally, heuristic algorithms to perform wavelength allocation and a lower bound on the fiber requirement are discussed.

As the second research problem of this thesis, the multicast optical protection problem that refers to the problem of provisioning protection systems to multicast traffic on WDM mesh networks is investigated. To solve this problem, two main categories of protection systems are considered. For the first category, six new multicast protection strategies against single link failures are designed and introduced. For another protection category, an extension of point-to-point protection techniques to protect multicast traffic is presented. In this category, five protection strategies are studied. The main objectives to study the optical protection problem are to examine the ease of restoration process, the working and spare fiber requirement of each studied protection approach, and also to compare those examined terms among studied protection approaches. Moreover, techniques for wavelength allocation and spare capacity placement for restorable WDM networks are comprehensively studied. To achieve the main objectives, ILP mathematical models are developed to minimize the working and/or spare fiber requirement. Finally, this thesis introduces wavelength allocation and ILP-based heuristic algorithms as alternative tools to obtain the working and spare fiber requirement.

Based on network experiments, the numerical results demonstrate that the multicast protection methods generally require fewer fibers than the point-to-point protection methods. However, in an environment of networks supporting both unicast and multicast traffic simultaneously, additional fibers required for point-to-point protections are compensated by a single and simpler network protection control plane. This is in contrast to a network using a multicast protection system that requires an extra control plane for link restoration of multicast traffic. In addition, the network design outcomes show that the proposed ILP-based heuristic algorithm potentially generates near-optimal solutions for designing multicast WDM networks both with and without link protection.

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List of Symbols

Δ	splitting fanout of optical power splitters
Br	number of backup optical branches
BSON	broadcast-and-select network architecture
$\bar{d}$	average nodal degree of a network
DJP	disjoint path protection approach
EON	European optical network
G	total number of destinations of a multicast session
ILP	integer linear programming
L	total number of physical links of a network
LIR	light-tree-interrupted reconfiguration protection approach
LP	link protection approach
LR	light-tree reconfiguration protection approach
LT	light-tree wavelength assignment method
M	maximal number of wavelengths multiplexed per fiber
MC-OXC	multicast-capable cross-connect
MC-RWA	multicast routing and wavelength assignment
N	total number of nodes in a network
N_c	total number of constraints in a generated ILP program
N_v	total number of variables in a generated ILP program
NSFNet	national science foundation network
8N-14L	experimental network with 8 nodes and 14 links
10N-21L	experimental network with10 nodes and 21 links
OADM	optical add-drop multiplexer
OB	optical branch protection approach
OBF	optical-branch-fixed protection approach

List of Symbols (cont.)

OEO	optical-electrical-optical conversion
OMP	optical mesh protection approach
OXC	optical cross-connect
PBF	physical-branch-fixed protection approach
Problem A	optimization problem of working and spare fibers
Problem B	optimization problem of spare fibers
PRR	physical route reconfiguration protection approach
PVLT	partial virtual light-tree wavelength assignment method
Q	number of candidate rings per node pair
$\overline{Q}$	average Number of candidate rings per node pair
RWA	routing and wavelength assignment
8- ring	ring network with 8 nodes
SF+WF	spare fiber + working fiber spare capacity placement technique
SLB	single link basis protection approach
Sprint USNet	sprint US continental IP backbone
SW+WW	spare wavelength channel + working wavelength channel spare capacity placement technique
SW+WW+SR	spare wavelength channel + working wavelength channel spare capacity placement technique with stub release
UK-Net	UK network infrastructure
WDM	wavelength division multiplexing technology

Chapter 1

Introduction

1.1 Background and Signification of the Research Problems

Optical fibers have been globally recognized as the most effective transmission medium to transport data information in telecommunication networks, especially in high-capacity long-haul networks where they must serve application services among national and/or continental domains. The main good characteristics of optical fibers are huge bandwidth, low signal attenuation, low power requirement, and also low space requirement for installation [1-2]. Thus, under this condition, we have witnessed a wide deployment of optical fibers in numerous communication technologies which to date became available in marketplace, several of which are fiber distributed data interface (FDDI), synchronous digital hierarchy (SDH), and synchronous optical network (SONET) technologies.

Although optical fibers have potentially large bandwidth and have been deployed in existing networks to meet large traffic volume requirements, network operators are still facing the problem of bandwidth shortage in their networks. This causes from the fact that the growth rate in data and voice traffic on communication networks, particularly in parts of Internet, is explosively exponential [3-6]. As dictated in [6], leading service providers reported that the amount of traffic on their backbones will be double every six to nine months. This is largely in response to the

300% growth per year in Internet traffic (data traffic), while traditional voice traffic grows at a annual rate of only 13%; see Figure 1.1.

Therefore, to handle this problem effectively, network operators have introduced wavelength division multiplexing technology (WDM) [7-13] to their networks as an instrument to increase the existing network capacity. The WDM technology refers to as an optical technology that allows a network to transmit several information streams, each of different wavelengths, simultaneously on a single optical fiber. With the advancement in optical technology [14-15], it is practically feasible to multiplex 100 wavelengths in a fiber with each wavelength modulated at 10 Gb/s to provide a throughput of 1 Tb/s [16].

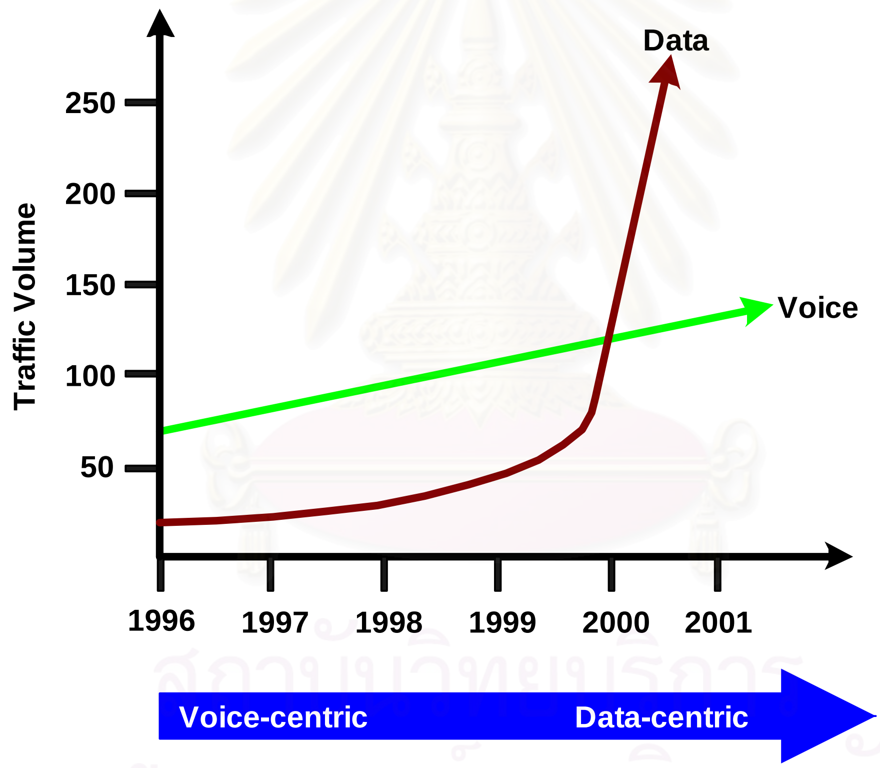


Figure 1.1: Past and projected future growth of data and voice traffic.

In the early stage of using the WDM technology, it was utilized to expand bandwidths of existing point-to-point fiber links of networks. This result has been a creation of *opaque optical networks* [17] in which the optical data signal undergoes *optical-to-electrical-to-optical* (OEO) conversion at every intermediate node. Hence, all networking processes are entirely done at higher transport layers (e.g., SONET, SDH, asynchronous transfer mode (ATM), and internet protocol (IP)) in order to guarantee that the optical data signal reaches its destination. However, as the recent advances in optical amplifiers and optical cross-connects (OXCs), it is possible to put the networking works to the optical WDM layer in stead of higher transport layers and the network can be operated in all-optical domain. Thus, this results in no requirement of OEO conversion at intermediate nodes and also a significant increment in network's throughput with respect to that of opaque networks. This new network architecture is called the *all-optical network*. An OXC has the main functions to switch the incoming optical signal of an input fiber link to the same wavelength on an output fiber link. The main service in all-optical networks is called the *lightpath* that refers to as an optical connection on a particular wavelength that may span a number of fiber links from the source to the destination.

Due to the introduction of WDM technology and OXCs, it has created a need for routing wavelength demands over optical networks. This is one of main crucial aspects of designing optical networks. In conventional term, this aspect is regarded as the problem of routing and wavelength assignment (RWA) [17-21]. How the RWA problem is significant can be explained through a simple example [22] as follows.

In an N-node network, if each node is equipped with N-1 transceivers (optical transmitters and receivers) and if there are sufficient wavelengths on all fiber links, then each node pair of the network can set up a light-path to connect each other: thus there is no problem to solve in the network. However, as we respect to the practical point of view, the cost of transceivers is rather expensive and the number of wavelength channels that can be supported in a fiber is limited by technological constraints. Hence, under these networking constraints, the RWA problem is introduced to the network to determine routes and wavelengths on those routes so that all required connections can be established, while all networking constraints are satisfied.

Apart from this scenario, another signification of RWA problem is that in the phase of network dimensioning, solutions of RWA problem are basically utilized to evaluate network resources and also costs to implement networks. Thus, under this, the RWA problem is more crucial and challenges network designers to find effective algorithms to cope with the RWA problem.

In literature, there are numerous research papers that aim to handle the RWA problem [18-21, 23-28]. For example, reference [23] provided an RWA study minimizing the number of transceivers used in networks. In [25-27], the researchers computed the minimum number of fibers needed to support given traffic demands by using the RWA heuristic algorithms and also integer linear programs (ILP). In [18], the researchers proposed several techniques to obtain lower bounds on the minimum number of wavelengths and also proposed the ILP mathematical model and its duality to solve the RWA problem.

As considered, although many research studies have been conducted to examine the RWA problem, such research studies would not be sufficient for application to real telecommunication networks. This is because those research studies have focused on the RWA problem only with point-to-point communications (unicast), while for multicast communications, they have not been addressed. As reported in [22, 29], service providers said that due to the popularity of Internet, traffic patterns carried on networks have been changed considerably. In stead of requiring only point-to-point connections to serve service applications, many customers initially request service providers to support new emerged applications (especially data applications developed on IP standard) in the form of multicast communications. Examples of new applications are distributed game, multimedia conferencing, software/file distribution, internet news distribution, and video on demand.

Moreover, the researchers in [30] have demonstrated other signification advantages of multicast communications. Namely, multicast services not only efficiently support natural multicast traffic applications but also provide the improved performance for unicast traffic by substantially reducing the number of hops a packet has to transverse, thus upgrading the quality of service (QoS). In [31], the author has further shown other important advantages of the multicasting in optical networks. For instance, the traffic grooming in generalized multi-protocol label switching networks (GMPLS) [32, 33] and virtual private networks (VPNs) [34] can be enhanced by using the multicasting.

Therefore, with respect to the advantages of the multicasting in optical WDM networks, this thesis has a main objective to take the problem of routing and wavelength assignment with multicast traffic in consideration with an expectation that studying results in the thesis would be beneficial for optical network design. In addition, since unicast and broadcast communications can be considered as special cases of multicast communications, all of the major findings in the thesis are also expected to be well applied to study unicast and broadcast communications.

Here, it should be noted that the problem of routing and wavelength assignment with multicast traffic conventionally refers to as the *multicast routing and wavelength assignment (MC-RWA)* problem [18, 31, 35].

In addition to addressing the MC-RWA problem in this thesis, there is another research issue that is equally important and should be included in the thesis, that is, the problem of optical network protection or providing survivability [16, 36] to multicast WDM networks. How this issue is important can be described as follows.

Since optical WDM networks are in most cases designed to be the core of transmission systems, such networks carry an enormous quantity of demands, usually operated at a bit rate of more than 100 Gb/s. Therefore, a single element (fiber link or node) failure in a core network can lead to a large amount of data loss, even for a few seconds. Moreover, with many business customers becoming increasingly dependent on telecommunication networks [36], this failure could further result in the signification losses in revenue. Hence, with the catastrophic consequences, it is essential that certain network protection measures must be provided at the network so that service continuity can be maintained despite failures. In particular, for multicast services, a single element failure on a multicast service may have a larger impact because several destinations become disconnected as apposed to a failure on a unicast connection. Consequently, under this scenario, it is here worth to study the problem of optical protection in WDM networks on which multicast services are being supported.

1.2 Multicasting in Optical WDM Networks

In this section, we describe the fundamental knowledge of implementing the multicasting in optical WDM networks. This includes the architecture of multicast optical WDM networks and also hardware devices necessary for the multicasting.

Multicast communication refers to as the requirement of transmitting information from a source node to a set of destination nodes in a network. The basic structure to support the multicast communication is the *tree* [37, 38]. For a WDM networks, the tree spanning on it is technically called the *light-tree* [30], which is a generalized extension of lightpath as described in the previous section.

Figure 1.2 shows a multicast optical WDM network in which a light-tree is being supported for serving a multicast demand. As demonstrated, the multicast optical WDM network consists of some of nodes interconnected by fiber links. Each optical fiber in a network link is capable of supporting a limited number of WDM wavelength channels and each network node is equipped with an OXC. The OXC has the functions to transmit, terminate, and also pass through optical signals. Which function is active depends on the OXC acting as the source, destination, or intermediate nodes of the data signal.

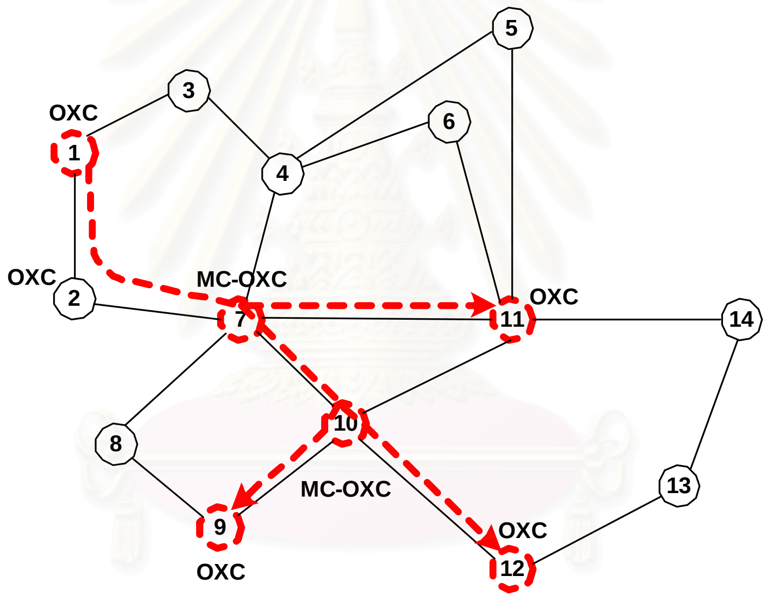


Figure 1.2: Multicast WDM network with a light-tree.

To realize the multicasting in the network, OXCs must be enhanced to have an extra capability, namely, multicast-capable (MC-OXC) and a key hardware device for MC-OXCs is an *optical power splitter* [1]. Optical power splitters are capable of splitting an incoming optical signal arriving at an input port to identical optical signals at multiple output ports. Because these are passive devices, after passing a Δ-way optical splitter each output signal has the power less than or equal to $1/\Delta$ times the input signal power. Technically, the value of Δ of optical splitters, which is specified for invention, is called the *fanout* [31, 39].

Figure 1.3 illustrates a possible architecture of MC-OXCs [22]. It is worth noting that we select this architecture for study because it is easy to understand the implementation of the multicasting in optical networks. The reader is advised to see [40] for more detail of MC-OXCs.

As shown in Figure 1.3, when the data information arrives at an input port of the MC-OXC, it is fist demultiplexed into separate wavelengths, each carrying a different signal. If signals are not used for transporting multicast messages, they are then directly guided to the optical space switch for switching them to the corresponding output ports. If otherwise, the signals are sent to the ports connected with optical power splitters so as to be duplicated and further routed to the optical space switch for going out to the appropriate output ports. In addition, due to the decrease of power after passing optical splitters, optical amplifiers may be equipped within optical splitters to boot the power of signals.

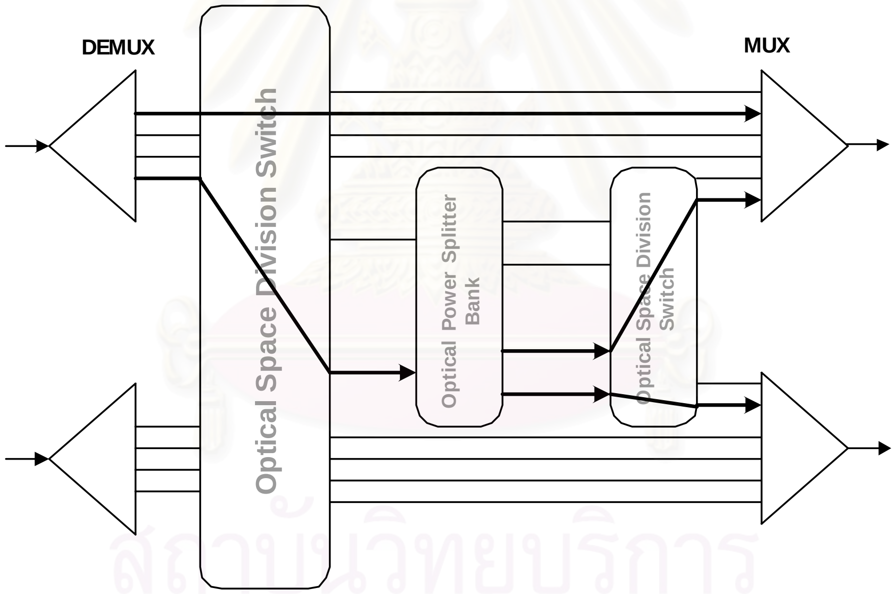


Figure 1.3: MC-OXC architecture.

As an alternative architecture, the MC-OXC in Figure 1.3 is possibly operated with wavelength converters which are established at MC-OXC input ports; this switching architecture is shown in Figure 1.4. The main purpose for introducing wavelength converters to the MC-OXC is to decrease the wavelength collision [41] that arises when two optical signals with the same wavelength need to leave at the same output fiber. Thus, with using wavelength converters, it can lead to the reduction of wavelength collision and also the reduction of number of fibers needed for connecting MC-OXCs. As a result, the total number of fibers needed for serving traffic demands for the whole network could be decreased.

Note that in this thesis, we further investigate this alternative MC-OXC with the aim to clarify the effectiveness of wavelength converters to the network performances, especially to the wavelength capacity required for serving traffic demands.

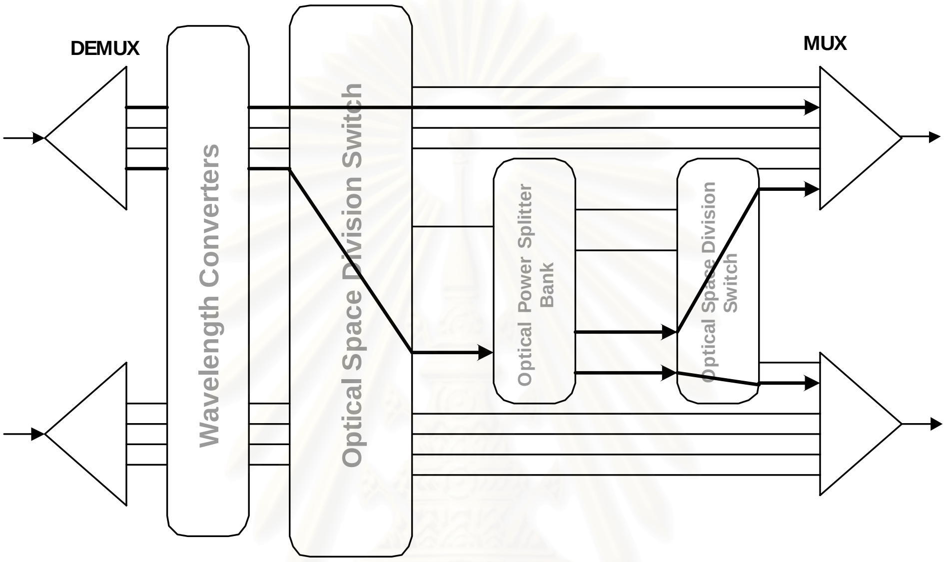


Figure 1.4: MC-OXC architecture with wavelength conversion capability.

1.3 Literature Review

As described, this thesis addresses two main problems for research, *i.e.*, the MC-RWA problem and the optical protection problem. In this section, we review the research papers that were published in conferences and journals and also relevant to the above two main problems. Furthermore, how the research work in the thesis differs from the research works in the pervious papers is identified here.

1.3.1 MC-RWA Problem

For the study of MC-RWA problem, it actually involves different network environments depending on the construction and the types of network, namely, local area networks (LANs), wide area networks (WANs), or core networks. A summary of survey contents is given and illustrated in Table 1.1.

In order to construct a LAN with the WDM technology, it is typically implemented based on the broadcast-and-select optical network (BSON) architecture as shown in Figure 1.5. A BSON architecture basically consists of a passive star coupler and a number of network nodes. Each network node is connected with the passive star coupler by using a pair of optical fibers, one for transmitting and the other one for receiving.

Table 1.1: Summary contents of MC-RWA problem in optical WDM networks.

WDM Network Archetectures	Application Areas	References	Major research issues	Approaches
Broacast-and-select (BSON)	LANs	[42-46]	- Minimize blocking probability - Maximize bandwidth sharing	-Wavelength assigment scheduling algorithms - Mulicast multimedia access protocols (MACs)
Wavelength-routed networks with mesh and multi-ring designs	WANs, MANs	[47], [48]	- Minimize session blocking probability - Minimize the number of hops of trees - Minimize the number of transceivers	- Dynamic multicast routing and wavelength assignment (dynamic MC-RWA)
Wavelength-routed transport/ backbone networks with mesh and multi-ring designs	-Core and backbone networks -International and Intercontinental areas	[29], [30], [40], [51-55]	- Minimize the number of wavelengths per link -Minimize the network cost - Minimize the number of hops of packets - Satisfy Qos agreement - Optimize wavelegnth converter and power splitter placements	- Static multicast routing and wavelength assignment (static MC-RWA)

As demonstrated in Figure 1.5, all the network nodes in the BSON are directly connected with the passive star coupler and the passive star is itself devised by employing combiners and splitters. Thus, for the BSON mechanism, if a node in the network needs to send information to the other one, the information on a particular wavelength will be first sent to the passive start coupler and the passive star coupler will then broadcast that information to all other nodes in the network. At the destination node, the information can be received by tuning the wavelength of optical receiver to match with the wavelength of the information. Due to the broadcast capability of the passive start coupler, the multicasting and broadcasting in BSONs are inherently very efficient.

Since optical data signals share the fiber infrastructure, the number of distinct wavelengths required is theoretically equal to the number of nodes (N) in the BSON so that no traffic demand is blocked due to the lack of wavelength resources. However, BSONs naturally deal with LANs in which the traffic pattern is quite dynamic (namely, traffic demand requests arrive and departure in a random manner) and also the cost of transmitters and receivers established at nodes of BSONs is rather expensive. Therefore, from these reasons, it is not effective to allocate as large as N wavelengths to support traffic demands. Consequently, the MC-RWA problem will arise in BSONs.

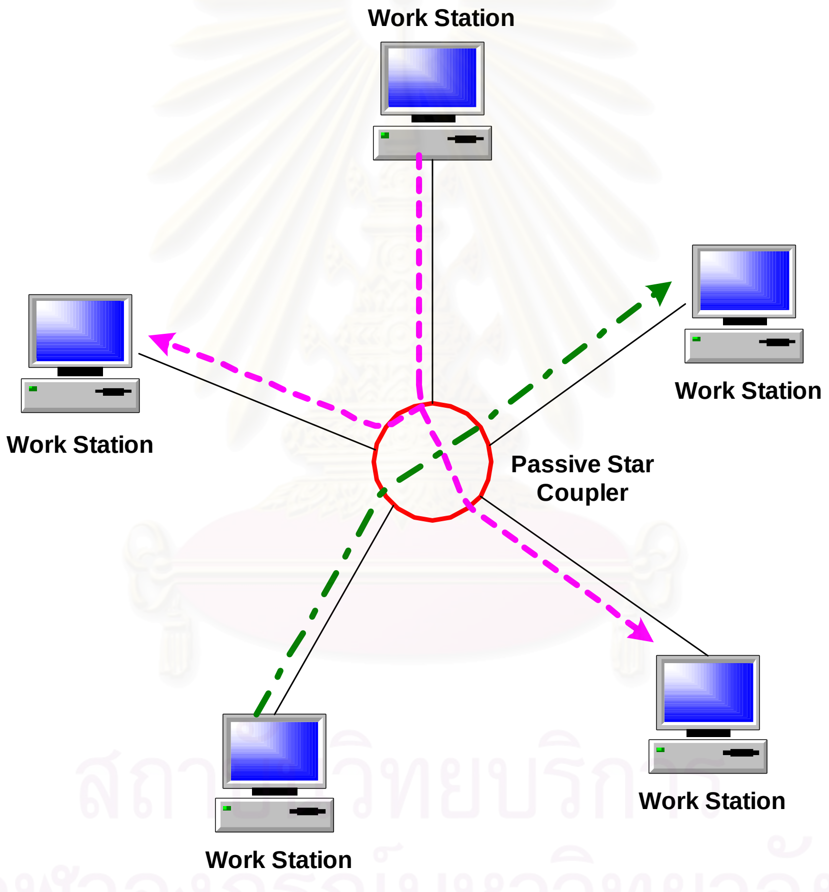


Figure 1.5: Broadcast-and-select optical network (BSON) architecture.

The definition of MC-RWA problem in BSONs is to, given the multicast traffic characteristic and the number of transceivers of each node, design multicast wavelength assignment scheduling algorithms so that the blocking probability is minimized. Note that the multicast routing assignment is not concerned with this problem definition because in BSONs, only a single path exists between each node pair. In addition, with this problem, it further leads to the problem of designing multicast multimedia access protocols in BSONs.

In literature, the MC-RWA problem in BSONs has been investigated in many research papers, for examples [42-46]. In [42, 43], multicast sessions are set up with the concept of single hop, while references [44-46] use the concept of multi-hop instead of single hop to carry multicast demands. With the single hop concept, if a multicast session arrives at a node and there are wavelength resources sufficient for it, the BSON then establishes a light-tree to support it and the data in the session is transported to all desired destinations without passing any intermediate node. Contrarily, in the multi-hop BSON, if in a part of destinations the corresponding receivers are not tuned to the wavelength of source node, the BSON is allowed to transmit data passing through some intermediate nodes so that the intermediate nodes retransmit data on the different wavelengths which match to the receiving wavelengths of that part of destinations. Comparing these two concepts, the research papers showed that the multi-hop concept generally provides lower blocking probability than the single hop concept, especially in the condition of high traffic load. However, the multi-hop concept employed in BSONs results in the higher network cost with respect to that of the single hop. This is because an extra cost is incurred for running the signaling of multi-hop concept.

In this thesis, we do not deal with the MC-RWA problem in BSONs because BSONs are not scalable and cost-effective for building transport optical networks as the case considered in the thesis, in which much larger service areas are covered with respect to those of BSONs. Being not scalable and cost-effective of BSONs [41] are due to the fact that the network size of BSON grows at the rate of the number of nodes (N). As N increases, the stability requirements for transmitters and receivers become critical since the selected wavelength must be received at the destination. In addition, when N increases, the optical signal power at the receiving end dramatically decreases because of the 1/N power split of the passive star coupler. Therefore, with these reasons, BSONs are not scalable and constrained to local areas, where a limited number of nodes can be physically connected.

Let us now consider the case of WANs. Since WANs are typically designed to cover relatively large service areas such as metropolitan domains, the high cost of fiber installation results in a network with low connectivity, where the network topology is arbitrarily connected. In this condition, the MC-RWA problem refers to as the problem of finding optimal routing and wavelength allocation patterns for given multicast sessions. However, since WANs lie in the areas where the traffic behavior is still dynamic as in the case of LANs, the MC-RWA problem in WANs thus associates with the dynamic traffic condition. In general, this problem is called *dynamic MC-RWA problem*.

Over the last few years, the dynamic MC-RWA problem has been investigated in [47, 48]. In [47], the researchers proved that the dynamic MC-RWA problem is a hard problem and falls in the class of NP-completeness [38, 49]. However, if the dynamic MC-RWA problem is decomposed to the multicast routing problem and the wavelength assignment problem, reference [47] showed that only the wavelength assignment problem can be solved in linear time. Thus, with these mathematical proofs, the researchers in [47] proposed a dynamic programming algorithm for the wavelength assignment problem in order to find near-optimal solutions with the objectives to minimize the number of hops of multicast trees and to minimize the number of transmitters used in a network. In [48], although the researchers decoupled the dynamic MC-RWA problem to the multicast routing problem and wavelength assignment problem as in [47], an approximation analytical method was alternatively presented to find the call-blocking probability. To model the analytical formulation, the path decomposition approach [50] is used. The results in [48] showed that the analytical method is useful to approximate the call-blocking probability in several optical multicast networks such as NSFNet network and 3×3 regular torus network.

As examined, the dynamic MC-RWA problem for WANs is however not relevant to the case of long-haul transport networks as considered in the thesis, where multicast traffic demands are inherently *quasi-static* and any traffic variations take place over long timescales. Hence, no traffic blocking is allowed in transport networks. In consequent, the dynamic MC-RWA problem for WANs turns out to be the *static MC-RWA problem* for the transport network environment.

In the case of transport networks, the static MC-RWA problem is defined as: given a set of multicast sessions, design effective algorithms to find optimal multicast routing and wavelength assignment for all given multicast sessions. In general, it is desirable to design effective algorithms so as to find MC-RWA solutions that are optimal with respect to the network cost or some network performance metrics.

In literature, the static MC-RWA problem for transport networks has been intensively studied in [29, 30, 40, 51-55]. In [30], the static MC-RWA problem is formulated as an optimization problem with two possible objective functions, namely, minimizing the network average packet hop distance, and minimizing the total number of transceivers in the networks. The benefit of using light-trees instead of lightpaths to support unicast and broadcast traffic was also quantitatively demonstrated in [30]. In [29], the researchers have an objective to assess the usefulness of implementing the multicasting in optical networks by comparing the results of networks with multicasting with those of network without multicasting. To achieve this, an MC-RWA heuristic algorithm was proposed. The simulation results in [29] indicated that making the multicasting in optical networks results in the average bandwidth saving and also the wavelength resource savings with respect to the case without multicasting.

In [51], the researchers discussed the QoS multicast in the MC-RWA problem. The QoS of multicasting in [51] was characterized by the upper bound on delay from a source to any destination along a tree. To find sub-optimal QoS trees, reference [51] proposed two heuristic algorithms for solving the MC-RWA problem with minimizing the number of wavelengths per link. The simulation results in [51] demonstrated that while all given multicast sessions satisfy the QoS agreement, the heuristic algorithm based on wavelength reassignment outperforms the one based on load balancing. Though the static MC-RWA problem of WDM networks was proved to be NP-hard in [56], reference [52] showed that only the problem of static wavelength assignment on a multicast tree is not NP-hard. In addition, the total cost to be optimized on a multicast tree including the costs of light splitting and wavelength conversion was defined and comprehensively investigated. To minimize the defined cost, a simple approximation algorithm was proposed and employed.

In [40], the static MC-RWA problem was examined with a consideration of two alternative MC-OXC architectures, *i.e.*, splitter-and-delivery (SaD) and multicast-only splitter-and-delivery (MOSaD) switches. Given multicast traffic demands, the results obtained from the ILP formulations suggested that MOSaD is more effective than SaD. Finally, in [53], the MC-RWA model employed in the study is based on the logical topology of network and allows that multiple multicast streams can be multiplexed on a light-tree. Moreover, in [53], the MC-RWA model takes the bounds on end-to-end delay of light-tree and the placement of wavelength converters and power splitters in consideration. In order to study the results of the model, the researchers proposed an integer linear program.

In this thesis, although we consider the static MC-RWA problem similar to that in the above references, our MC-RWA model analyzed here has significant differences. A network assumption used in all previous works is that there is only a single fiber per physical link (namely, *a single-fiber system*) and the aim is generally to determine the minimal number of wavelengths or number of transceivers used in networks. Considered in practice, such the assumption would currently be inappropriate in design. This is due to the fact that for all types of optical fiber available on the market, the maximum number of wavelengths per fiber is still restricted by many technical constraints. These constraints are due to: 1) the optical fiber itself, *e.g.*, chromatic dispersion, cross-talk, and several types of noise occurring from non-linearity; and 2) other devices coupled with optical fibers such as lasers, receivers, and optical amplifiers. Under this scenario, the maximum number of wavelengths per fiber should thus be included in the model as a new constraint and a more appropriate assumption should be *a multi-fiber system*, *i.e.*, allowing more than one fiber per physical link, instead.

Therefore, in the thesis, we include the multi-fiber system in our MC-RWA model and aim to study the effect of multi-fiber system by determining the minimal total number of fibers required as a function of the maximum number of wavelengths per fiber. To determine the minimal number of fibers, we present new exact ILP formulations. As differentiated from previous works, when multicast traffic demands are given, our proposed ILP formulations not only optimally route and assign wavelengths to light-trees, but also find optimal light-trees simultaneously. Therefore, the proposed ILP formulations actually provide optimal-cost solutions. Since the MC-RWA problem is NP-hard, we additionally present simple heuristic algorithms based on our ILP and develop simple lower bound techniques to validate the performance of our heuristic algorithms.

Moreover, while all research works in the references have focused on the static MC-RWA problem in transport networks based on the mesh design approach, it is surprise that the study of static MC-RWA problem for networks based on the alternative multi-ring design [36, 57-59] have not been addressed. The multi-ring design is one of popular network design techniques as prevalent used in several existing transport networks because of its simple implementation and low complicated operation. Hence, in the thesis, the MC-RWA problem is investigated not only with the mesh network design, but also with the multi-ring network design. Employing the proposed ILP formulations corresponding to each design method, the thesis presents a comparative study between the mesh and multi-ring designs including many design aspects such as the network resource requirements, and the complexity of network control and management.

At the end of this subsection, to complete the literature review of MC-RWA problem, there is another research area dealing with this issue. In [60], the researcher derived an upper bound on wavelength requirement for the multicasting in all-optical networks by employing some properties of expander graphs. In [61], a multicasting study for a class of regular optical networks such as linear arrays, rings, tori and hypercubes was provided. To be wide-sense non-blocking for multicast communications, the necessary and sufficient conditions on the minimum number of wavelengths required were also presented and proved.

1.3.2 Optical Protection Problem

In the study of protection problem in multicast optical WDM mesh networks, two main classes of protection systems are intensively considered here, that is, *point-to-point protection* and *multicast protection* systems. To regard this methodology, this section first surveys pervious studies concerned with point-to-point protection systems, and followed by the literature review of multicast protection systems.

1.3.2.1 Point-to-Point Optical Protection Problem

Point-to-point optical protection refers to as the techniques to recovery affected point-to-point connections or lightpahts after some network elements failed in optical WDM networks. Because the single link failures are the predominant form of failures in optical networks, we primarily focus on pervious works that considers point-to-point protection techniques against single link failures. A summary of survey contents is given and demonstrated in Figure 1.6.

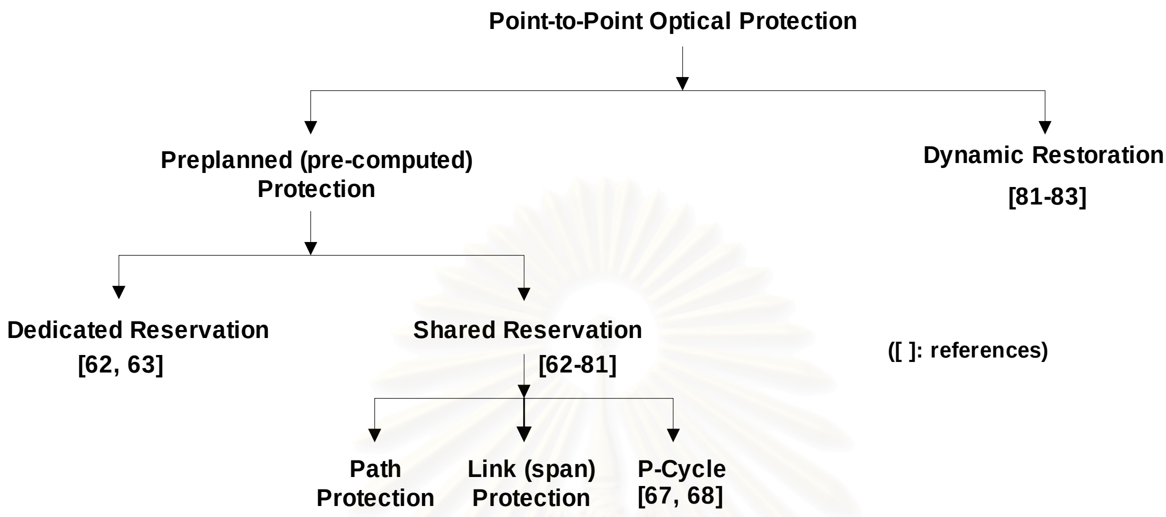


Figure 1.6: Different point-to-point optical protection schemes against single link failures.

As illustrated, the recovery techniques to restore affected lightpaths are typically classified into two classes [62]: the preplanned (pre-computed) protection and the dynamic restoration. The preplanned protection is that after setting lightpaths, a network immediately determines the backup paths for such lighpaths. In events of single link failure, the determined backup paths are activated against failures. With the preplanned protection, the network has to reserve a part of network resources as the *spare* exclusively used for supporting the backup paths.

Furthermore, in reserving spare resources for backup paths, the preplanned protection can be divided to two types: the dedicated and shared reservations as shown in Figure 1.6. In the dedicated reservation, the network will reserve the spare resources for backup paths of each working lightpath. Meanwhile, with the shared reservation, the spare resources in the network can be shared among several backup paths as long as these backup paths are not activated for protection simultaneously.

In literature, numerous research works have carried out on the preplanned protection problem. The work in [63] presented a comparison of capacity requirement among several preplanned protection techniques such as the dedicated protection, the shared-span and shared-path protections and also provided the ILP model for each protection technique. Moreover, the influence of average nodal degree of network on the capacity requirement for protection was quantitatively investigated. In [64], the classification of protection/restoration schemes was demonstrated and the mathematical models used to minimize the number of working and spare wavelengths for the preplanned protections were also presented. In addition, the advantages and disadvantages of each protection technique were technically discussed. In [65], the path and link protections were carried out. The ILP and stimulated annealing algorithm were provided to study the network installation cost required for each protection technique. How the designed stimulated annealing algorithm is effective was also studied by comparing its results to those obtained from the ILP.

In [41], the path and link protections were also investigated as in [65]. However, total number of working and spare fibers required against the single link failures is alternatively measured to qualify the disadvantages and advantages of such two protection approaches. The effect of network connectivity on the number of wavelengths required and the benefit of using wavelength converters for protection were also addressed in [41]. The work in [66] proposed a protection solution that is fast, distributed, and scalable. The concepts of demand bundling and optical virtual paths to ensure the network scalability both in terms of the traffic volume and network size were also investigated. Moreover, a data communication network used to support signaling messages of the optical network was discussed in detail. In [67, 68], the researchers proposed the concept of “p-cycle” to protect working routes against single link failures. With the p-cycle concept, spare optical fibers are formed to be spare rings and such spare rings are provided for restoration. The simulation results in [67, 68] showed that although networks with the p-cycle needs more spare capacity than those with path protection approach, the p-cycle approach inherently leads to more improved restoration time than the path protection approach.

As opposed to the preplanned protection, networks based on the dynamic restoration do not determine backup paths in advance before a failure occurrence and also do not dedicatedly reserve spare resources for the backup paths. When the failure arises and is detected, a network with dynamic restoration will calculate the new lightpaths to restore the disrupted ones and then choose resources for supporting such new lightpaths from available resources. As we can see, this technique is in general more resource utilization than the preplanned protection, but may not guarantee 100% restorability. Moreover, networks employing the dynamic restoration typically suffer from the disadvantages of long restoration time and complicated signaling system. The following is some examples of works related to the dynamic restoration.

In [81], the researchers proposed the simple formulations to calculate the restoration-switching time for several protection techniques and also described how to manage the restoration signaling when cables are cut. An efficient distributed algorithm to determine backup paths was also presented. The restoration processes used to improve the restoration time were introduced and qualitatively studied. Moreover, the work in [81] included a comparative study between the distributed restoration approach and the centralized protection approach in the aspects of the restoration speed and the overall cost to set the protection system. In [82], the capacity performance of dynamic provisioning in survivable WDM networks was intensively investigated. Three types of lighpahts were considered, that is, the unprotected, 1+1 protected and mesh-restored lightpaths. Moreover, to obtain the backup lightpaths, the discovery of topology information via the network routing protocols was addressed.

Apart from the research area demonstrated in Figure 1.6, there are a number of research studies concentrating on point-to-point protection approaches to handle node failures and dual fiber link failures. The work in [84] studied mesh-restorable networks with complete dual failure restorability. The computational results in [84] indicated that the spare capacity established to full protect against single link failures can be naturally used to protect a high average part of working demands against dual link failures. In [85], the researchers investigated networks that are in the state of maintenance. How to route some working paths out of maintained links was studied by using the span-protection approach.

Since optical WDM networks are usually designed as the optical layer to support different higher-layer services such as SDH/SONET connections, ATM virtual circuits, and IP datagram traffic, there are thus some studies focusing on the incorporation of protection approaches among the optical layer and the higher network layers. For example, the work in [86] presented two interaction techniques to decide which network layer should be first activated to handle the failure. The researchers in [87] used the simulation results to assess the attractiveness of each interaction technique. In [87], the researchers reviewed various protection and restoration techniques in an IP-over-WDM network. In addition, the work in [87] formulated the ILP program and developed the heuristic program to investigate the protection and restoration performances of IP-over-WDM networks.

In this thesis, while all the point-to-point protection approaches proposed in literature have been conducted to protect the point-to-point connections or lightpaths, we here alternatively propose the study of how to apply those point-to-point protection schemes to protect multicast traffic or light-trees against single link failures. Moreover, in the thesis, we shall provide the disadvantages and advantages of employing this protection idea in multicast WDM networks in such aspects as the capacity requirement, and the ease of fault operation and management.

In the study of optical protection problem, we investigate the protection approaches based on only the preplanning protection. This is because in transport networks considered here, it is preferable to use the preplanning protection to guarantee the restoration time and 100% survivability as opposed to the dynamic restoration.

1.3.2.2 Multicast Optical Protection Problem

Prior to surveying multicast optical protection problem in literature, the definition of multicast optical protection used in the thesis should be described first. The multicast optical protection refers to here as the protection techniques that are specifically designed for protecting multicast sessions or light-trees against single link failures on optical WDM networks.

In literature, specific protection systems for multicast services have been initially studied in ATM networks. With the benefit of management overhead, the virtual path (VP) is typically utilized for the restoration of ATM networks. In [88], the authors studied how to build multicast trees in self-healing ATM networks and presented a multicast restoration technique against single link failures. In [89], it is a continuous work of [88]. Several backup path schemes for multicast trees were provided and assessed. The backup bandwidth usage and the average restoration time are the simulation results to evaluate the restoration performance. Moreover, the capacity sharing techniques were discussed in [89].

Although we examine the multicast protection problem similar to the above references, the network technology studied in the thesis is however the WDM not the ATM. Therefore, the environment of network model to design multicast protection approaches between the WDM and ATM is considered different in several features such as the types of network capacity, the routing constraints, and the placement of multicast trees on networks to achieve the performance targets.

Let us now turn back to WDM networks. At the time of writing the thesis and under the literature available, we found two papers that directly researches the protection problem of WDM networks with multicast traffic. In [90], the authors aimed to protect multicast sessions in WDM networks by using the concept of directed-link disjointnees as originally proposed in [91]. This protection idea is considered similar to the dual-tree scheme for fault-tolerant multicast in [92]. With this idea, it is possible to set up a backup tree for recovering a disrupted tree. The ILP formulations were derived to minimize the cost to establish both working and backup trees. In addition, the work in [90] includes the limits of splitting fanout and the number of optical splitters in consideration of network design.

In [93], it is a continuous work of [90]. The authors proposed two new protection approaches for protecting multicast sessions against a single fiber cut. These two approaches are the segment and path-pair protection methods. Both methods allow spare capacity to be shared among backup disjoint paths of a multicast session on a network. As considered, these methods employ a limited spare resource sharing technique in computation of the protection cost. In addition, [93] introduces an ILP program and several heuristic algorithms to compute the cost to provision protection systems to optical networks. A study of dynamic provisioning of survivable multicast connections in WDM networks is also provided in [93].

However, our work in the thesis significantly differs from the work in [90, 93]. This is because the thesis proposes and studies the new multicast protection strategies that consider the fully spare resource sharing in determining the total network capacity. This is in contrast to [90, 93] that takes only the spare resource dedication and limited spare resources sharing in determination. While the single fiber system is generally assumed in [90, 93], we study more sophisticated optical networks where the multiple fiber system is employed. Moreover, the thesis studies three techniques to place the spare wavelength channels to achieve 100% survivability against single link failures. With these techniques, they let us understand a tradeoff between the spare fiber requirement and the spare fiber management. All the protection approaches studied in the thesis and their classification are summarized and shown in Figure 1.7.

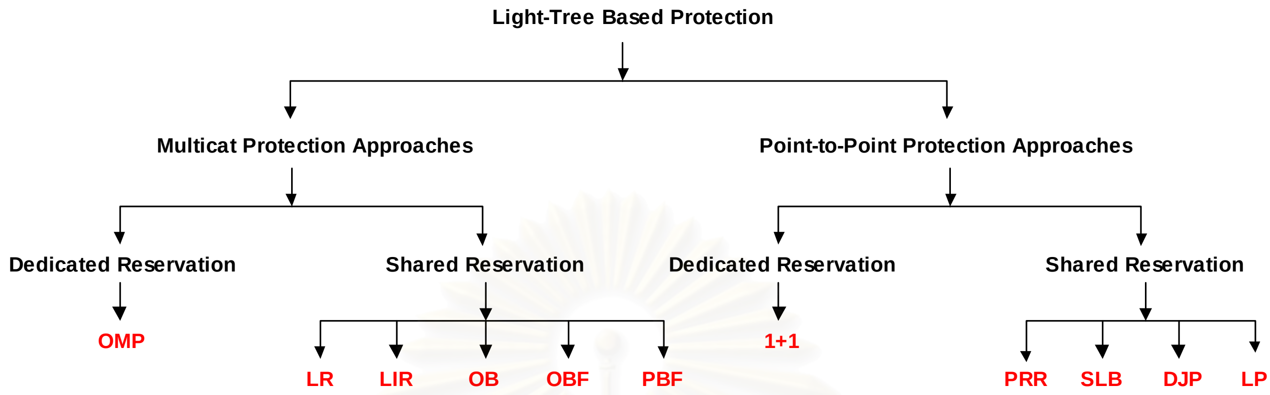


Figure 1.7: Classification of light-tree based protection schemes studied in the thesis.

1.3.3 Multicast Routing under Optical Layer Constraints

To route light-trees and their backup trees for protection on optical WDM networks, network designers should establish them not only to meet network performance targets such as the minimum cost or the maximum throughput, but also to satisfy the technical constraints occurred in the optical layer of optical networks. Examples of optical layer constraints are the power loss introduced when the optical signal transverses several fibers and optical splitters, the limited number of wavelength multiplexed in a fiber, the limited fanout of optical splitters and also the wavelength conversion capability of MC-OXCs in optical networks. With these optical layer constraints, they have created a new research issue in MC-RWA and multicast optical protection problems as these constraints are not the problem experienced in electronic circuit- or packet-switched networks.

In literature, the MC-RWA problem with the power-efficient design was studied in [40]. The calculation of power loss for unicast and multicast connections was also presented and included to be a constraint in the ILP program maximizing overall profit obtained from the traffic establishment. In [94], the problem of light-tree routing with optical power budget constraints was investigated. To guarantee the optical signal quality received by destination nodes, the heuristic algorithm was proposed. The simulation results in [94] demonstrated that balanced light-trees tend to provide the better performance in terms of the signal quality than unbalanced light-trees.

In [53] and [95], the MC-RWA problem with sparse light splitting was studied. The ILP programs and heuristic algorithms were presented to determine optimal places of optical power splitters in WDM networks. The numerical results in both references provided the same conclusion that for a set of static multicast demands, the network with spare light splitting generally provides the good performance as same as the network where optical power splitters are established within all network nodes.

Finally, for the research works related to the wavelength conversion capability, the works in [39] and [90] investigated this issue by employing the mathematical formulations. The computational design outcomes showed that the wavelength conversion is beneficial to reduce the cost of setting the multicast traffic in both cases with and without protection against single link failures.

However, in all these analyses, there are limited results to demonstrate the influence of the limited fanout of optical splitters and the wavelength conversion capability on the capacity requirement in both MC-RWA and optical protection problems. Moreover, no conclusion about the effect of limited number of wavelengths per fiber on the capacity requirement has been drawn in literature. Therefore, in the thesis, the detailed investigations are carried out to study the capacity requirement as the functions of 1) the limited fanout, 2) the wavelength conversion capability of MC-OXCs, and 3) the limited number of wavelengths per fiber in both MC-RWA and optical protection problems.

1.4 Objectives of the thesis

1 Study the problem of routing and wavelength allocation for accommodating multicast traffic in optical WDM networks which are implemented based on two network design approaches, *i.e.*, mesh and multi-ring design approaches, and also provide a comparative study between those two design approaches in terms of the wavelength capacity requirement.

2. Investigate the influence of three optical layer constraints, *i.e.*, the maximum number of wavelengths multiplexed per fiber, the splitting degree (fanout) of

optical power splitters, and the wavelength conversion capability of optical cross-connects, on the wavelength capacity requirement in optical WDM mesh and multi-ring networks with multicast traffic.

3. Propose six multicast protection strategies, *i.e.*, light-tree reconfiguration protection (LR), light-tree-interrupted reconfiguration protection (LIR), optical branch protection (OB), optical-branch-fixed protection (OBF), physical-branch-fixed protection (PBF), and optical mesh protection (OMP) strategies, to protect multicast traffic against all single link failures in WDM mesh networks.
4. Present how to apply five protection approaches, *i.e.*, physical-route reconfiguration protection (PRR), single link basis protection (SLB), disjoint path protection (DJP), link protection (LP), and 1+1 protection approaches that are originally designed for point-to-point traffic, to protect multicast traffic against all single link failures in WDM mesh networks.
5. Provide an analysis and comparison in the aspects of the working and spare capacity requirement, the ease of management and operation, and the practical feasibility among those eleven protection techniques (*e.g.*, six approaches in 3. and five approaches in 4.) and also study advantages and disadvantages of employing point-to-point protection systems instead of multicast protection systems.
6. Investigate the effect of the maximum number of wavelengths multiplexed per fiber, the splitting degree (fanout) of optical power splitters, and the wavelength conversion capability of optical cross-connects on the working and spare capacity requirement in those eleven protection approaches.

1.5 Scope of the thesis

As the MC-RWA and optical protection problems are the main problems investigated in the thesis, the scope of research works can be described as follows.

1.5.1 Scope of the Study of MC-RWA Problem

1. Propose mathematical formulation models to calculate the minimum number of fibers needed to support given multicast sessions in optical WDM networks that are implemented based on the mesh and multi-ring design approaches.
2. Develop techniques to find lower bounds on the minimum number of fibers needed in both optical WDM mesh and multi-ring networks.
3. Design ILP-based heuristic algorithms for assigning wavelengths to light-trees in WDM mesh and multi-ring networks with multicast traffic.
4. Provide a comparative study between the mesh and multi-ring design approaches in the aspects of the minimum number of fibers, the system capacity, the capacity utilization, and the ease of operation and management.
5. Analyze the influence of three optical layer constraints, *i.e.*, the maximum number of wavelengths multiplexed per fiber, the limited fanout of optical power splitters, and the wavelength conversion capability of optical cross-connects, on the wavelength capacity requirement in WDM mesh and multi-ring networks with multicast traffic.

1.5.2 Scope of the Study of Optical Protection Problem

1. Propose six multicast protection strategies, *i.e.*, light-tree reconfiguration protection (LR), light-tree-interrupted reconfiguration protection (LIR), optical branch protection (OB), optical-branch-fixed protection (OBF), physical-branch-fixed protection (PBF), and optical mesh protection (OMP) strategies, to protect multicast sessions against all single link failures in WDM mesh networks.
2. Present how to apply five point-to-point protection approaches, *i.e.*, physical-route reconfiguration protection (PRR), single link basis protection (SLB), disjoint path protection (DJP), link protection (LP), and 1+1 protection approaches, to protect multicast traffic against all single link failures in WDM mesh networks.

3. Propose mathematical formulation models to calculate the minimum number of working and spare fibers and the minimum number of spare fibers alone that are required for those eleven protection approaches (*e.g.*, six approaches in 1. and five approaches in 2.).

4. Provide an analysis and comparison in the aspects of the working and spare capacity requirement, the ease of management and operation, and the practical feasibility among those eleven protection techniques and also study advantages and disadvantages of employing point-to-point protection systems instead of multicast protection systems.

5. Study three spare capacity placement techniques, *i.e.*, spare fiber + working fiber method (SF+WF), spare wavelength channel + working wavelength channel method (SW+WW), and spare wavelength channel + working wavelength channel method with stub release (SW+WW+SR), in terms of the spare fiber requirement and the spare fiber management for those eleven protection methods.

6. Analyze the effect of the maximum number of wavelengths multiplexed per fiber, the limited fanout of optical power splitters, and the wavelength conversion capability of optical cross-connects on the working and spare capacity requirement in those eleven protection approaches.

7. Develop ILP-based heuristic algorithms for wavelength allocation in optical WDM networks with those eleven protection approaches.

8. Develop a sequential solution algorithm to estimate the minimum number of working and spare fibers required in large-scale WDM networks in which those eleven protection approaches are employed.

1.6 Expected Prospects

1. Acquire a basic knowledge in the implementation of mathematical formulation models for solving the MC-RWA and optical protection problems in multicast optical WDM networks.

2. Understand the effect of the maximum number of wavelengths multiplexed per fiber, the limited fanout of optical power splitters, and the wavelength

conversion capability of optical cross-connects on the wavelength capacity requirement in multicast WDM mesh and multi-ring networks and also on the working and spare capacity requirement for each studied protection strategy.

3. Understand technical differences between multicast optical WDM networks that are designed by the mesh and multi-ring approaches in terms of the minimum number of fibers required, the system capacity requirement, the capacity utilization, and the ease of operation and management.
4. Know the attractiveness of using each studied protection strategy to protect multicast sessions against single link failures in WDM mesh networks in features of the spare capacity requirement and the operation complexity of restoration process and also know advantages and disadvantages of employing point-to-point protection systems instead of multicast protection systems to achieve 100% survivability in multicast WDM networks.
5. Understand a tradeoff between the spare fiber requirement and the spare fiber management in optical WDM networks based on three studied spare capacity placement techniques.
6. Know a performance of using the presented sequential solution algorithm in approximating the minimum number of working and spare fibers required in each studied protection approach.

1.7 Research Procedure

1. Study previous research papers relevant to the research works in the thesis**.**
    - 1.1 Study research papers relevant to the MC-RWA problem.
    - 1.2 Study research papers dealing with the optical protection problem.
2. Based on the knowledge provided in previous research works, the research steps for the MC-RWA problem are described as follows.
    - 2.1 Implement ILP programs for solving the MC-RWA problem in mesh and multi-ring WDM networks.
    - 2.2 Test the correctness of designed ILP programs by using several networks and multicast traffic matrices.

   2.3 With the designed ILP programs, develop heuristic algorithms for wavelength allocation in both mesh and multi-ring networks.

   2.4 Develop techniques to find lower bounds on the minimum number of fibers required in mesh and multi-ring networks.

   2.5 Collect and analyze computational results obtained from the designed ILP programs, the lower bound techniques and the heuristic algorithms.

   2.6 Summarize the major findings as we found in step 2.5.

3. For the optical protection problem in multicast WDM mesh networks, the research procedure is described as below.

   3.1 Formulate ILP model for each studied protection strategy.

   3.2 Test the correctness of designed ILP programs by using several networks and multicast traffic metrics.

   3.3 With the designed ILP models, develop heuristic algorithms for wavelength allocation for all studied protection schemes.

   3.4 Collect and analyze computational results obtained from the designed ILP programs of all studied protection schemes.

   3.5 Summarize research results as found in step 3.4

   3.6 Develop the sequential solution algorithm for all studied protection schemes.

   3.7 Test the performance of the sequential solution algorithm by comparing its simulation results with the computational results collected in step 3.4

   3.8 Conclude the performance of the designed sequential solution algorithm.

4. Collect the conclusions in steps 2.6, 3.5, and 3.8 and also check whether those conclusions meet all the objectives of the research work of the thesis.

5. Write the thesis.

1.8 Organization of the thesis

As proposed in sections 1.6 and 1.8, this thesis intends to study the design of multicast WDM networks. The rest of thesis is organized as follows.

Chapter 2 studies the MC-RWA problem. The basic ideas of the mesh and multi-ring design approaches are elaborately discussed. Three techniques to allocate wavelengths to light-trees of multicast sessions are proposed. Moreover, to determine wavelength capacity requirements of multicast WDM networks, ILP formulations corresponding to the presented wavelength allocation methods are introduced for optimal solutions of MC-RWA problem. Lower bounds on the fiber requirement are also discussed. Finally, heuristic algorithms for assigning wavelengths to light-trees are implemented and described.

In Chapter 3, ILP formulations, lower bound techniques, and heuristic algorithms as presented in Chapter 2 are conducted to study the MC-RWA problem. Two large optical networks are employed as experimental networks. Based on numerous computational results, the performance of lower bounds techniques is analyzed. A comparative study between the mesh and multi-ring design schemes is then provided. Finally, Chapter 3 discusses the influences of the limited fanout, the wavelength conversion at MC-OXC nodes, and the network connectivity on the wavelength capacity requirement.

Chapter 4 deals with the link protection in multicast WDM mesh networks. Two main categories of light-tree based protection strategies, *i.e*, multicast and point-to-point protections, are considered. For the class of multicast protection, six new protection approaches are proposed. Meanwhile, for the class of point-to-point protection, five protection approaches are proposed. To project a evolution picture of designing studied protection approaches, a new simple diagram is presented. This diagram is very useful to enhance the understanding of restoration mechanism, the restoration management complexity, and also the fiber requirement for studied protection methods. Moreover, in this chapter, techniques to allocate wavelengths to restoration paths and to place spare wavelength channels so as to achieve 100% link restorability are introduced.

In Chapter 5, ILP mathematical models of all protection approaches in Chapter 4 are derived. Wavelength assignment algorithms of all protection approaches are also presented in this chapter.

Chapter 6 provides results and discussion of the multicast optical protection problem. With several test networks, the computational results are analyzed in the aspects of the spare fiber requirement, the fiber utilization and also the network capacity requirement. In addition, a comparative study among studied light-tree protection approaches is presented.

In Chapter 7, an ILP-based heuristic algorithm for designing large survivable multicast WDM networks is introduced. To study the performance of the proposed ILP-based algorithm, several small-and large-sized networks are employed.

Finally, Chapter 8 presents a summary of major findings in this thesis and provides suggestions for future work.

Chapter 2

Multicast Routing and Wavelength Assignment (MC-RWA)

2.1 Introduction

In this chapter, the multicast routing and wavelength assignment in both mesh and multi-ring optical WDM networks are technically discussed. Moreover, ILP mathematical models, wavelength assignment algorithms, and techniques to determine lower bounds on the fiber requirements are presented here.

This chapter is organized as follows. Section 2.2 describes the definition of light-tree to support multicast sessions. Section 2.3 describes the concepts of mesh and multi-ring design methods. In section 2.4, we formally state our MC-RWA problem definitions based on both design techniques as well as the network assumptions used in the problems. The wavelength allocation policy of light-trees is introduced in section 2.5. In section 2.6, the mesh and multi-ring ILP formulations are developed. Based on the ILP models, the heuristic algorithms for the MC-RWA problem are proposed in section 2.7. Finally, section 2.8 presents the lower bounds on the total number of fibers required by both design methods.

2.2 Light-Tree Definition

Prior to studying the multicast routing and wavelength assignment in optical WDM networks, the definition of light-tree to serve multicast sessions should be described first.

In the thesis, a light-tree is defined as a combination of *optical branches* [96]. An optical branch is here defined as a lightpath provided to connect between two nodes that are members of a multicast session. To reach all members of the multicast session, the optical branches to form the light-tree must cover all members of the multicast session. Figure 2.1 shows an example of a light-tree in accordance with the definition.

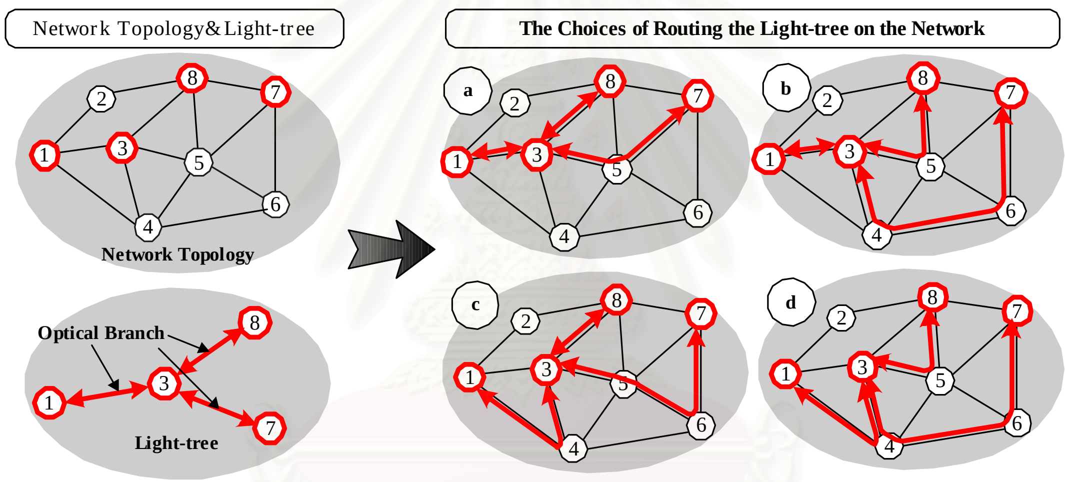


Figure 2.1: An example of a light-tree spanning on the network.

As illustrated, Figure 2.1 shows a light-tree composing of three optical branches 1-3, 3-8, and 3-7. The end nodes of each optical branch are the members of the light-tree. As we can see, the nodes of light-tree which are capable of replicating and splitting the data information must be the members of multicast session. In this example, it is node 3. Hence, at node 3, optical power splitters have to be included within its OXC.

In addition, Figure 2.1 shows that the sample light-tree is created on the logical topology of the optical network. Thus, there exist choices to accommodate the light-tree on the physical topology. In Figure 2.1, four different routing patterns for accommodating the light-tree are given as the examples.

2.3 Mesh and Multi-Ring Design Approaches

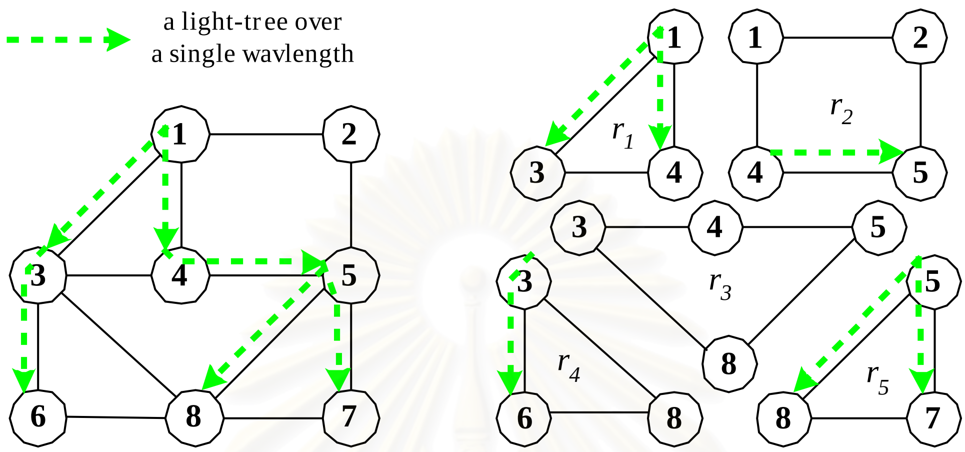
In this section, the concepts of mesh and multi-ring design techniques for realizing optical transport networks are described. Let us first explain the concept of the multi-ring design approach.

2.3.1 Multi-Ring Design Approach

The multi-ring design approach historically originated from the fact that the use of only a single ring to construct optical transport infrastructures or long-haul networks is, in most cases, not practically feasible. This is because: (1) employing a single ring network to cover all nodes of a large network may result in inefficient bandwidth utilization, (2) with a technical constraint, the number of network nodes may exceed the limit for a single ring, and (3) the QoS of network services may fail in single ring networks. For these reasons, we therefore need to consider a network design employing multiple rings instead.

In the multi-ring approach, the designed network is built by a set of rings that covers all nodes and spans of the network. To implement a ring, the number of optical add-drop multiplexers (OADMs) is needed and established at the ring nodes. OADMs have the functions to add, drop, and transit traffic demands to reach their final destinations. To support unicast traffic, an optical path connecting between a source and destination is routed around a ring of the network. If the source and destination are on separate rings, a number of rings will be required to serve the optical path. Therefore, to hand-off the traffic between the rings, OXCs are typically exploited as a means to bridge and switch the traffic to cross over the rings. Likewise, a multicast session can be served on a multi-ring network by embedding a corresponding light-tree on the rings. To route a light-tree, the thesis has a criterion that each branch of the light-tree, *e.g.*, between a source and destination or between the destinations, must be accommodated over a single ring; see Figure 2.1, for example. Thus, from the description, the main problem of designing multi-ring optical networks is the selections of rings from the number of possible rings and the patterns of the routing and wavelength allocation with an objective to minimize the network cost.

source	destination
1	**3, 4 , 5, 6 , 7, 8**



Mesh Design	
Link i.d.	**No. fibers**
(1,3)	1
(1,4)	1
(3,6)	1
(4,5)	1
(5,8)	1
(5,7)	1
Total No. fibers =	**6**

Multi-Ring Design		
Ring i.d.	**Ring Graph**	**No. fibers**
r_1	1-3-4	3
r_2	1-2-4-5	4
r_3	3-4-5-8	0
r_4	3-6-8	3
r_5	5-8-7	3
Total No. fibers =		**13**

Figure 2.2: An example of the routing and wavelength allocation and the calculation of the number of fibers needed for a multicast session under the mesh and multi-ring design techniques.

2.3.2 Mesh Design Approach

Although the employment of multiple rings to implement large backbone networks is technically rather simple and has advantages in network management and operation, multi-ring networks are less flexible in aspects of the network scalability and serving ongoing growth in traffic demand. Moreover, multi-ring networks usually have inefficient capacity utilization since the number of fibers of all nodes of a ring must be equal and the traffic is restricted to be routed around the rings. Therefore, to eliminate these drawbacks and improve the capacity utilization, the mesh network design is deployed as an alternative network solution. Mesh networks exploit OXCs to be allocated at all nodes of networks for the traffic switching instead of using OADMs as in multi-ring networks. Accordingly, the optical connections and light-trees can be made on the networks without the considerations of ring routing and capacity constraints. This consequently results in greater flexibility to choose paths and trees over mesh networks, and also more optimal placement of optical fibers on the links of the networks. Hence, this makes it possible to optical fiber saving with respect to multi-ring networks. Figure 2.2 shows an illustrative example of an optical network designed by the mesh and multi-ring methods with a given multicast traffic session. Figure 2.2 also demonstrates how to determine the number of fibers required for each design technique. As shown in Figure 2.2, the main problem of the mesh optical network design is to find the routing and wavelength patterns, and to use as few network resources as possible.

2.4 Problem Definitions and Network Assumptions

Consider an optical network represented by an undirected graph $G = (N, L)$, where N denotes a set of optical nodes, $i = \{1,2,3,...N\}$, with $|N| = N$. Meanwhile, the physical links are represented by a set of undirected links, $L \subseteq N \times N$, where a physical link ij is in the set L if there exists a link connecting nodes i and j. In the model, we assume that each physical link is bi-directional and may consist of more than one optical fiber to serve the traffic demands of the network. Each optical fiber is limited to multiplexing the number of wavelengths up to M. The average nodal degree of a network, $\bar{d}$, is defined as the average number of physical links incident at the nodes of the network:

$$\bar{d} = \frac{2L}{N}. \tag{2.1}$$

At each node of the network, OXCs for mesh networks and OADMs for multi-ring networks are established to route the traffic from sources to destinations and can also transmit or terminate the traffic if the OXC and OADM acts as the source or destination, respectively. To serve the multicast traffic, all nodes of the network are equipped with optical splitters to route and split the multicast traffic to reach the sets of its destinations. Optical splitters are characterized by the fanout, Δ, the maximum splitting number. For example, if an optical power splitter is able to split an optical signal to at most 3 output ports, its fanout will be 3. Usually, one of the output ports of the optical splitter is connected to drop the signal locally at the node and the remaining output ports are switched to different channels on outgoing fiber links. In the model, the optical switching is also assumed to be strictly non-blocking in the spatial domain and in the reconfiguration sense. The multicast communications of the network are defined as a set of $R = \{r_1(s_1, D_1), r_2(s_2, D_2),..., r_K(s_K, D_K)\}$ with $K = |R|$, where $r_k(s_k, D_k) \in R$ represents a multicast traffic request for setting up a light-tree from the source s_k to a group of destinations D_k $(s_k \notin D_k)$. Note that the light-trees designed in this thesis are based on the virtual topology of the network. This means that each branch of a light-tree can be routed over one of the possible paths on the physical topology.

As we already introduced all network assumptions that we use in the model, we are now ready to provide the formal definitions of our MC-RWA problems.

The MC-RWA problem definition of the mesh network design**:** Given an undirected graph $G = (N, L)$ denoting an WDM optical network, a set of multicast traffic requests (R), the number of maximal wavelengths per fiber (M), and the fanout (Δ), find a set of light-trees (T), and the patterns of routing (π_r) and wavelength assignment (π_λ) corresponding to the set of light-trees, such that the total number of optical fibers to support the light-trees is minimal. Namely,

$$Z^*_{mesh}(M, T, \pi_r, \pi_\lambda, \Delta) \le Z_{mesh}(M, T', \pi'_r, \pi'_\lambda, \Delta),$$

where $Z^*_{mesh}(M, T, \pi_r, \pi_\lambda, \Delta), Z_{mesh}(M, T', \pi'_r, \pi'_\lambda, \Delta)$ are the minimal number of optical fibers required and any feasible solution, respectively.

The MC-RWA problem definition of the multi-ring network design**:** Given an undirected graph $G = (N, L)$ denoting an WDM optical network, a set of multicast traffic requests (R), the number of maximal wavelengths per fiber (M), and the fanout (Δ), find a set of light-trees (T), a set of rings (Φ), and the patterns of routing (π_r) and wavelength assignment (π_λ) corresponding to the set of light-trees, such that the total number of optical fibers to support the light-trees is minimal. Namely,

$$Z^{*}_{ring}(M,T,\Phi,\pi_r,\pi_\lambda,\Delta) \le Z_{ring}(M,T^{'},\Phi^{'},\pi^{'}_r,\pi^{'}_\lambda,\Delta),$$

where $Z^{*}_{ring}(M,T,\Phi,\pi_r,\pi_\lambda,\Delta), Z_{ring}(M,T^{'},\Phi^{'},\pi^{'}_r,\pi^{'}_\lambda,\Delta)$ are the optimal solution of the multi-ring network design and any feasible solution, respectively.

2.5 Multicast Wavelength Allocation Policy

As demonstrated in Figure 2.2, the sample light-tree is spanned on the sample network and a single unique wavelength is assigned to all its branches (source to destination, destination to destination) along its physical links. Considered from the wavelength assignment perspective, the wavelength assignment scheme illustrated in Figure 2.2 is actually one of the possible techniques for assigning wavelengths to light-trees. In this section, we introduce a set of the multicast wavelength assignment techniques deployed in mesh and multi-ring networks and all techniques are elaborately studied in this thesis.

On a WDM network, we classify the wavelength assignment methods for multicast communications into three different methods as follows:

(1) *Light-tree method (LT)*: for this method when setting up a light-tree on an optical network, we are able to choose only a single wavelength to every branch concatenated to form the light-tree (one wavelength to one light-tree).

(2) *Virtual Light-tree method (VLT)*: an optical network using the VLT method has an ability to assign wavelengths to a light-tree based on a *link-by-link fashion*, *i.e.*, a wavelength on a physical link serving the light-tree can differ from that of other physical links. With this scheme, optical networks must therefore include wavelength converters at all network nodes.

(3) *Partial Virtual Light-tree method (PVLT)*: for this method, optical networks are still able to assign several wavelengths to a light-tree as with the VLT technique. However, optical networks using this method will allocate the wavelengths based on a *branch-by-branch fashion* instead, which is more stringent than the VLT method. Namely, a wavelength of a

branch of a light-tree can differ from that of other branches, but the wavelength along the links of a branch cannot be changed. Therefore, to employ the PVLT method, wavelength converters are needed as with the VLT method. However, we anticipate that the number of wavelength converters used for the PVLT approach would be less than that for the VLT approach. Note that the PVLT approach is a compromise method between the LT and VLT methods.

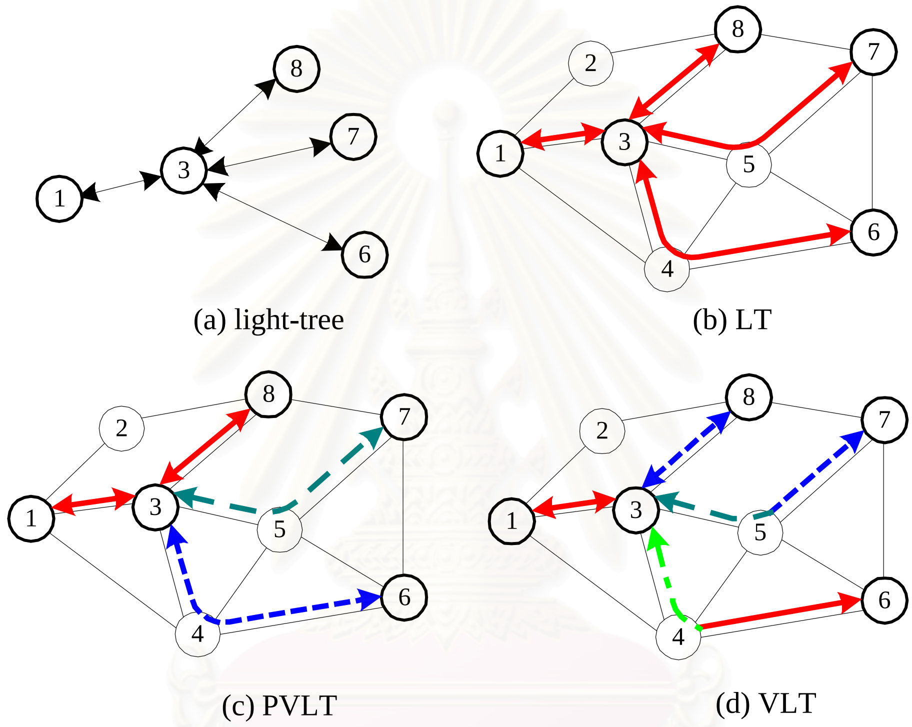


Figure 2.3: Multicast wavelength assignment techniques: (a) a light-tree composed of four optical branches. (b) Light-Tree (LT) technique, (c) Partial Virtual Light-Tree (PVLT) technique, and (d) Virtual Light-Tree (VLT) technique. Different styles of line refer to different wavelengths allocated for the sample light-tree.

To clearly understand the mechanism of each proposed wavelength assignment technique, an illustrative example of allocating wavelengths for a light-tree is given in Figure 2.3.

2.6 Mesh and Multi-Ring Multicast ILP Formulations

In this section, new ILP formulations are developed for solving the MC-RWA problems as defined in section 2.4. Although, we concentrate only on the study of the multicasting in WDM networks, the ILP models developed here can also be applied for unicast and broadcast traffic. This is because unicast and broadcast communications are special cases of multicast communication. Therefore, the proposed ILP models are actually generalized mathematical models for determining the network resources for serving any type of traffic demands.

2.6.1 Notations

Let us introduce the parameters (or inputs of the problem) and the variables (or outputs of the problem) used to form the proposed ILP formulations. In the following, we define:

Network Parameters:

N	total number of nodes of the network;
L	total number of physical links of the network;
$K = \|R\|$	total number of multicast traffic requests of the network;
$r_k(s_k, D_k)$	multicast traffic request r_k from source s_k to set of destinations D_k ;
t_{r_k}	total traffic demand of the multicast traffic request r_k in units of wavelength channels;
Δ	the fanout of optical splitters;
M	a maximal number of wavelengths per fiber;
$\delta_{ij,p}^{sd}$	takes the value of one if route p of node pair sd passes through link ij , and zero, otherwise;
P_{sd}	a set of candidate routes of node pair sd
Q	a set of possible rings to form the network;
n_q	total number of physical links of ring $q \in Q$;
$\zeta_{p,ij}^{sd,q}$	takes the value of one if route p of node pair sd of ring q passes through link ij and zero, otherwise;

I_∞ an arbitrarily high constant integer;

Network Variables:

f_{ij} total number of optical fibers on physical link ij ;

$x_{r_k}^{ij}$ a Boolean variable, an optical branch between nodes i and j to form a light-tree for carrying multicast demand r_k ;

$a_{r_k,p}^{sd}$ a candidate physical route p of node pair sd for multicast demand r_k (for the VLT system);

$a_{r_k,p,\lambda}^{sd}$ a candidate physical route p of node pair sd occupying wavelength λ for multicast demand r_k (for the LT and PVLT systems);

$W_{r_k,\lambda}$ wavelength channel λ occupied by multicast demand r_k (only for the LT system);

Rf_q total number of optical fibers of a link of ring q (every link of ring q has the same number of optical fibers);

$ar_{r_k,p}^{sd,q}$ a candidate physical path p of node pair sd for multicast demand r_k routed over ring q , *i.e.*, a clockwise or counter-clockwise path (for the VLT system);

$ar_{r_k,p,\lambda}^{sd,q}$ a candidate physical path p of node pair sd for multicast demand r_k routed over ring q with wavelength λ (for the LT and PVLT systems).

In the next subsection, we present the new ILP formulation based on the logical network topology for finding the optimal light-tree structures to carry a given set of multicast traffic demands.

2.6.2 Light-Tree Creation Formulation

To determine an optimal light-tree T_k for supporting multicast request, $r_k(s_k, D_k)$, let us construct a fully connected logical graph $G_k = (N_k, A_k)$ corresponding to $r_k(s_k, D_k)$. The set of nodes N_k of graph G_k has elements consisting of s_k and the set of destinations, D_k , namely $N_k = \{i \in N_k | i \in D_k \vee i = s_k\}$, and $|N_k|$ is defined as the total number of nodes N_k. Meanwhile, the set of logical arcs A_k is defined mathematically as $A_k = \{ij \in A_k \mid i, j \in N_k \wedge i \neq j\}$.

Based on the graph, $G_k = (N_k, A_k)$, we can develop the light-tree formulation by employing a concept of transforming the graph G_k to the optimal light-tree T_k. In the transformation, some of the logical arcs A_k are taken out from the graph G_k. We define for each arc, $ij \in A_k$, a Boolean variable $x_{r_k}^{ij}$ which is equal to one if arc ij is included in the light-tree T_k as an optical branch, and zero, otherwise. Since the light-tree should have $|N_k| - 1$ optical branches, the first two constraints of the formulation are

$$\sum_{ij \in A_k} x_{r_k}^{ij} = |N_k| - 1, \qquad (2.2)$$

$$x_{r_k}^{ij} \in \{0,1\}, \qquad \forall ij \in A_k. \qquad (2.3)$$

Moreover, based on the definition of a tree, the light-tree T_k should not contain a cycle and should be connected. Given a subset S of N_k, we define a *cutset* $\vartheta(S)$ by $\vartheta(S) = \{ij \in A_k \mid i \in S, j \notin S\}$. Therefore, we can express the tree definition in terms of the constraints:

$$\sum_{ij \in \vartheta(S)} x_{r_k}^{ij} \geq 1, \qquad \forall S \subset N_k, S \neq \phi, N. \qquad (2.4)$$

For optical networks, another limitation of the multicasting is the performance of the optical splitters, characterized by the fanout Δ. Therefore, the light-tree solution should satisfy this limit by using the constraints:

$$\sum_{j: ij \in A_k} x_{r_k}^{ij} \leq \Delta, \qquad \forall i \in N_k. \qquad (2.5)$$

2.6.3 Mesh Network Design Formulation

For the MC-RWA problem definition of the mesh network design, we can describe the corresponding ILP formulation based on an optical network $G = (N, L)$ and the light-tree constraints introduced above as follows.

• VLT wavelength assignment method

Minimizing the total number of fibers:

$$Z^{*}_{mesh} = \min : \sum_{ij \in L} f_{ij} \qquad (2.6)$$

subject to the constraints (2.2)-(2.5), and:

$$\sum_{p \in P_{sd}} a^{sd}_{r_k,p} = t_{r_k} \times x^{sd}_{r_k} , \quad \forall sd \in A_k , \forall r_k \in R \qquad (2.7)$$

$$M \times f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a^{sd}_{r_k,p} \delta^{sd}_{ij,p} \geq 0 , \qquad \forall ij \in L \qquad (2.8)$$

$$a^{sd}_{r_k,p} \in Z^{+} , \quad \forall p \in P_{sd} , \forall sd \in A_k , \forall r_k \in R \qquad (2.9)$$

$$f_{ij} \in Z^{+} , \qquad \forall ij \in L . \qquad (2.10)$$

As formulated for the VLT wavelength allocation technique, the objective function (2.6) is the minimization of the total number of optical fibers needed to support the multicast demand set, R . Constraint sets (2.2), (2.3), (2.4), and (2.5) as introduced in the pervious subsection are contained in the formulation to find the optimal light-trees. Constraints (2.7) ensure that exactly physical routes are selected for optical branches of the light-trees. Due to the link-by-link wavelength assignment of VLT, constraint set (2.8) states that the wavelength capacity of each physical link should be sufficient to meet the multicast traffic load crossing to it. Finally, constraints (2.9) and (2.10) limit the network variables of the physical routes and optical fibers to be in the nonnegative integer set, Z^{+}.

• PVLT wavelength assignment method

For the PVLT system, a physical route selected for an optical branch of a light-tree requires the same wavelength along the path. Therefore, in contrast to the VLT systems, a wavelength dimension is needed. Hence, the ILP formulation of the PVLT is as below.

Minimizing the total number of fibers:

$$Z^*_{mesh} = \min : \sum_{ij \in L} f_{ij} \ , \tag{2.11}$$

subject to the constraints (2.2)-(2.5), and:

$$\sum_{p \in P_{sd}} \sum_{\lambda=1}^{M} a^{sd}_{r_k,p,\lambda} = t_{r_k} \times x^{sd}_{r_k} \ , \quad \forall sd \in A_k, \forall r_k \in R \tag{2.12}$$

$$f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a^{sd}_{r_k,p,\lambda} \delta^{sd}_{ij,p} \geq 0 \ , \quad \forall \lambda = \{1,2,\ldots, M\}, \ \forall ij \in L \tag{2.13}$$

$$a^{sd}_{r_k,p,\lambda} \in Z^+, \qquad \forall \lambda = \{1,2,\ldots, M\},$$

$$\forall p \in P_{sd}, \forall sd \in A_k, \forall r_k \in R \tag{2.14}$$

$$f_{ij} \in Z^+, \qquad \forall ij \in L \ . \tag{2.15}$$

Similar to the VLT formulation, the objective function (2.11) aims to minimize the optical fiber requirement, while constraints (2.2), (2.3), (2.4), and (2.5) are used to determine the optimal light-trees. Constraints (2.12) enforce that in addition to selecting the physical routes, wavelengths must be assigned to them. Constraints (2.13) ensure that for any physical link, the channel capacity of each wavelength can accommodate the traffic routed on it. Constraints (2.14) and (2.15) imply that all the network variables are non-negative integers.

- **LT wavelength assignment method**

For multicast optical networks with the LT system, the mathematical model can be formulated as below.

Minimizing the total number of fibers:

$$Z^*_{mesh} = \min : \sum_{ij \in L} f_{ij} \ , \tag{2.16}$$

subject to the constraints (2.2)-(2.5), and:

$$\sum_{p \in P_{sd}} \sum_{\lambda=1}^{M} a^{sd}_{r_k,p,\lambda} = t_{r_k} \times x^{sd}_{r_k} \ , \qquad \forall sd \in A_k, \forall r_k \in R \tag{2.17}$$

$$f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a^{sd}_{r_k,p,\lambda} \delta^{sd}_{ij,p} \geq 0 , \qquad \forall \lambda = \{1,2,..., M\}, \ \forall ij \in L \quad (2.18)$$

$$\sum_{\lambda=1}^{M} W_{r_k,\lambda} = t_{r_k} , \qquad \forall r_k \in R \quad (2.19)$$

$$a^{sd}_{r_k,p,\lambda} \leq I_{\infty} \times W_{r_k,\lambda} , \qquad \forall \lambda = \{1,2,..., M\},$$

$$\forall p \in P_{sd} , \forall sd \in A_k , \forall r_k \in R \quad (2.20)$$

$$W_{r_k,\lambda} \in Z^{+} , \qquad \forall \lambda = \{1,2,..., M\}, \forall r_k \in R \quad (2.21)$$

$$a^{sd}_{r_k,p,\lambda} \in Z^{+} , \qquad \forall \lambda = \{1,2,..., M\},$$

$$\forall p \in P_{sd} , \forall sd \in A_k , \forall r_k \in R \quad (2.22)$$

$$f_{ij} \in Z^{+} , \qquad \forall ij \in L . \quad (2.23)$$

As we can see, the constraints of the LT system resemble those of the PVLT system, except the new constraints (2.19)-(2.21) that are specially formulated for the LT technique. Constraints (2.19) state that the wavelengths must be selected to support each multicast demand, while (2.20) contains linking (forcing) constraints to ensure that no physical path selected from constraints (2.17) is permitted to route on wavelength λ, unless the multicast traffic demand selects wavelength λ. The parameter I_{∞} in constraints (2.20) is an arbitrarily high constant. Constraints (2.21) limit that the wavelength variables must be in the set of non-negative integers.

2.6.4 Multi-Ring Network Design Formulation

Based on the MC-RWA multi-ring problem definition, the ILP formulations corresponding to the wavelength assignment techniques can be represented as below:

- **VLT wavelength assignment method**

Minimizing the total number of fibers of all rings:

$$Z^{*}_{ring} = \min : \sum_{q \in Q} (n_q \times Rf_q) \quad (2.24)$$

subject to the constraints (2.2)-(2.5), and:

$$\sum_{q \in Q} \sum_{p=1}^{2} ar_{r_k,p}^{sd,q} = t_{r_k} \times x_{r_k}^{sd} \ , \quad \forall sd \in A_k , \forall r_k \in R \tag{2.25}$$

$$M \times Rf_q - \sum_{r_k \in R} \sum_{sd} \sum_{p=1}^{2} ar_{r_k,p}^{sd,q} \zeta_{p,ij}^{sd,q} \geq 0 \ , \quad \forall ij \in L , \forall q \in Q \tag{2.26}$$

$$ar_{r_k,p}^{sd,q} \in Z^{+} , \quad p = \{1,2\},$$

$$\forall sd \in A_k , \forall r_k \in R , \forall q \in Q \tag{2.27}$$

$$Rf_q \in Z^{+} , \qquad \forall q \in Q \ . \tag{2.28}$$

As developed for the VLT assignment system, the objective function (2.24) is to minimize the total number of fibers allocated on the rings. As in the mesh design formulations, constraints (2.2), (2.3), (2.4), and (2.5) are included to determine the optimal light-trees. Constraints (2.25) express that the physical routes over the rings must be selected for each optical branch of the light-trees. Notice that constraints (2.25) simultaneously perform the selection of rings and paths over the rings. Constraints (2.26) ensure that the wavelength capacity of each chosen ring is sufficient to meet the traffic load flowing on it. Constraints (2.27) and (2.28) ensure that the variables representing the physical routes of the rings and the numbers of fibers are nonnegative integers.

- **PVLT wavelength assignment method**

In addition to selecting the rings and routing the light-trees over the rings as in the VLT multi-ring formulation, for the PVLT method each optical branch of the light-trees requires only one wavelength. Therefore, the PVLT multi-ring problem can be formulated as follows. Note that the explanations of constraints (2.29)-(2.33) are similar to those for the VLT multi-ring models.

Minimizing the total number of fibers of all rings:

$$Z_{ring}^{*} = \min : \sum_{q \in Q} (n_q \times Rf_q) \tag{2.29}$$

subject to the constraints (2.2)-(2.5), and:

$$\sum_{q\in Q}\sum_{p=1}^{2}\sum_{\lambda=1}^{M} ar_{r_k,p,\lambda}^{sd,q} = t_{r_k} \times x_{r_k}^{sd}, \quad \forall sd \in A_k, \forall r_k \in R \tag{2.30}$$

$$Rf_q - \sum_{r_k\in R}\sum_{sd}\sum_{p=1}^{2} ar_{r_k,p,\lambda}^{sd,q}\zeta_{p,ij}^{sd,q} \geq 0, \quad \forall\lambda = \{1,2,..., M\},$$

$$\forall ij \in L, \forall q \in Q \tag{2.31}$$

$$ar_{r_k,p,\lambda}^{sd,q} \in Z^+, \quad \forall\lambda = \{1,2,..., M\},\ p = \{1,2\},$$

$$\forall sd \in A_k, \forall r_k \in R, \forall q \in Q \tag{2.32}$$

$$Rf_q \in Z^+, \quad \forall q \in Q. \tag{2.33}$$

- ## LT wavelength assignment method

Based on the PVLT multi-ring formulation and constraints (2.19), (2.20), and (2.21) only used for the LT wavelength assignment method, we can thus apply them to formulate the ILP program for LT multi-ring design scheme as below.

Minimizing the total number of fibers of all rings:

$$Z_{ring}^* = \min : \sum_{q\in Q}(n_q \times Rf_q) \tag{2.34}$$

subject to the constraints (2.2) -(2.5) and:

$$\sum_{q\in Q}\sum_{p=1}^{2}\sum_{\lambda=1}^{M} ar_{r_k,p,\lambda}^{sd,q} = t_{r_k} \times x_{r_k}^{sd}, \quad \forall sd \in A_k, \forall r_k \in R \tag{2.35}$$

$$Rf_q - \sum_{r_k\in R}\sum_{sd}\sum_{p=1}^{2} ar_{r_k,p,\lambda}^{sd,q}\zeta_{p,ij}^{sd,q} \geq 0, \quad \forall\lambda = \{1,2,..., M\},$$

$$\forall ij \in L, \forall q \in Q \tag{2.36}$$

$$\sum_{\lambda=1}^{M} W_{r_k,\lambda} = t_{r_k}, \quad \forall r_k \in R \tag{2.37}$$

$$ar_{r_k,p,\lambda}^{sd} \leq I_\infty \times W_{r_k,\lambda}, \quad \forall\lambda = \{1,2,..., M\},$$

$$p = \{1,2\}, \forall sd \in A_k, \forall r_k \in R \tag{2.38}$$

$$ar_{r_k,p,\lambda}^{sd,q} \in Z^+, \quad \forall\lambda = \{1,2,..., M\},\ p = \{1,2\},$$

$$\forall sd \in A_k, \forall r_k \in R, \forall q \in Q \qquad (2.39)$$

$$W_{r_k,\lambda} \in Z^+, \qquad \forall \lambda = \{1,2,..., M\}, \forall r_k \in R \qquad (2.40)$$

$$Rf_q \in Z^+, \qquad \forall q \in Q. \qquad (2.41)$$

From the developed ILP formulations, the number of constraints (N_c) and the number of variables (N_v) for each network design method are given in Tables 2.1 and 2.2.

Table 2.1: Number of constraints (N_c) and number of variables (N_v) for the ILP mesh formulations.

Muticast Mesh Design Formulation		
VLT	N_C	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+N_k\right)+\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+L$
	N_v	$(P+1)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+L$
PVLT	N_C	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+N_k\right)+\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+(L\times M)$
	N_v	$(P\times M+1)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+L$
LT	N_C	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+N_k\right)+(M\times P+1)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+(L\times M)+K$
	N_v	$(P\times M+1)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+L+(K\times M)$

Table 2.2: Number of constraints (N_c) and number of variables (N_v) for the ILP multi-ring formulations. Note that $\overline{Q}$ denotes the average number of candidate rings per node pair.

Muticast Multi-Ring Design Formulation		
VLT	N_C	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+N_k\right)+\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+\sum_{q=1}^{Q}n_q$
	N_v	$(2\overline{Q}+1)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+Q$
PVLT	N_C	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+N_k\right)+\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+M\sum_{q=1}^{Q}n_q$
	N_v	$(2\overline{Q}\times M+1)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+Q$
LT	N_C	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+N_k\right)+(2\overline{Q}\times M+1)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+M\sum_{q=1}^{Q}n_q+K$
	N_v	$(2\overline{Q}\times M+1)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+Q+(K\times M)$

2.7 Heuristic Network Design Algorithms

After calculating the number of variables and the number of constraints, the proposed ILP formulations turn out to have large number of variables and constraints when the network gets larger. In particular, for the LT and PVLT wavelength assignment systems, the number of variables and constraints are also increased as the number of wavelengths per fiber increases. Therefore, this implies that an optimal solution of MC-RWA problem cannot be obtained in a reasonable time for large networks. In this section, we introduce heuristic approaches for finding good solutions in the cases of LT and PVLT methods by using the solution from the ILP model of the VLT method.

For the development of heuristic approaches, the MC-RWA problem is decomposed into two sub-problems: the light-tree and routing allocation sub-problem, and the wavelength assignment sub-problem. These two sub-problems are considered separately and in sequence.

2.7.1 Multicast Mesh Design Algorithm for the LT and PVLT techniques

Based on the mesh ILP model of the VLT system, the sequence of steps of the mesh algorithm is as follows.

- STEP 1: Generate the linear formulation of VLT mesh design corresponding to the given traffic demands, based on the objective function (2.6) and the constraints (2.2)-(2.5) and (2.7)-(2.10).

- STEP 2: Solve the linear formulation generated in STEP 1 and record its solution, $\{x^{ij}_{r_k}, a^{sd}_{r_k,p}\}$.

- STEP 3: If the solution of PVLT is needed, generate the linear formulation based on the objective function (2.11) and the constraints (2.13)-(2.15). Otherwise, if the solution of the LT system is needed, generate the linear formulation with the objective function (2.16) and the constraints (2.18)-(2.23). For either PVLT or LT, generate the additional following constraints and include them into the model:

$$\sum_{\lambda=1}^{M} a_{r_k,p,\lambda}^{sd} = a_{r_k,p}^{sd} \quad , \forall p \in P_{sd}, \forall sd \in N_k, \forall r_k \in R\,, \qquad (2.42)$$

where $a_{r_k,p}^{sd}$ variables in the constraints are replaced by the solution recorded in STEP 2.

- STEP 4: Solve the new linear formulation generated in STEP 3. The network solution obtained from the new formulation and the solution recorded in STEP 2 become the results of the PVLT and the LT mesh designs.

2.7.2 Multicast Multi-ring Design Algorithm for the LT and PVLT techniques

Similar to the mesh design algorithm, the multi-ring design algorithm for the LT and PVLT methods can be performed as follows.

- STEP 1: Generate the linear formulation of VLT multi-ring design corresponding to the given traffic demand, based on the objective function (2.24) and the constraints (2.2)-(2.5) and (2.25)-(2.28).

- STEP 2: Solve the linear formulation generated in STEP 1 and record its solution, $\{x_{r_k}^{ij}, ar_{r_k,p}^{sd,q}\}$.

- STEP 3: If the solution of PVLT is needed, generate the linear formulation based on the objective function (2.29) and the constraints (2.31)-(2.33). Otherwise, if the solution of the LT system is needed, generate the linear formulation with the objective function (2.34) and the constraints (2.36)-(2.41). For either the PVLT or LT system, generate the additional following constraints and include them into the model:

$$\sum_{\lambda=1}^{M} ar_{r_k,p,\lambda}^{sd,q} = ar_{r_k,p}^{sd,q} \quad , \forall p \in P_{sd}, \forall sd \in N_k, \forall r_k \in R\,, \forall q \in Q\,, \qquad (2.43)$$

where $a_{r_k,p}^{sd,q}$ variables in the constraints are replaced by the solution recorded in STEP 2.

- STEP 4: Solve the new linear formulation generated in STEP 3. The solution obtained from the new formulation and the solution recorded in STEP 2 are the results of the PVLT and the LT multi-ring designs.

2.8 Lower Bounds on the Fiber Requirement

In this section, we present the three distinct techniques to determine lower bounds on the total number of fibers for implementing optical mesh and multi-ring networks. When a network topology and traffic matrix is given, a lower bound on the total number of fibers is defined as the maximum value obtained from three lower bound techniques. Since in calculating the lower bounds, no wavelength continuity constraints are imposed, the lower bounds derived here are only for the VLT wavelength assignment methods. Nevertheless, they can be adopted for comparison with two other assignment methods: the LT and PVLT methods.

The first lower bound technique relies on the fact that the number of optical fibers allocated on a network should be sufficient to make the network connected: for any node pair of a mesh network, there should be at least one path connecting between source and destination. Meanwhile, for a multi-ring network, there should be at least a number of fibers sufficient to from a ring and connect all nodes together. Therefore, the first lower bound can be simply determined by the equations:

$$Z_{LB,1} = N - 1 \,, \qquad \text{for the mesh design,} \tag{2.44}$$

$$Z_{LB,1} = N \,, \qquad \text{for the multi-ring design,} \tag{2.45}$$

where N is the total number of nodes of the network.

As we can see, the lower bounds computed by the above technique are without considering the traffic demands and the number of wavelengths per fiber (M). Hence, in general the first technique does not provide a good lower bound. In order to improve the lower bounds, the second lower bound technique includes the traffic demands and the number of wavelengths per fiber in the calculation. The ILP formulations of the VLT mesh and multi-ring designs as presented in section 2.6 are employed in the second technique, but in the models all the integrality constraints, that is, the constraints (2.9) and (2.10) for mesh design and the constraints (2.27) and

(2.28), are relaxed. Therefore, if the result of the linear relaxation programming is Z, the lower bound of the second technique is then:

$$Z_{LB,2} = \lceil Z \rceil, \tag{2.46}$$

where $\lceil x \rceil$ denotes the lowest integer greater than or equal to x. In addition, we can further improve the lower bounds $Z_{LB,2}$ by introducing the cutting plane methods [38, 49, 96] into the models. With the cutting plane methods, extra constraints that satisfy the feasible integer solution space (the convex hull) of ILP models, but do not satisfy the solution space of a liner relaxation programming, are included in the models. Therefore, tighter lower bounds can be obtained. Note that in this thesis, the Gomory cutting plane algorithm as available in CPLEX 6.6 optimization software is deployed.

For the last lower bound technique, we can obtain a lower bound that takes the traffic demand and the number of wavelengths per fiber into account as follows. We first generate the VLT mesh and multi-ring formulations for $M = 1$ and then solve them to determine the minimal numbers of fibers. At $M = 1$, the solutions obtained from the models of mesh and multi-ring methods can be interpreted as the minimal total wavelength channels needed to support the multicast traffic demands. Note that in the case of mesh design, it is easy to see that 100% optical fiber usage is guaranteed to occur at $M = 1$. Therefore, if the minimal numbers of fibers needed at $M = 1$ equal to $Z^*_{mesh}(M = 1)$ and $Z^*_{ring}(M = 1)$ for mesh and multi-ring designs, respectively, then for any value of $M \geq 2$, the number of fibers required should be at least:

$$Z_{LB,3} = \left\lceil \frac{Z^*_{mesh}(M = 1)}{M} \right\rceil, \quad \text{for the mesh design,} \tag{2.47}$$

$$Z_{LB,3} = \left\lceil \frac{Z^*_{ring}(M = 1)}{M} \right\rceil, \quad \text{for the multi-ring design.} \tag{2.48}$$

Using the three proposed methods, we can consequently determine the final lower bounds for mesh and multi-ring networks as:

$$Z_{LB} = \max(Z_{LB,1}, Z_{LB,2}, Z_{LB,3}). \tag{2.49}$$

Chapter 3

Computational Results and Discussion for the MC-RWA Problem

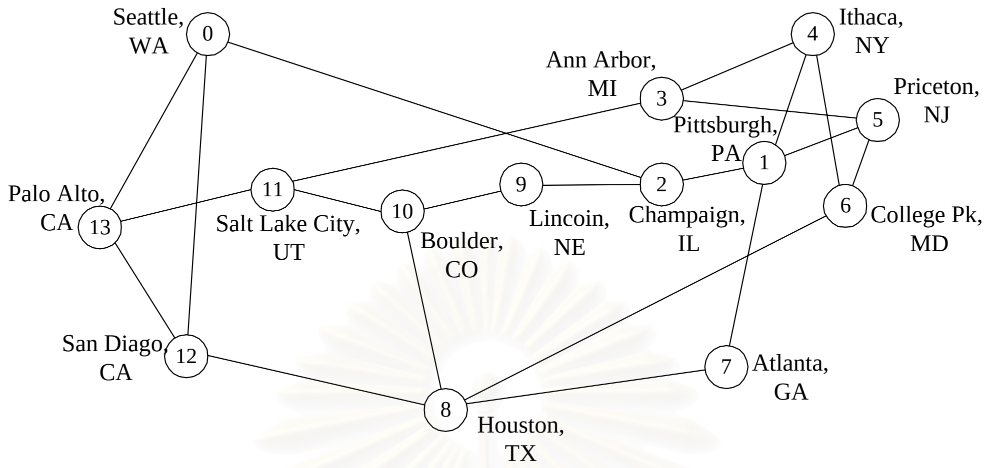
3.1 Introduction

In this chapter, we present and discuss network design solutions obtained from the ILP formulations, the heuristic algorithms, and the lower bound techniques as proposed in the preceding chapter.

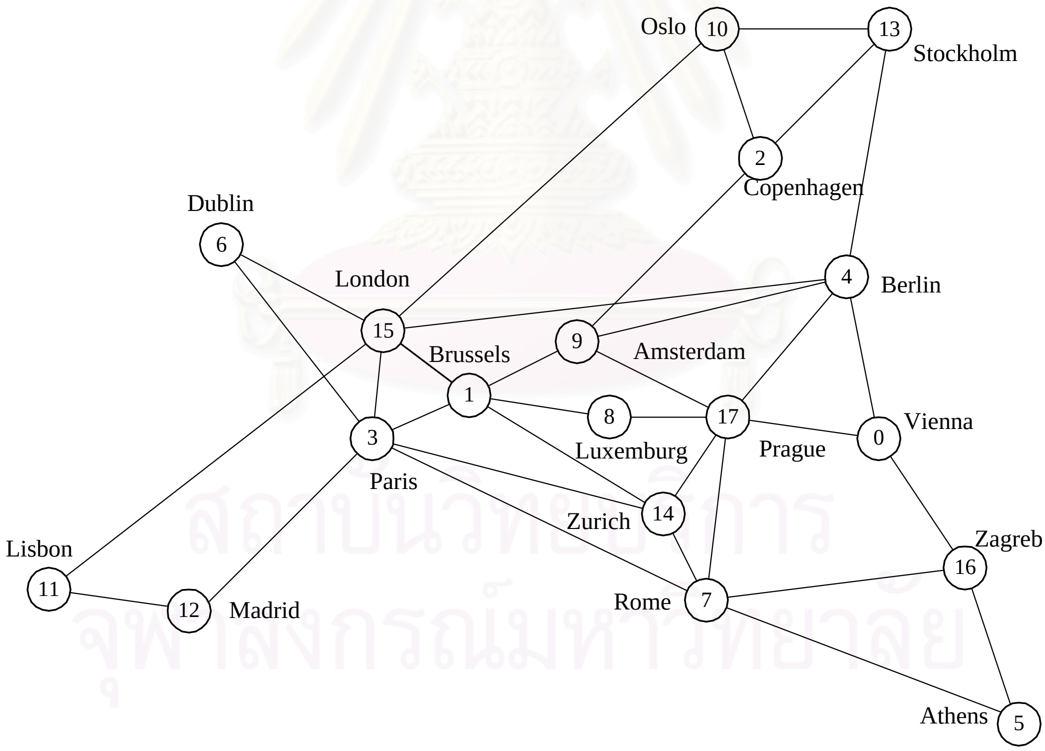
In section 3.2, we describe the setting of experiments to study the MC-RWA problem. With the experimental results, section 3.3 investigates the performance of the proposed lower bound techniques by comparing lower bound values with their optimal values. In section 3.4, the effect of the restricted fanout of optical power splitters on fiber requirements of mesh and multi-ring networks are discussed. In section 3.5, the system capacity and its utilization of WDM networks based on mesh and multi-ring designs are analyzed. By using networks with various values of connectivity, section 3.6 provides a comparative study in terms of the network capacity required between mesh and multi-ring design methods. Finally, section 3.7 examines the benefits of having wavelength converter equipped within MC-OXCs nodes and also investigates the effectiveness of the proposed heuristic algorithm.

3.2 Experimental Networks and Setting

In this section, we present the results obtained from the ILP formulations, the heuristic algorithms, and the lower bound techniques by using the NSFNet backbone [41] and the European Optical Network backbone (EON) [26]. The experimental network topologies and their network parameters are shown in Figure 3.1. All the ILP models implemented for the discussion are solved by the CPLEX 6.6 MIP solver [97] on a PC 2GHz Intel Pentium 4 with 512 MB of RAM. For the mesh design, the ILP models are formulated with sets of 10 and 5 shortest paths for each node pair corresponding to the NSFNet and EON networks, respectively. In addition, sets of 50 and 100 smallest rings by size are provided for the multi-ring ILP models of the NSFNet and EON networks, respectively. To set up the experiment, we solve the optimization problems only in the case of the VLT system, while for the PVLT and LT systems we employ the proposed heuristic algorithms to determine the results. Experimentally, the optimal solutions of the NSFNet network in most cases were found within two hours, while for the larger EON network, on average they were found within a day. Note that the optimal solutions at $M = 1$ used for determining the lower bounds were typically obtained in a few seconds for both test networks. Throughout this section, we let a parameter G be the total number of destinations of a given multicast session. Moreover, in the experiments each network node is set to require a 2-wavelength-channel multicast session, while its destinations are randomly selected with a fixed value of G. By the optimization process, all the results shown in this section except the last subsection 3.7 are for the VLT system.



a) NSFNet backbone ($N = 14, L = 21, \overline{d} = 3$).



b) EON backbone ($N = 18, L = 32, \overline{d} = 3.5$).

Figure 3.1: Experimental optical backbones.

3.3 Performance of the Lower Bound Techniques

To study the performance of the multicast lower bound techniques, Figures 3.2 and 3.3 show results corresponding to the NSFNet and EON networks, respectively. When the fanout, Δ is set to 2, 3 and 4, we plot the minimal number of fibers required and the lower bounds as a function of the number of wavelengths per fiber, *M*. In the Figures 3.2 and 3.3, we also present the outcomes for both network designs, *i.e.*, mesh and multi-ring designs with a fixed value of *G*. The *G* parameter is varied from 4 to 10. First, consider the case of mesh network design. Figures 3.2 and 3.3 quantitatively demonstrate that the curves of lower bounds and the optimal results behave very similarly. The lower bounds determined from our techniques are very close to the optimal values obtained from the ILP models of the VLT system. In addition, the results show that this observation is consistent regardless of the influence of Δ and *G* values on the network design. In the experimental details, we also notice that for the first range of the number of wavelengths per fiber ($2 \leq M \leq 16$), the lower bounds of mesh networks are in most cases identical to their optimal values; see the NSFNet and EON mesh designs with *G*=8 and 10, for example.

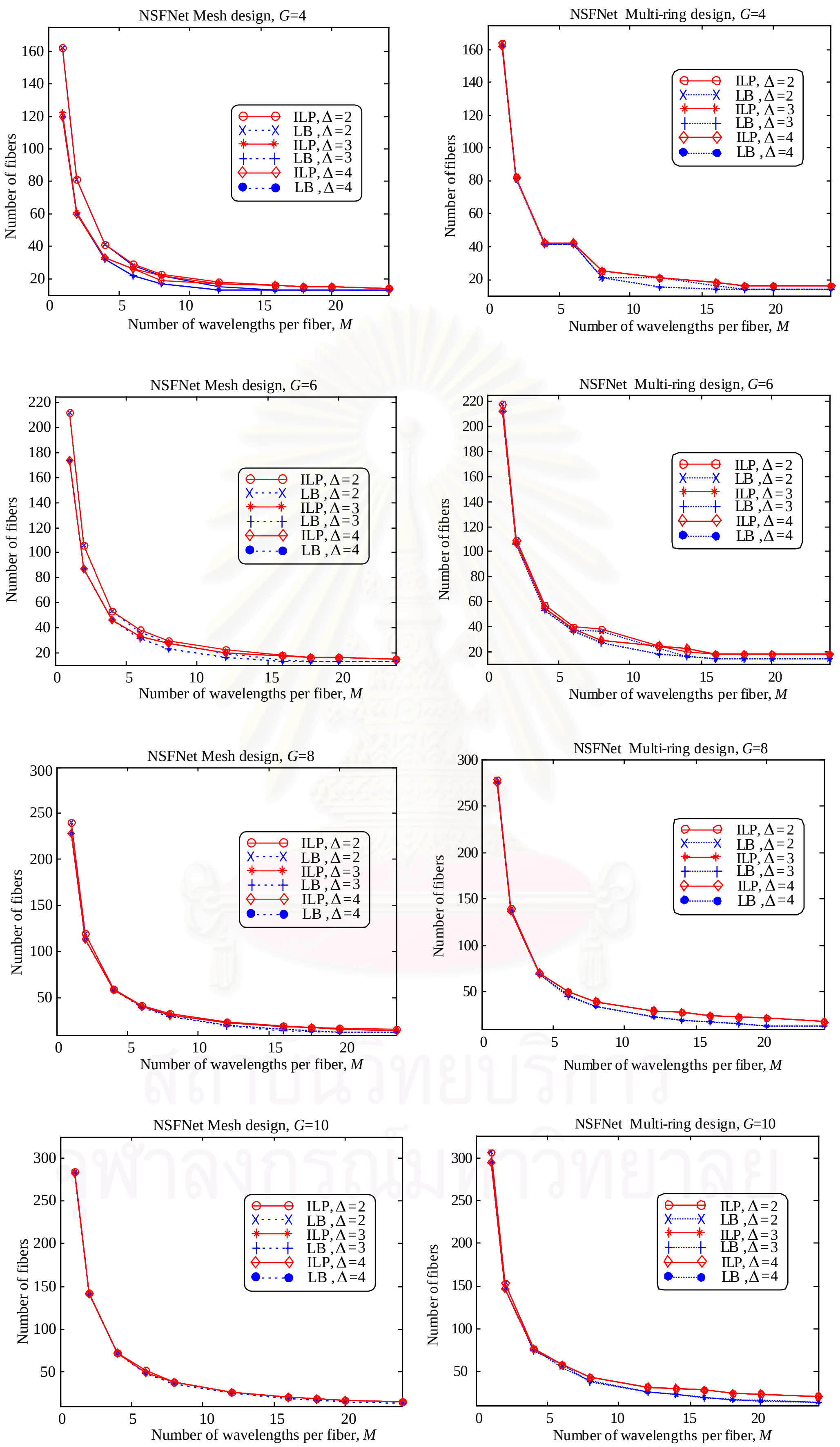


Figure 3.2: Numerical results for the NSFNet backbone.

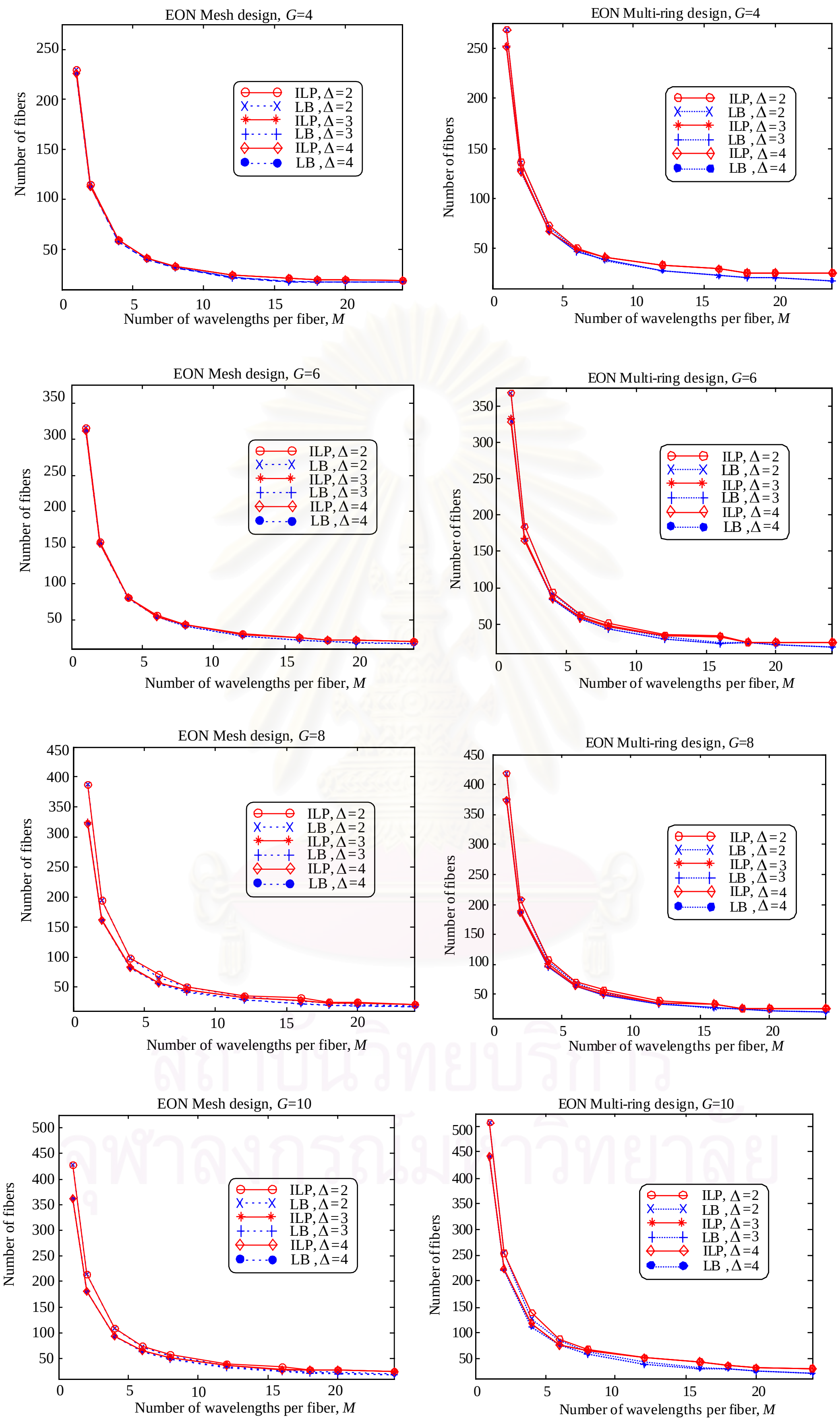


Figure 3.3: Numerical results for the EON backbone.

Let us now investigate the case of multi-ring design. Figures 3.2 and 3.3 indicate that our lower bound techniques return the results that are close to the actual minimal number of fibers required, especially for small values of M. This remark is similar to that for the case of mesh design. However, when the number of wavelengths per fiber gets larger, we observe that in multi-ring design, there exists a gap between the curves of lower bound and the optimum. For example, in the EON multi-ring design with G=10, the lower bound and optimal curves are initially separated at M=12 and the gap width is relatively constant as M increases. Nevertheless, when measuring the gap we found that the distance between the two curves is rather short. In addition, as will be analyzed, a network implemented at these large values of M generally falls in the state of over-provision of wavelength capacity, leading to a waste of network resources and network costs as well.

Therefore, based on the discussion, we can conclude that with multicast traffic the proposed lower bound techniques potentially provide good, tight lower bounds for both mesh and multi-ring designs.

3.4 Effect of Restricted Fanout on the Fiber Requirement

Using the EON network, Figures 3.4 and 3.5 illustrate how a limited fanout affects the number of fibers required to support the multicast traffic. In Figure 3.4, for varying the values of G each data point represents the ratio of the number of fibers with the specified fanout Δ=3 to that with the fanout Δ=2. Note that Δ=2 implies that each multicast demand must be accommodated on a chain structure instead of on a light-tree, see Figure 4.4 for clarify. Similarly, data plotted in Figure 3.5 are the ratios of the number of fibers with the fanout Δ=4 to that with the fanout Δ=3. Let us first consider Figure 3.4. It shows that for both mesh and multi-ring methods, the ratios of all data points are always equal to or less than 1. Particularly, for $1 \le M \le 16$ and large G values, there are several cases where the fibers can be saved by more than 15% for both mesh and multi-ring schemes with respect to the results for Δ=2. Thus, this confirms our knowledge that using the light-tree structure can reduce the requirement of optical fibers, leading to transmission line cost savings. However, the data of Figure 3.4 also suggest that the fiber saving obtained by employing light-trees tends to disappear as M increases. For instance, the ratios for mesh designs are equal to 1 when $M \geq 25$. Consequently, this implies that we may not have to employ optical chains to support multicast traffic if the number of available wavelengths per fiber is high enough.

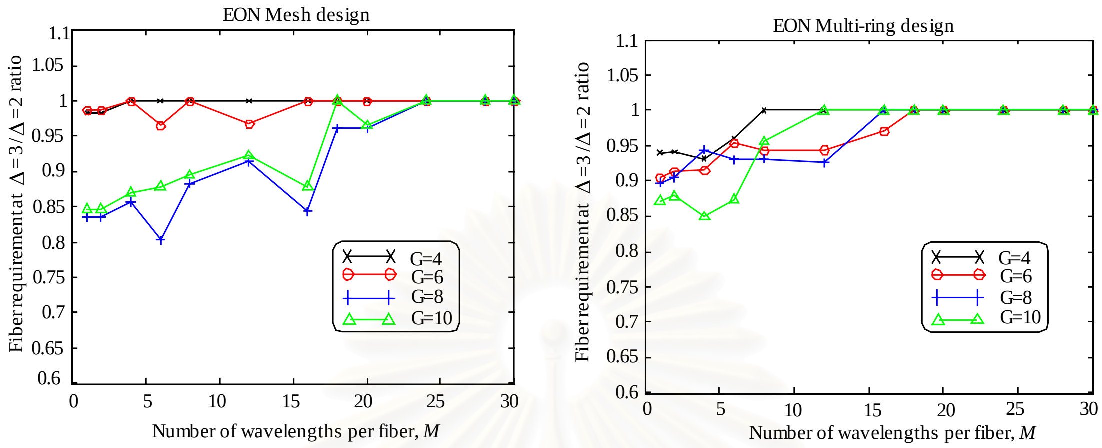


Figure 3.4: Ratio fiber requirements at $\Delta = 3$ and $\Delta = 2$ versus *M*.

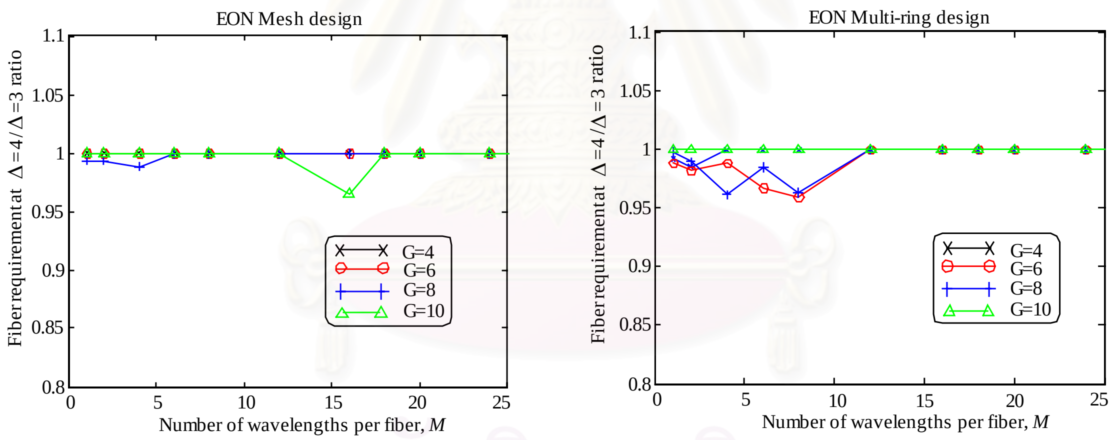


Figure 3.5: Ratio fiber requirements at $\Delta = 4$ and $\Delta = 3$ versus *M*.

When further increasing the fanout of optical splitters, Figure 3.5 indicates that the fiber reduction is very low and can be negligible. This is because the increment of Δ from 3 to 4 leads to fiber saving less than 5% and as we can see the ratios are typically equal to 1. Further studying the effect of fanout on the fiber requirement of the EON network, we have found that for both mesh and multi-ring methods the results for $\Delta \geq 5$ are identical to those of $\Delta = 4$ for every value of *M*. Therefore, this finding signifies that increasing the fanout to more than 4 cannot decrease the number of fibers needed to serve the traffic. It should be noted that this scenario is also found for other test networks.

Thus, based on the experiments, we can conclude that for static multicast traffic the fiber reduction achievable by allowing the high values of Δ is not substantial and can be omitted. By providing only small values of Δ, we obtain the same minimal number of fibers as in the case of a high value of Δ.

3.5 System Capacity and Its Utilization

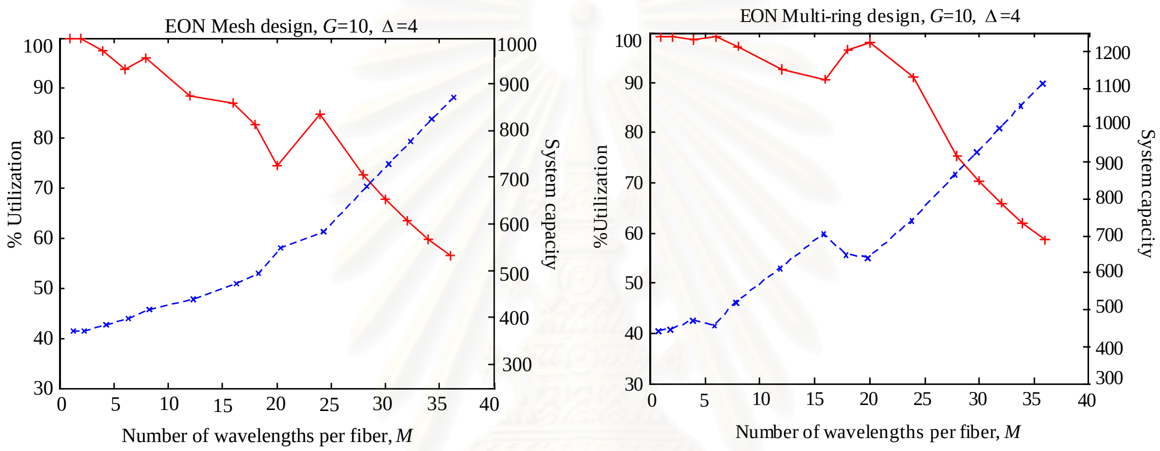


Figure 3.6: System capacity and its utilization versus the number of wavelengths per fiber, *M*. For both graphs, the bold and dashed curves are associated with the left and right vertical axes, respectively.

To discuss the employment of multi-fiber systems in optical networks in terms of the number of wavelengths multiplexed in a fiber, Figures 3.2, 3.3 and 3.4 are needed. As we can see, all the graphs in Figures 3.2 and 3.3 behave similarly. Here, let us discuss only the graphs in the case of EON, *G*=10, and Δ=4. Figure 3.6 consequently shows the system capacity and its utilization. Now, consider the network using the mesh design. In Figure 3.3, the EON mesh design graph with *G*=10 and Δ=4 illustrates that the total number of fibers tends to decrease as the number of available wavelengths per fiber, *M* increases. Particularly, for low *M* values the total number of fibers drops rapidly. For example, if the network employs fibers at *M*=2, the total number of fibers can be reduced to around half of that of *M*=1. Nevertheless, instead of rapidly dropping, after *M*=8 the resulting curve becomes flattened and no reduction of the number of fibers can be observed for values of $M \geq 24$. Therefore, regarding this observation, the increment of $M \geq 24$ results in the abruptly increment in system capacity and in effect, the sharp drop of its utilization; see Figure 3.6. Therefore, our experiment suggests that under the conditions of the mesh approach, it may be more cost-effective for the network to employ a small number of wavelengths per fiber.

For the multi-ring design counterpart, the resulting curves in Figures 3.3 and 3.6 are the same as those of the mesh design, meaning that the above discussion of the mesh design can be applied to the multi-ring design. In contrast, however, we found some rather distinctive points of the multi-ring method. As demonstrated in Figure 3.6, the system capacity drops at some points when increasing the value of *M* from 1 to 25. This scenario is constrast to the system capacity curve for a mesh design. A particularly noticeable capacity drop is at *M*=20, leading to the highly efficient use of fibers (98%) again, excluding the former values of *M*. Investigating in details, we found that at those points the network can find sets of rings to fit the given traffic demand better than at other points. Therefore, based on the results, it can be summarized that in addition to small values of *M*, the multi-ring networks may be implemented with high fiber usage efficiency at some large values of *M*.

3.6 Capacity Comparison between Mesh and Multi-ring Designs

To analyze the differences in the numbers of fibers needed for the mesh and multi-ring techniques, in Figure 3.7 we plot the multi-ring to mesh fiber requirement ratio versus a range of *M* values. As shown, we present only two cases, *i.e.*, Δ=2 and 3. For $\Delta \geq 4$, the same results as in case of Δ=3 were obtained.

Let us consider Figure 3.7. As expected, across the range of *M* values shown in the figures the EON network implemented with the multi-ring approach always needs more fibers than that with the mesh approach. This observation is true for all specified values of *G* and Δ. For instance, the test network with Δ=3 and *G*= 10 needs as many as 50% additional fibers when using the multi-ring design at *M*=15 with respect to the mesh design. However, for some data points the extra number of fibers for the multi-ring design is only around 10%, specifically at *G*=6 and Δ=3. In the design, the additional fiber requirement of the multi-ring networks with respect to the mesh networks is caused by the constraint that the multicast traffic must be accommodated over the rings, thus resulting in the lower flexibility to route the traffic demands. In addition, Figure 3.7 suggests that the resulting ratios fluctuate somewhat over the range of low *M* values, but the fiber requirement ratio begins to be constant for *M* beyond 25 for both $\Delta = 2$ and 3.

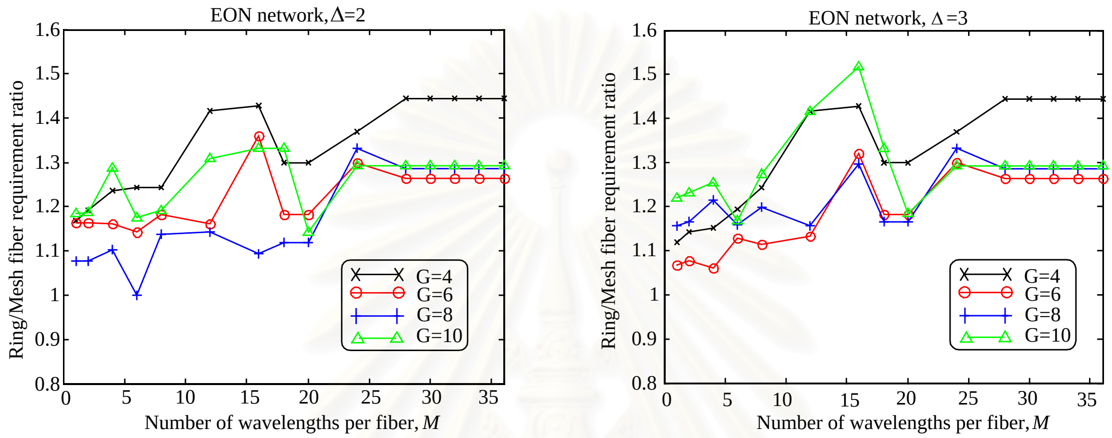


Figure 3.7: Multi-ring to mesh fiber requirement ratio for a range of *M* values.

In order to further study the differences between two design systems in terms of capacity requirement, Figure 3.8 is introduced to show such differences as a function of the average nodal degree of the network, $\bar{d}$. In the experiments, all test networks are fixed to 13 nodes and we vary the number of physical links according to the specified nodal degree. All the test networks are depicted in Figure 3.9. As shown in Figure 3.8, only the results at M=1 are reported. This is because the 100% capacity utilization for M=1 lets us clearly view the resource comparison between the two network design systems. Moreover, since the results at $\Delta \geq 3$ of all test networks are identical for all values of *M*, we present these results by one curve for each network design system.

Examining the relation between the capacity requirement and the connectivity, Figure 3.8 demonstrates that for both design approaches, the network capacity has an inverse relationship with the nodal degree, $\bar{d}$. This is because as the networks connectivity increases, shorter paths become available for accommodating the light-trees, resulting in more saving the network capacity. Additionally, Figure 3.8 shows that for each design method, there exists a gap between the results for Δ =2 and $\Delta \geq 3$. However, the gap is considered narrow and can be neglected. Hence, this observation confirms the conclusion in subsection 3.4 that only small Δ values are sufficient to provide the same minimum capacity requirement as in the case of a large Δ value.

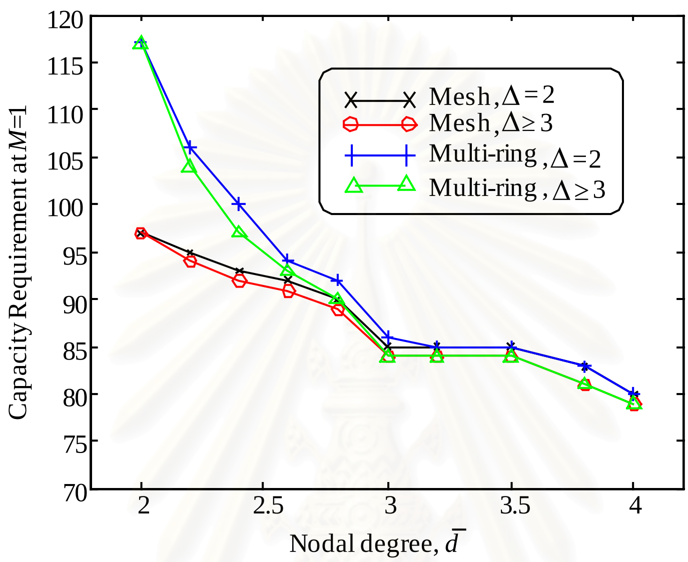


Figure 3.8: Number of fibers needed at *M*=1 versus the nodal degree ($\bar{d}$).

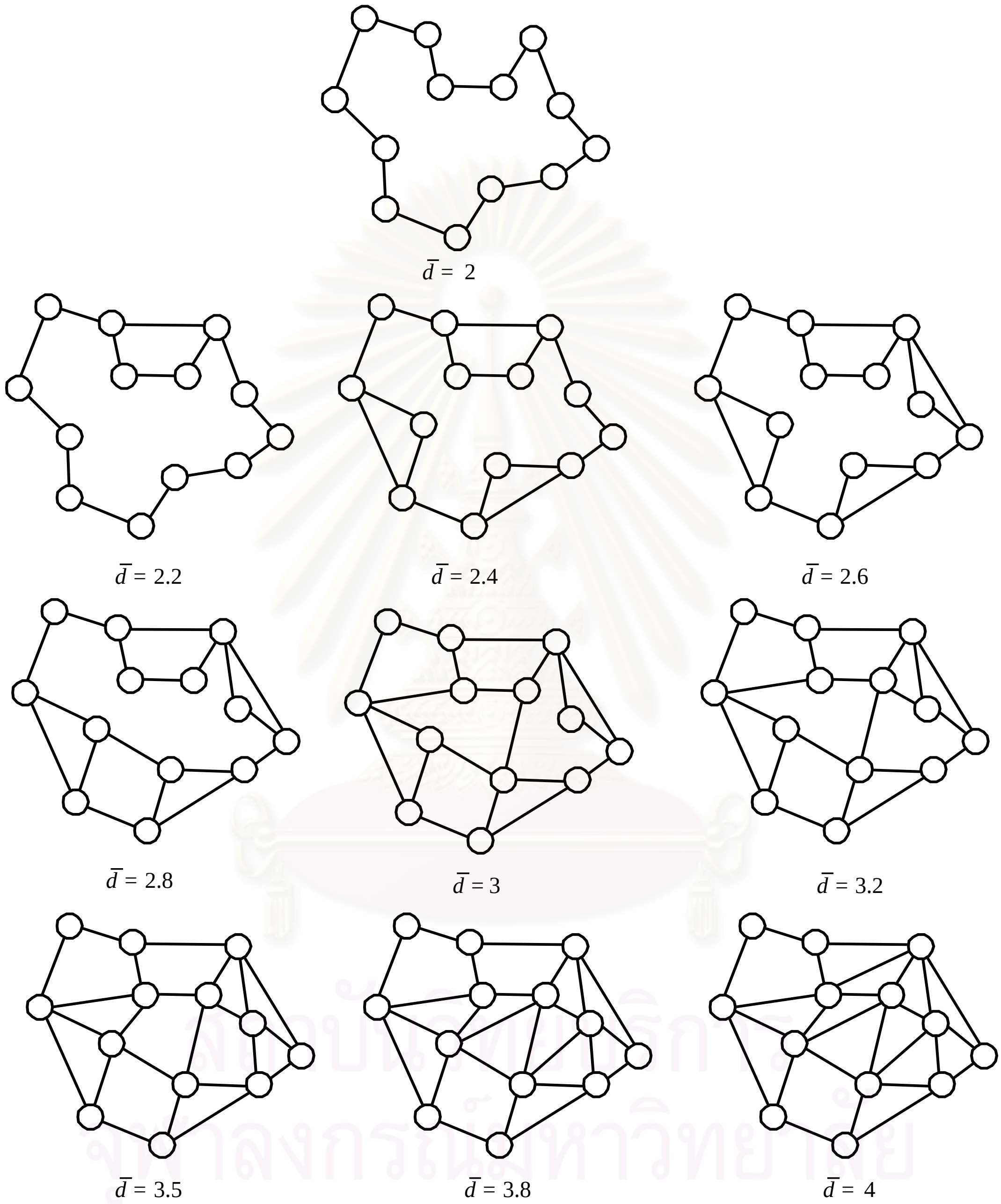


Figure 3.9: Experimental networks with various values of nodal degree.

As a comparison, Figure 3.8 also indicates that at a fixed Δ, the capacity gap between the multi-ring and mesh approaches is narrower when the level of network connectivity increases. No capacity gap can be noticed when $\bar{d} \geq 2.8$. Hence, the requirement of capacity of additional fibers for multi-ring technique in comparison with the mesh technique is relaxed for the highly connected network, $\bar{d} \geq 2.8$.

Therefore, based on the discussion, we can conclude that under the same multicast traffic pattern, the multi-ring design approach generally requires more network capacity than the mesh approach, resulting in the lower resource utilization by the multi-ring approach. However, the extra cost of the multi-ring technique is balanced by network control and management that are simpler than those for networks based on the mesh design. Moreover, the experiments show that the extra cost of the multi-ring design can be diminished by increasing the network connectivity.

3.7 Wavelength Assignment Techniques and Heuristic Algorithm Performance

Employing the heuristic algorithms as introduced in chapter 2, numerical results for the LT, PVLT and VLT systems in the cases of the EON mesh and multi-ring networks with G=10 are reported in Figure 3.10. For other cases, the similar characteristics are obtained.

The results in Figure 3.10 are shown in terms of the PVLT to VLT fiber requirement ratio and the LT to VLT fiber requirement ratio. At M=1, the number of fibers required by the LT, PVLT and VLT are equal for both network design methods, confirming the equivalence of these three systems. Thus, it is not an issue at this point. Considering the mesh design, Figure 3.10 shows that the number of fibers required for the PVLT and VLT are typically identical. VLT can save as many as 4% of the fibers for M=16 and Δ=3 with respect to PVLT. However, 4% saving is not considered substantial. Similarly, studying the differences between LT and VLT, the mesh design ratios demonstrate that the LT system in most cases requires a number of fibers equal to that of the VLT system. As shown, the difference is at most only 4%, which is not significant. Therefore, linking the observations of the PVLT to VLT ratio and the LT to VLT ratio, it is concluded that there is no noticeable difference among the three wavelength assignment schemes in the mesh design.

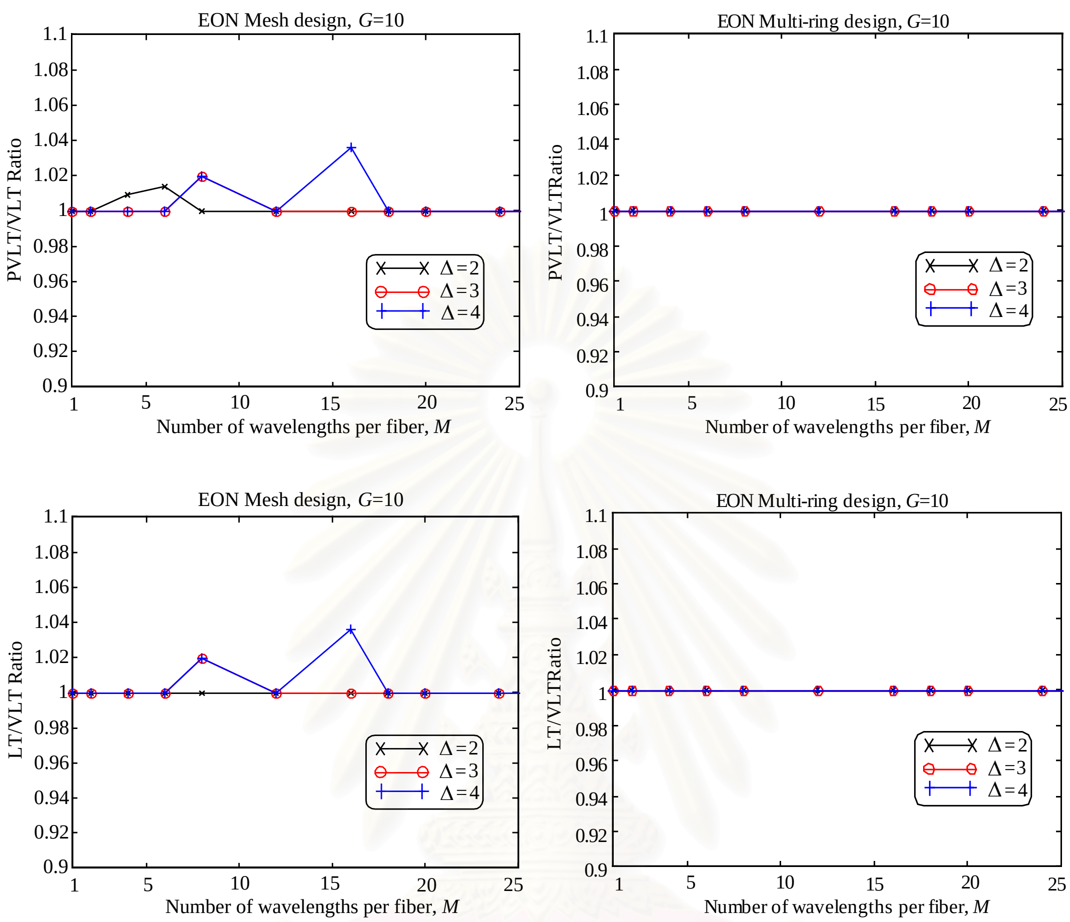


Figure 3.10: Ratios of fiber requirements among the VLT, PVLT and LT wavelength assignment techniques.

Let us focus on the multi-ring technique. In Figure 3.10, the ratios of the PVLT to VLT and the LT to VLT are equal to 1 for all values of M, meaning that the total number of fibers for the VLT, PVLT and LT are identical. Therefore, as concluded for the mesh design, the VLT, PVLT and LT of the multi-ring technique are the same in terms of fiber requirements. Note that for both network design techniques, we also found these conclusions for other test networks.

Due to these conclusions, we can further conclude that the benefits of wavelength converters equipped at MC-OXCs can be negligible for both mesh and multi-ring design approaches. Additionally, in the aspect of wavelength assignment, at one extreme is the VLT technique, the most flexible technique to assign wavelengths to light-trees. At the other extreme is the LT technique, the least flexible wavelength assignment technique. Therefore, it can be induced that other wavelength assignment methods do not decrease the number of fibers considerably.

Finally, let us investigate the performance of the heuristic algorithms to obtain the PVLT and LT network outcomes. Based on the results, there is a slight difference among the VLT, PVLT and LT systems. In most cases, the results of the three systems are the same. Since all VLT results reported here are optimal, we can summarize that our heuristic algorithms potentially provide the good near-optimal solutions for the PVLT and LT systems. Also, in tests for the relatively large EON network, we found that the heuristic algorithms can completely solve the network problems within on average, 30 minutes for the mesh design and only a few seconds for the multi-ring techniques. This is acceptable for our heuristic algorithms to be useful for large network problems. Moreover, as concluded, the lower bounds are close to the VLT results and the LT and PVLT results are also close to the VLT results. Thus, these statements imply that in addition to the VLT network, our lower bound techniques can be appropriately extended to work with the LT and PVLT networks as good estimators of the fiber requirement for the LT and PVLT networks.

Chapter 4

Light-Tree Protection Approaches for Multicast Sessions on WDM Mesh Networks

4.1 Introduction

As described in Chapter 1, this thesis deals with the optical protection problem of multicast WDM mesh networks. In this chapter, we elaborately study this problem.

Section 4.2 presents six new multicast protection strategies to protect multicast session against single link failures in WDM mesh networks. In section 4.3, we propose a concept of applying point-to-point protection techniques, which are historically employed to protect unicast connection, to protect multicast sessions. Five point-to-point protection strategies are examined. In addition, section 4.3 describes the advantages and disadvantages of using point-to-point protection systems instead of multicast protection systems to protect multicast sessions. In section 4.4, a new simple diagram of the evolution of protection design is presented. Section 4.5 introduces three wavelength allocation techniques deployed in restoration process of networks. In section 4.6, three spare capacity placement techniques to guarantee 100% link-survivability are investigated. Finally, with the study of protection systems, section 4.7 formally defines two optical protection problems investigated in the thesis.

4.2 Multicast Protection Strategies

In this section, six new multicast protection strategies are proposed as follows.

4.2.1 Light-Tree Reconfiguration Protection Strategy (LR)

As described, under normal operation, an optical network employs light-trees to support multicast traffic. For the light-tree reconfiguration protection strategy (LR), in event of a single link failure, all the ongoing light-trees are released and reconfigured to avoid a failed link. Although there are a number of light-trees not directly interrupted by the failure, a network using this protection is capable of rearranging them in the restoration process. Accordingly, the LR protection is in principle considered very flexible to handle any interruption, resulting in the minimal requirement of capacity resources. To see how the LR protection works on the network, Figure 4.1 demonstrates its mechanism.

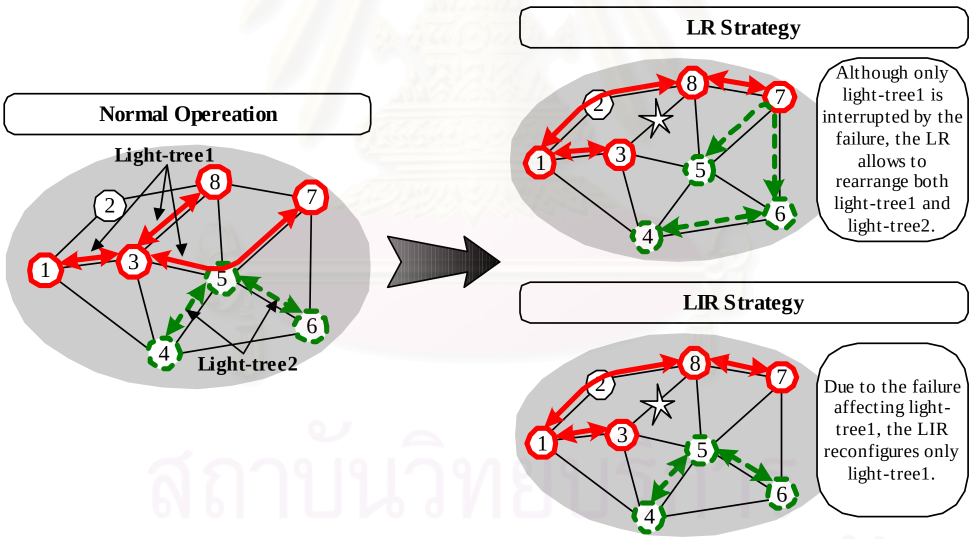


Figure 4.1: An example of a network using the LR and LIR protection strategies.

As illustrated in Figure 4.1, there are two light-trees, *i.e.*, light-tree 1 and 2, working on the example network. When link 3-8 is cut, we observe that only light-tree 1 is disturbed by the failure. Thus, light-tree 1 should be reconfigured to recover from the failure. However, the LR protection can perform to reconfigure not only light-tree 1 but also light-tree 2 in the restoration process, as shown in Figure 4.1.

Consider LR protection method. Although LR is conceptually preferable as it needs the minimal network resources to provide survivability, networks may suffer from several disadvantages. For instance, the reconfiguration of all light-trees on the entire network is not extremely desirable. This is because the rearrangement of all the traffic on the network usually takes a long time, not automatically reacting to the faulty event and degrading QoS of traffic as well. In addition, a network with LR protection would need a signaling system that is very efficient and very complicated, thereby requiring intricate network operation and management. Therefore, due to these disadvantages, the LR protection is considered impractical. However, the design outcomes of LR approach are useful as a benchmark to assess the performance of other, more practical light-tree protection approaches.

4.2.2 Light-Tree-Interrupted Reconfiguration Protection Strategy (LIR)

For the light-tree-interrupted reconfiguration protection approach (LIR), some part of its protection mechanism is identical to the LR approach. Employing the LIR approach, the network still has a capability to reconfigure the light-trees against a link failure. However, unlike LR, the LIR protection permits only light-trees traversing a failed link to change. Figure 4.1 illustrates the difference between the LR and LIR techniques. As shown, for the LIR approach, after the failure occurred at link 3-8, only the interrupted light-tree 1 is subject to rearrangement, while light-tree 2, which is not affected by the failure, remains unchanged.

As exemplified, we obviously see that LIR is less flexible than LR. It is thus expected that LIR would require more extra wavelength capacity to provision the survivability on networks than LR. However, this drawback of the LIR protection with respect to the LR protection is compensated by more easily managing the network after the failure occurs. In consequence, the LIR protection is more attractive to implement than the LR protection.

4.2.3 Optical Branch Protection Strategy (OB)

As explained above, both LR and LIR protections are designed by relying on the concept of reconfiguration of light-trees. If we consider the reconfiguration in detail, it should be remarked that only portions of light-trees are disrupted by the failure. As shown in Figure 4.1, only optical branch 3-8 of light-tree 1 is disrupted. Therefore, from this viewpoint, the network does not essentially reconfigure all optical branches of disrupted light-tree. It is adequate to rearrange only the optical branches that are directly corrupted by the failure. This observation is the main idea in designing the optical branch protection strategy (OB).

Upon the failure, the network deploying the OB protection must first seek out which optical branches of light-trees are disrupted. As already found, the interrupted optical branches are released and the network will then set up new optical branches, here called *backup optical branches*, so as to replace the interrupted ones. Under the OB protection, the network has flexibility to select the backup optical branches as long as they still make the light-trees connected and are also able to recover from the failure. Additionally, the OB technique allows the network to change the backup optical branches in accordance with different failure events. This implies that the network can choose different backup optical branches for different positions of the fault. For clarity, an example of a network with the OB protection is given in Figure 4.2.

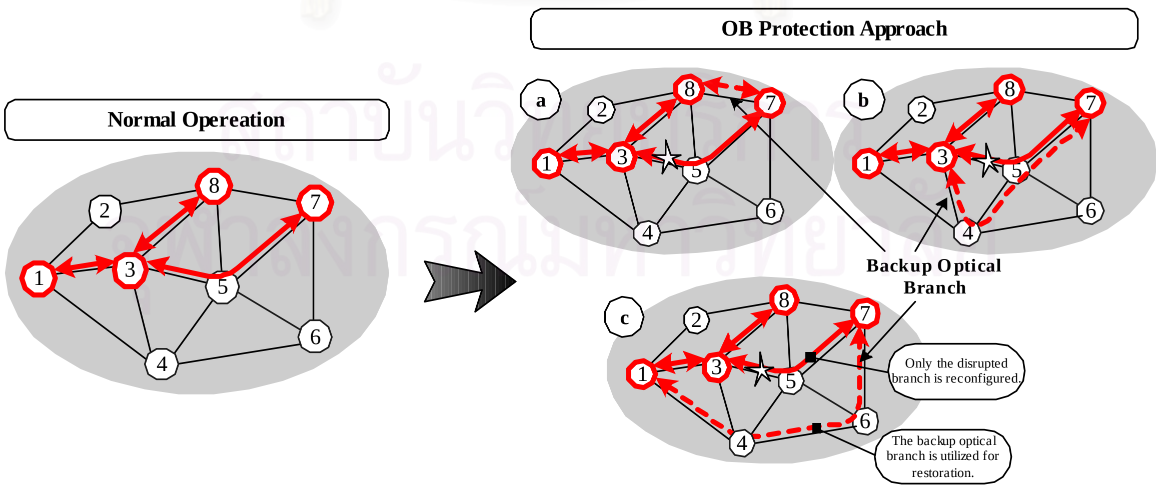


Figure 4.2: An example of a network with OB protection approach.

As shown, upon the fiber link 3-5 failure, the network detected that optical branch 3-7 is being disrupted. In the OB technique, the network will then replace the disrupted branch by allocating a backup optical branch. To set up the backup optical branch, the backup optical branch must be initiated from nodes which are members of the affected light-tree. From Figure 4.2, the network has three possible ways to establish the backup optical branch for restoration. Namely, the backup branch is possibly initiated at node 8, 3, or 1, but all backup branches of choice have to be terminated at node 7. All possible restoration scenarios are shown in cases a, b, and c in Figure 4.2.

Intentionally, the OB protection is designed to directly handle the optical branches that are corrupted by the failure. Therefore, the OB method is more practical to realize than the LR and LIR methods. This is because with respect to LR and LIR, the OB protection is more effective in such features as a smaller database size to store backup routes, and a simpler protection management system. Overall, the restoration time can be reduced. However, the OB method has a shortcoming, *i.e.,* it would need more network resources than the LR or LIR technique.

4.2.4 Optical-Branch-Fixed Protection Strategy (OBF)

The optical-branch-fixed protection technique (OBF) is historically derived from the OB protection with the aim to simplify the backup optical branch computation to protect against link failure. As stated, the OB technique can protect the network by assigning backup optical branches to replace failed ones. This idea is also included in the OBF scheme. However, as opposed to OB, the OBF protection will employ a certain number of backup optical branches to restore a light-tree from all possible failure scenarios. Figure 4.3 illustrates the OBF technique.

As previously exemplified in Figure 4.2, for OB, there are three possible ways to establish the backup optical branch when the link 3-8 is cut. However, in the OBF approach the network will initially determine a number of backup branches for each light-tree and the network will then deploy them for protection against all possible link failures. As demonstrated in Figure 4.3, the network decides to exploit two backup optical branches, *i.e.,* optical branches 1-7 and 8-7, against all possible events of failure. Therefore, in the case of the failed link 3-8, the network is restricted and has to select the backup optical branch from the two prior determined backup branches. As shown in Figure 4.3, the network with OBF finally selects the backup branch 8-7 for restoration. Notice that this is in contrast to the three choices to choose the backup branch in the OB protection.

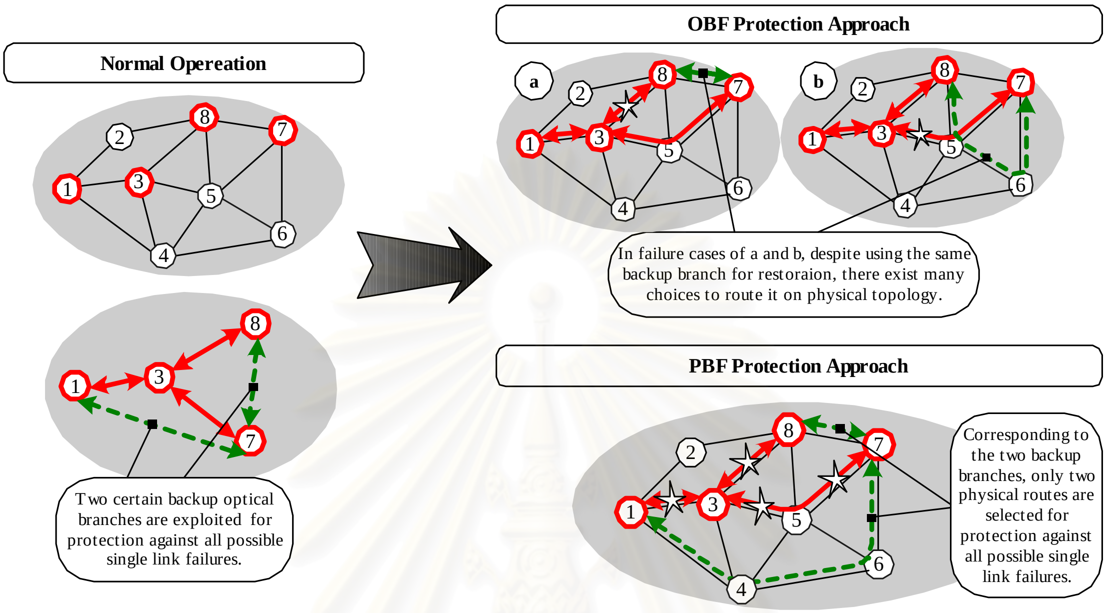


Figure 4.3: An example of a network using the OBF and PBF protection strategies.

Determining the number of backup branches (Br) for the OBF scheme strongly depends on the shape of the light-trees, which further relies on the fanout (Δ) of optical power splitters. To illustrate this relation, Figure 4.4 gives an example. Before describing Figure 4.4, we here note that in this thesis, we count the splitting degree, or fanout, of an optical power splitter based on optical branches exploited in normal operation, excluding backup optical branches. This is because this thesis assumes that optical splitters used for backup branches in restoration are allocated separately from those used for optical branches under normal operation.

In Figure 4.4, we present the light-trees by circles connected by bold lines. Meanwhile, the dashed lines represent the backup optical branches. As considered, the different fanout specified by optical splitters results in the different minimum number of backup optical branches needed for restoration against events of failure. For instance, in the case of Δ=2, the minimal number of backup branches required for restoration is 1 (Br=1). However, for Δ=3, the minimal value of Br depends on the shape of the light-tree. Figure 4.4 shows the cases of Br=2 and 3 at Δ=3. Furthermore, we notice that the value of Br can be increased from its minimum. In

Figure 4.4, at $\Delta=2$ the values of Br can be possibly increased to 2, 3, or 4. The increment in the number of backup branches signifies that the network has more choices in selecting backup optical branches for restoration; hence it is possible to save on network spare capacity. Therefore, under this scenario, the number of backup optical branches is a key factor in designing the OBF protection. In chapter 6, we shall quantitatively analyze the effect of this factor on fiber requirements of networks.

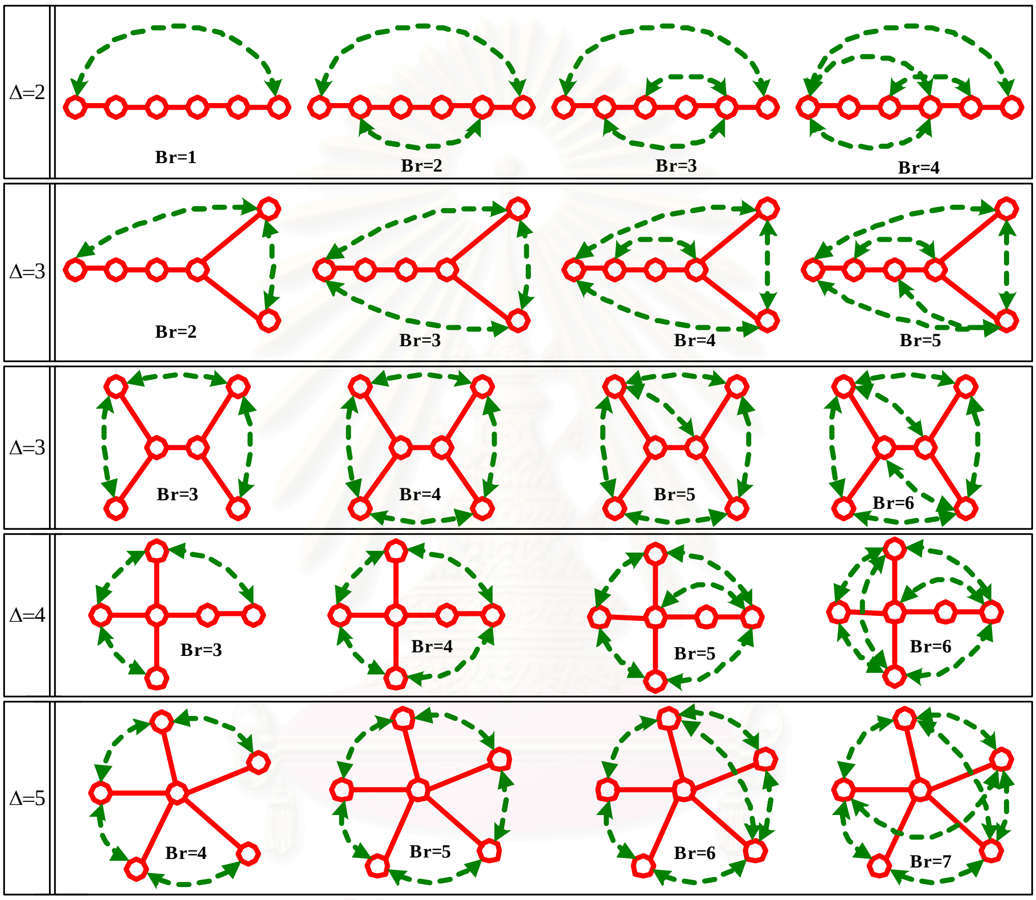


Figure 4.4: Effect of light-tree shape on the number of backup optical branches (Br) needed for restoration.

4.2.5 Physical-Branch-Fixed Protection Strategy (PBF)

With regard to the design of multicast protection strategies, the OBF strategy is obviously a limited version of the OB strategy. In the same manner, the physical-branch-fixed protection strategy (PBF) is designed to be a limited version of the OBF strategy. As with OBF, in the PBF technique, each light-tree operating on a network has a certain number of backup optical branches to restore it. However, as in the definition of light-trees, the optical branches are based on the logical topology. Thus in OBF, there are many possible physical routes that can be selected to support the backup optical branch. Consequently, although for two different failure events, OBF uses the same backup optical branch for restoration, the physical routes for those two failure events may be different. Therefore, to reduce the complexity of OBF, the PBF technique has a following additional constraint. For each backup optical branch, there must be only one physical route chosen, *i.e.*, one backup branch for each physical route. Figure 4.3 shows the difference between the OBF and PBF techniques.

As demonstrated, although OBF uses the same backup optical branch, *i.e.*, the backup branch 8-7 to restore the light-tree both in cases of link 3-8 and 3-5 failures, the selected corresponding physical routes are absolutely different. On the other hand, in the PBF protection, the network will be restricted and has to use only one physical route for each backup optical branch. Therefore, in Figure 4.3, the PBF protection employs the same physical route 8-7 for restoration both in cases of link 3-8 and 3-5 failures. In addition, Figure 4.3 shows that the PBF method always employs two backup physical routes against all possible link failures.

4.2.6 Optical Mesh Protection Strategy (OMP)

Consider five multicast protection strategies as explained above. Networks accommodate light-trees to support multicast services and employ the reconfiguration of light-trees or backup optical branches to protect them against failures. Alternatively, there is another technique to provide survivability to multicast services. It is named the optical mesh protection strategy (OMP). In the OMP strategy, the network does not construct light-trees as in the previous multicast protections. The network instead constructs *optical meshes*. In OMP, an optical mesh is defined as a mesh structure consisting of a number of optical branches connecting together and covering all members of a multicast session. In addition, the optical mesh must have the following properties. Each optical branch of the optical mesh must have an exactly corresponding physical route and upon any possible failure, the optical mesh must still be connected. Thus, to satisfy this property, the optical mesh for the OMP protection must be two-connected [37, 70]. Figure 4.5 illustrates the OMP method on the example network.

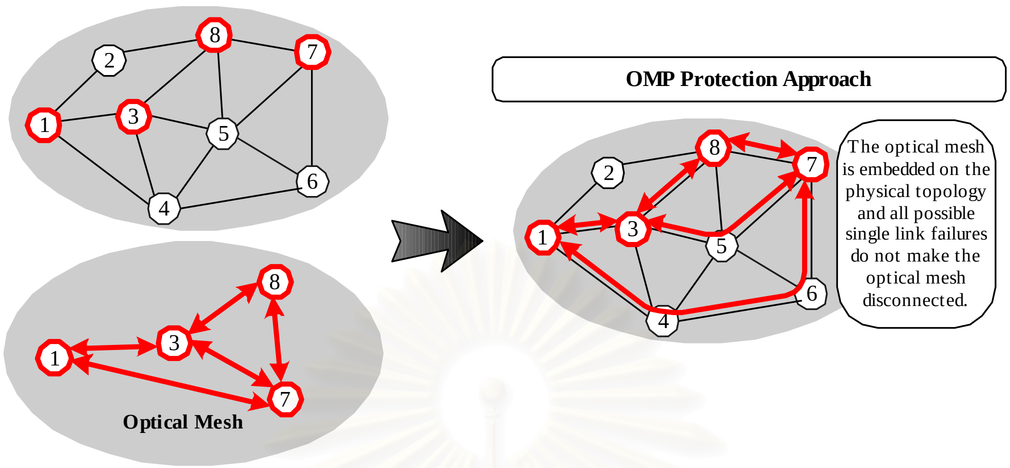


Figure 4.5: An example network employing the OMP method for protection.

In fact, the OMP protection can be viewed as a development of the PBF protection. To become OMP, after PBF has already chosen the backup physical routes for a light-tree, the network immediately reserve dedicated resources for such backup physical routes before the failure occurs. Therefore, from this circumstance, we can see that a light-tree combined with the backup physical routes will automatically become an optical mesh, resulting in the OMP protection.

Consider the OMP protection. Due to the dedicated reservation of network capacity, the restoration time of OMP is inherently very short with respect to the previous multicast protection approaches. However, for the same reason, low network capacity utilization can be found in networks using the OMP protection.

4.3 Point-to-Point Protection Strategies

As proposed, if we carefully examine the previous multicast protection approaches, we shall observe that the basic element used in the restoration is the light-tree. Upon a failure, the multicast protection techniques will attempt to recover the interrupted light-trees, resulting in changing their shape (or the sequence of nodes to receive the data) as shown in Figures 4.1-4.3. On the other hand, in the event of failure, we may desire to keep the light-tree shape the same as that before the failure occurs. Only one solution to meet this desire and also avoid link failures is to change only the physical routes corresponding to optical branches of light-trees, while the optical branches as seen on the logical topology are unchanged (see case b of Figure 4.2 for an example) Thus, from this standpoint, the basic restoration element is automatically changed from the light-tree to the physical route. Consequently, the protection strategies designed for lightpaths (point-to-point connections) can be extensively employed to protect multicast traffic. With respect to this scenario, point-to-point protection approaches can be classified as a class in providing survivability to multicast traffic, apart from the class of multicast protection approaches as previously proposed.

Here, it is worth noting that by using the point-to-point protection system for protecting multicast traffic, the network operation system will be less complicated with respect to the use of multicast protections since the network does not need the specific protection mechanism and system for multicast traffic. This results in that the network has only a single protection control plane to restore all types of traffic, including unicast, multicast, and also broadcast traffic. In addition, due to an unchanging light-tree shape for restoration, the point-to-point protection for multicast traffic can avoid the problems caused by the order of destination nodes in receiving the data signal as occurring in the multicast protection approaches.

In the following, we shall present the point-to-point protection strategies studied in this thesis.

4.3.1 Physical-Route Reconfiguration Protection Strategy (PRR)

As discussed, the point-to-point protections in multicast WDM networks are able to change (or reroute) only physical routes corresponding to optical branches of a light-tree, while the light-tree structure seen on the logical topology remains unchanged. Hence, the first protection technique is simple to design. For the physical-route reconfiguration protection strategy (PRR), which is adapted from the minimal cost protection approach (MC) in [25-27], in the event of a failure, all the ongoing physical routes established on the network are released and rearranged, regardless of whether the physical routes are directly affected by the failure.

To clearly understand the PRR technique, a network example is given in Figure 4.6. As demonstrated, it is clear that upon a failure, the PRR technique does not alter the light-tree structure as seen on the logical topology. In contrast, to avoid the failure, PRR will reroute all physical paths of light-trees working on the entire network instead.

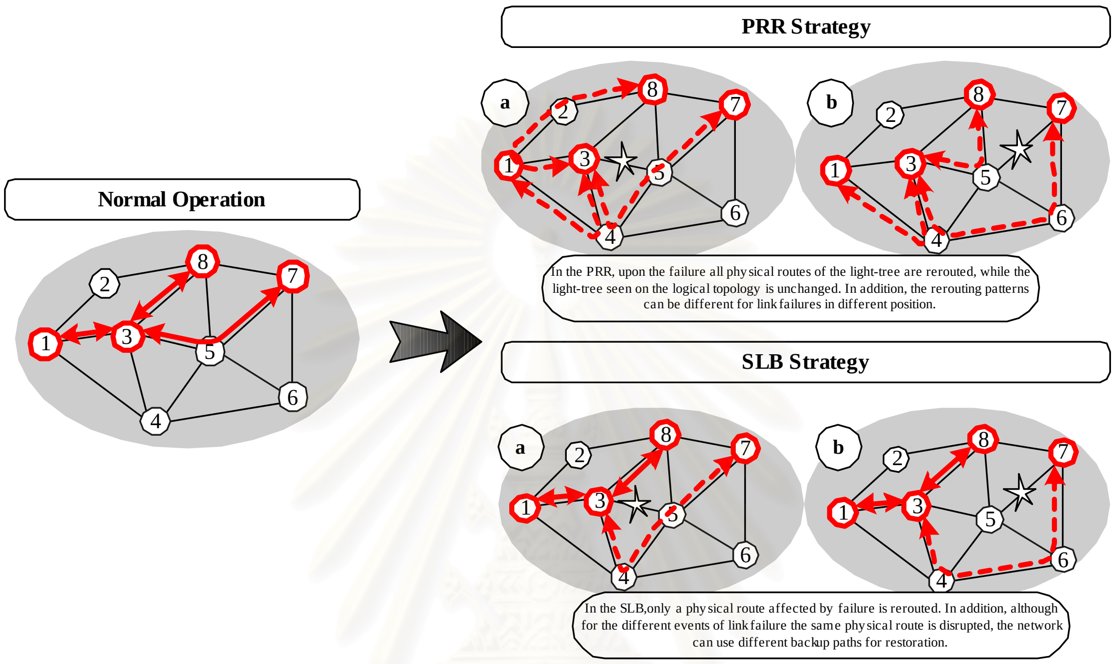


Figure 4.6: An example of a network using the PRR and SLB protection approaches.

Due to the rearrangement of physical paths by PRR in the restoration process, PRR is inherently very flexible with respect to other point-to-point protection approaches. Therefore, when compared with other point-to-point protections, PRR will require minimal network resources. However, this benefit comes at the cost of very complicated network management and operation, and also a slow restoration time.

4.3.2 Single Link Basis Protection Strategy (SLB)

As a point-to-point protection approach, the single link basis protection strategy [25-27] has a mechanism as follows. Unlike PRR, in events of link failure, a network with the SLB approach will reroute only the physical routes that pass through the failed link, while other routes are left undisturbed. Moreover, the SLB scheme has a property that each physical route can have different restoration routes depending on the location of the failed link. Figure 4.6 shows the difference between the PRR and SLB approaches.

As illustrated in case a) of Figure 4.6, upon the link 3-5 failure, the network with the SLB approach reroutes only the disrupted physical route 3-5-7 by using the restoration path 3-4-5-7, while other physical routes are unchanged. This is in contrast to PRR, which reroutes all the physical routes of the light-tree. In addition, for SLB, although the same physical route 3-5-7 is also disturbed by the other link 5-7 failure, the network can use a different restoration path. As shown in case b) of Figure 4.6, the SLB approach decides to employ the restoration path 3-4-6-7 as opposed to the restoration path 3-4-5-7 in case a).

From the example, we can see that SLB is less flexible in terms of rerouting physical routes than PRR. Thus, SLB is expected to require more network resources for protection than PRR. Nevertheless, the main advantage of SLB is that its protection management is simpler, thus leading to an improved restoration time.

4.3.3 Disjoint Path Protection Strategy (DJP)

Like the SLB approach, the disjoint path protection scheme (DJP) [25-27] only requires the rearrangement of the physical routes that are disrupted by the failure. However, in the DJP approach, the physical route and its restoration routes must be chosen to be disjoint. This means that the network must choose a restoration route that does not pass fiber links in common with the corresponding working physical route. This link disjointness implies that for DJP, only one restoration path for each working physical path suffices to protect it against all single link failures. Therefore, the DJP protection is the system of one working physical route for each restoration route (1:1 system).

In fact, the DJP approach can optionally be used against node failures if the network selects an active path and restoration path not sharing the same nodes. In this thesis, we select to study the DJP approach with node disjointness because it is attractive if the network is able to survive both node and link failures; see Figure 4.7 for an example of a network using DJP. As shown, each physical route of the light-tree has its own node-disjoint restoration route.

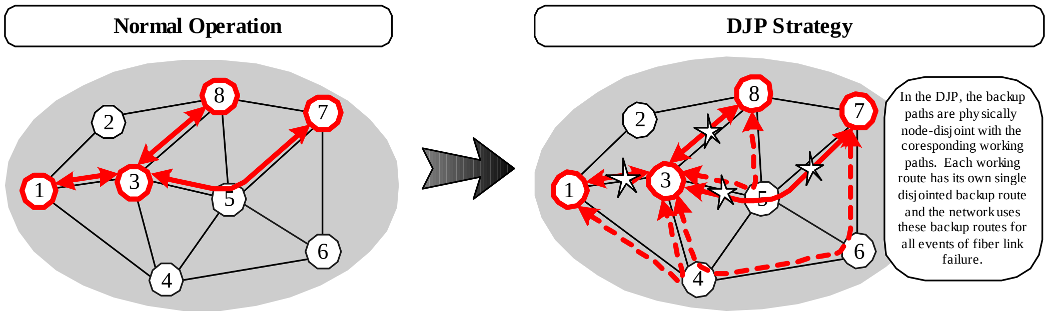


Figure 4.7: An example of a network using the DJP protection scheme.

4.3.4 Link Protection Strategy (LP)

As commonly known, the PRR, SLB and DJP protection schemes are classified as the path-based protection [63-65]. In path-based protection, upon a failure, the interrupted paths are rerouted on new entire physical routes between the end points of connections. On the other hand, an alternative class of point-to-point protection is the link protection [63-65]. In the link protection, all the physical routes of light-trees that transverse a failed link are rerouted around that failed link; see Figure 4.8 for example. As illustrated in case a), in the event of link 3-5 failure, only part 3-5 of working route 3-5-7 is rerouted to avoid the failure, while other parts of the route remain unchanged.

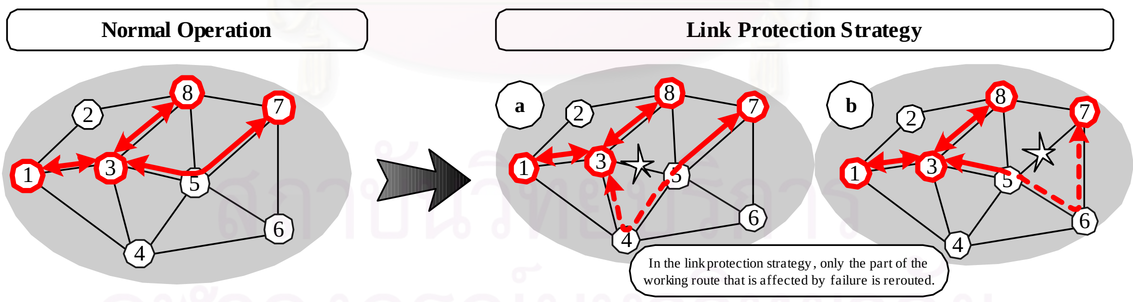


Figure 4.8: An example of a multicast network using the link protection strategy.

The key advantage of the link protection is that the protection system performs locally and is transparent to the end points of connection; hence its protection process is relatively faster than path-based protection counterparts. However, due to its restriction of rerouting the interrupted traffic, the network capacity needed for the link protection is expected to be more than that needed by the path-based protections.

4.3.5 1+1 Protection Strategy

The last protection strategy investigated in this thesis is the 1+1 protection technique, which has been intensively studied in the literature [16, 64]. For the 1+1 protection, at the time of setting up the physical routes of a light-tree, the network will allocate both physical routes and their dedicated node-disjoint backup routes simultaneously. If a failure occurs on the working route, the network will start employing the backup route. In fact, the 1+1 protection can be viewed as a point-to-point protection developed from the DJP technique if the network capacity of the node-disjoint restoration routes of the DJP technique is dedicated and reserved in advance before a failure happens.

Due to the dedicated reservation of network capacity in the 1+1 protection, its restoration time is inherently very short with respect to other point-to-point protection approaches. However, for the same reason, the network may suffer from low network resource utilization, incurring a high network cost for implementation.

4.4 Classification of the Light-Tree Protection Strategies

As introduced the light-tree protection strategies, it is noticed that we tried to explain their protection mechanisms by describing how we obtain one protection technique from another protection technique. For instance, in the LIR approach, we explained it by describing how to derive it from the LR approach. Thus, in this section, we aim to illustrate the whole line of developing light-tree protections as we study here. The simple diagram as depicted in Figure 4.9 presents the line of the light-tree protection development. At the top of the diagram of LR protection, the light-tree protections can be assigned to two techniques, *i.e.*, the LIR and PRR techniques. For the former protection, LIR is derived by combining LR with an extra constraint that only corrupted light-trees can be reconfigured for restoration. Meanwhile, PRR is derived from LR by including a limit that only the physical routes of light-trees are rerouted in the event of a failure.

At the LIR and PRR protections, the diagram shows two main classes of light-tree protections, i.e., multicast protections and point-to-point protections. As we can see, the multicast protections include the LIR, OB, OBF, PBF, and OMP protection methods, while the point-to-point protections include the PRR, SLB, DJP, LP, and 1+1 protection methods.

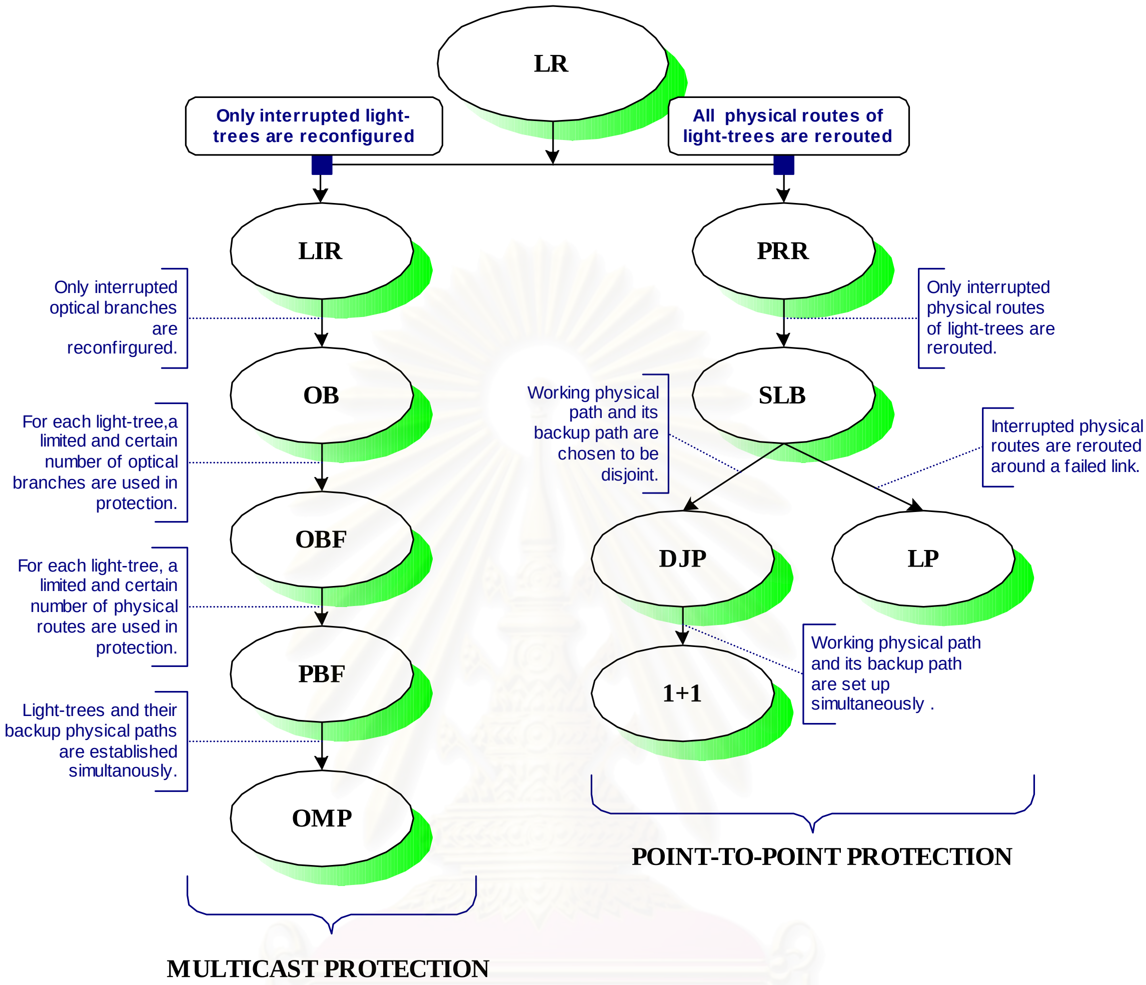


Figure 4.9: Simple diagram showing the whole line of developing the light-tree protection schemes.

On the line of the multicast protections, the OB technique can be obtained from LIR with the condition that only optical branches disrupted by a failure are reconfigured. The diagram in Figure 4.9 further indicates that OB can be advanced to be OBF by adding a constraint that for each light-tree, a certain number of optical branches are utilized for protection. Analogously, PBF can also be obtained from OBF with an extra condition that is identified in the diagram, and finally, the last multicast protection is OMP, which can be viewed as a modified version of PBF. How PBF can be evolved to be OMP is stated in the diagram.

We can explain the class of point-to-point protections in the same manner as the class of multicast protections, except for SLB. Figure 4.9 illustrates that SLB can be evolved to two different protection techniques depending on the limits combined with SLB. DJP uses the limit of node disjointness in the process of selecting the working and backup paths for light-trees. Meanwhile, LP is the SLB with the restriction that the interrupted routes must be rerouted around the failed link.

In fact, the diagram shown in Figure 4.9 is not only useful for projecting the evolution picture of light-tree protections, but also helpful in anticipating the capacity requirement for providing the protection, and the control/management complexity among the light-tree protection methods. As we can see, when comparing the capacity requirement among the multicast protection techniques, we have LR<LIR<OB<OBF<PBF<OMP (the capacity requirement increases from above to below in the diagram). In terms of network control complexity, we have an opposite trend LR>LIR>OB>OBF>PBF>OMP (the network control complexity increases from below to above in the diagram). In the same manner, for the point-to-point protections, we have LR<PRR<SLB<DJP<1+1 for the capacity requirement and LR>PRR>SLB>DJP>1+1 for the network control complexity.

4.5 Wavelength Allocation

Apart from the routing problem, another important problem that arises specifically in WDM networks is the wavelength allocation problem. In this section, we propose three distinct techniques of wavelength allocation for multicast traffic in resilient WDM networks.

4.5.1 Light-Tree Wavelength Allocation Method (LT)

In the LT method, when setting up light-trees to support multicast traffic, we are able to choose only one wavelength for each light-tree. In event of a fiber link failure, a disrupted light-tree in the LT method is restricted and must use the same wavelength as used in normal operation to restore the failure. According to the LT method, we can see that all OXCs of the network do not essentially need the wavelength conversion ability; therefore wavelength converters are not required.

4.5.2 Virtual Light-Tree Wavelength Allocation Method (VLT)

In the VLT method, assigning wavelengths to a light-tree in the condition of normal network operation relies on the fashion of *link-by-link basis*, *i.e.,* the wavelengths assigned to the light-tree can be different along the physical links serving it. When the link failure occurs and that light-tree is disrupted, the network is capable of assigning new wavelengths to restoration paths of the light-tree. Also, the wavelengths assigned in the failure condition are not essentially identical to the wavelengths of the light-tree used in normal operation. According to VLT, OXCs of the network must thus have the capability of full wavelength conversion.

4.5.3 Partial Virtual Light-tree Wavelength Allocation Method (PVLT)

With respect to the light-tree definition, a light-tree is constructed from a set of optical branches. In the PVLT method, a light-tree established on the network can occupy different wavelengths for different optical branches of the light-tree. However, along the physical links of each optical branch of the light-tree, the network must assign the same wavelength. In the event of a single link failure, the network also holds the PVLT criteria as in normal operation. Namely, each restoration path of an optical branch of the light-tree must occupy the same wavelength along its physical route. However, the wavelengths of the optical branch before and after the failure happens are not essentially identical.

As we can see, it should be noted that the PVLT wavelength allocation is a compromise method between LT and VLT in terms of the wavelength conversion ability of WDM networks. Thus, it is expected that the number of wavelength converters required by PVLT is in between those of LT and VLT.

By using the mathematical formulations as will be introduced in the next chapter, we can match the light-tree protection strategies with the wavelength allocation techniques as in Table 4.1.

In chapter 6, we shall show and discuss the numerical results for the LT, VLT, and PVLT wavelength assignments.

Table 4.1: Matching the light-tree protections with the wavelength allocation techniques.

Protection Strategy	Wavelength Allocation Technique		
	VLT	**PVLT**	**LT**
LR	✓	✓	✓
LIR	✓	✓	✓
OB	✓	✓	✓
OBF	✓	✓	✓
PBF	✓	×	✓
OMP	✓	×	✓
PRR	✓	✓	✓
SLB	✓	✓	✓
DJP	✓	✓	✓
LP	✓	✓	✓
1+1	✓	✓	✓

4.6 Spare Capacity Placement Techniques

To make optical networks restorable, it is inevitable to place the spare capacity for protection. In general, restoration paths employed to restore light-trees can be accommodated in networks with either dedicated spare capacity or shared spare capacity reservation. In dedicated spare capacity reservation, the spare wavelength channels are exclusively reserved for each light-tree for protection. The 1+1 and OMP protections are examples of using dedicated spare capacity reservation. In the shared spare capacity reservation, spare wavelength channels are allowed to be common or shared resources for rerouting disrupted light-trees if they are not interrupted by the failure simultaneously.

For shared spare capacity reservation, it is possible to classify the level of spare capacity sharing, leading to different techniques to establish spare capacity. In this thesis, we study three levels of spare capacity sharing.

4.6.1 Spare Fiber + Working Fiber Method (SF+WF)

For the SF+WF method, networks divide optical fibers into two groups, *i.e.*, working and spare fibers. The light-trees in normal operation are carried on the working fibers, while the spare fibers are exclusively available only for rerouting disrupted light-trees. The sharing of spare capacity is limited and arises only in the spare fibers.

We can see that the SF+WF method is simple to implement and it is currently exploited in commercial communications networks.

4.6.2 Spare Wavelength Channel + Working Wavelength Channel Method (SW+WW)

For the SF+WF method, the network uses a fiber as a granularity to separate the spare capacity out of the working capacity. Alternatively, in the SW+WW method, the network will instead employ the granularity of wavelengths to separate the spare and working capacity. For SW+WW, the network divides the wavelength channels of all fibers available in the network into two parts, that is, the working and spare wavelength channels. The working wavelength channels are for the working light-trees, while the spare wavelength channels are used for restoration. In addition, the scenario of spare capacity sharing in the SW+WW technique is permitted to occur only on the spare wavelength channels.

4.6.3 Spare Wavelength Channel + Working Wavelength Channel Method with Stub Release (SW+WW+SR)

Like SW+WW, the SW+WW+SR technique exploits the granularity of wavelengths in order to manage the wavelength channels of networks. However, unlike SW+WW, SW+WW+SR includes an extra option that is called *stub release* [70]. Stub release refers to a mechanism where, in the event of a failure, the portions of working wavelength channels occupied by corrupted light-trees are released and the network with the stub release will then make those channels available for restoration process. Thus, this implies that for SW+WW+SR, not only the spare wavelength channels but also the working wavelength channels released by the stub release can be utilized for supporting the restoration paths of light-trees.

Table 4.2: Combinations of the spare capacity placement techniques and the proposed light-tree protection schemes.

Protection Strategy	Spare Capacity Placement Technique			
	Dedicated	Spare Capacity Sharing		
		SF+WF	SW+WW	SW+WW+SR
LR	×	×	×	✓
LIR	×	×	×	✓
OB	×	✓	✓	✓
OBF	×	✓	✓	✓
PBF	×	✓	✓	×
OMP	✓	×	×	×
PRR	×	×	×	✓
SLB	×	✓	✓	✓
DJP	×	✓	✓	✓
LP	×	✓	✓	×
1+1	✓	×	×	×

Consider the SF+WF, SW+WW, SW+WW+SR approaches. It should be noted that as commonly known, how to place and manage the spare capacity directly affects the node-switching fabrication and the node-switching control. Thus, the SF+WF technique is considered the simplest technique to fabricate and manage node-switches, while the other two techniques, especially SW+WW+SR, may be more complicated. However, the complexity of spare capacity management are expected to be compensated by the savings in spare fibers as the sharing spare capacity level is increased from SF+WF to SW+WW and finally to SW+WW+SR. In this thesis, the discussion in terms of spare fiber requirements among the proposed techniques is provided in chapter 6.

In designing resilient WDM networks, the techniques of spare capacity placement must be combined with the protection schemes. The possible combinations between the spare capacity placement techniques and the protections are presented in Table 4.2.

4.7 Problem Definitions

From the proposed light-tree protections, wavelength allocation techniques and spare capacity placement techniques, we are ready to formally state the two network design problems [81] related to the protection and the capacity provisioning in resilient WDM networks. The two network design problems are intensively investigated in this thesis.

Prior to describing the network design problems, a new terminology, *i.e., a restoration light-tree,* should be introduced first. A restoration light-tree refers to the light-tree used in events of single link failure. How to obtain the restoration light-tree will strongly depend on the light-tree protection approach that the network employs.

Problem A: joint optimization. *Given a network described by nodes and links, a number of wavelengths per fiber, a set of multicast traffic demands, find both service (working) and restoration light-tree routing and wavelength patterns for all demands so that the total number of working and spare fibers is minimized.*

Problem B: minimum spare capacity. *Given a network described by nodes and links, a number of wavelengths per fiber, a set of multicast traffic demands, and a service light-tree routing and wavelength pattern, find a restoration light-tree routing and wavelength pattern for all demands so that the total number of spare fibers is minimized.*

From the definitions, network problems A and B are important network problems that reflect several scenarios in network design. For instance, network problem A involves a scenario in which network operators want to plan their networks for the long-term so that the networks are able to support the traffic demands at a time point in the future. For another example, problem A is concerned with traffic reconfiguration when networks are in the “clean” state [81].

Network problem B is relevant to the situation in which networks are in the state of operation and now carrying the traffic demands. Also, networks may have remaining capacity. Under this situation, problem B will become a realistic case if network operators aim to provide survivability to the traffic demands, and also need to know: 1) how many additional fibers are needed to achieve this aim, and 2) whether the remaining network capacity is enough to provide the survivability.

Due to the importance and significance of problems A and B in realistic network design, we shall therefore present the ILP formulations to solve both problems and analyze the results of both two problems in the next two chapters.

Chapter 5

ILP Formulations and Heuristic Algorithm of Studied Light-Tree Protection Approaches

5.1 Introduction

According to the proposed protection strategies, wavelength allocation techniques and spare capacity placement techniques, this chapter derives ILP formulation and also designs the heuristic algorithms.

Section 5.2 describes the network model deployed to formulate the ILP models. In sections 5.3 and 5.4, the ILP model of each studied protection method is developed in accordance to problems A and B, respectively. Finally, section 5.5 presents the heuristic algorithms for wavelength allocation in WDM networks with link protection.

5.2 Network Model

Consider an optical network represented by an undirected graph $G = (N, L)$, where N denotes a set of MC-OXC nodes, $i = \{1,2,3,...N\}$, with $|N| = N$. Meanwhile, the physical links are represented by a set of undirected links, $L \subseteq N \times N$, where a physical link ij is in the set L if there exists a link connecting nodes i and j. For the network, we assume that each physical link is bi-directional and may consist of more than one optical fiber to serve the traffic demands of the network. Each optical fiber is limited to multiplexing the number of wavelengths up to M .

As stated in problems A and B in chapter 4, the multicast traffic demands of the network are given as an input of the problem and they are defined as a set of $R = \{r_1(s_1, D_1), r_2(s_2, D_2), \ldots, r_K(s_K, D_K)\}$ with $K = |R|$, where $r_k(s_k, D_k) \in R$ represents a multicast traffic session needing to set up a light-tree from the source s_k to a group of destinations D_k $(s_k \notin D_k)$ in the network.

From the network model, we now introduce the main parameters and variables that are used in all ILP models of the light-tree protection approaches.

Network Parameters:

t_{r_k} total traffic demands of multicast traffic request r_k in unit of wavelength channel;

P_{sd} a set of candidate working routes of node pair sd ;

$E_{sd}^{ij'}$ a set of candidate restoration routes of node pair sd upon the failure of link ij';

$\delta_{ij,p}^{sd}$ takes the value of one if working route p of node pair sd passes through link ij , and zero, otherwise;

$\mu_{ij,e}^{sd,ij'}$ takes the value of one if restoration route e of node pair sd passes through link ij upon the failure of link ij', and zero, otherwise;

I_{∞} an arbitrarily high constant integer;

Network Variables:

f_{ij} total number of working fibers on physical link ij ;

f_{ij} total number of spare fibers on physical link ij ;

$x_{r_k}^{ij}$ a boolean variable, an optical branch between nodes i and j to form a light-tree for carrying multicast demand r_k in the normal network state;

$xf_{r_k,ij'}^{ij}$ a boolean variable, a backup optical branch between nodes i and j to form a restoration light-tree for carrying multicast demand r_k upon the failure of link ij';

$a_{r_k,p}^{sd}$ a candidate physical route p of node pair sd for multicast demand r_k (for the VLT system);

$a_{r_k,p,\lambda}^{sd}$ a candidate physical route p of node pair sd occupying wavelength λ for multicast demand r_k (for the LT and PVLT systems);

$u_{r_k,e}^{sd,ij'}$ a candidate restoration route e of node pair sd for multicast demand r_k upon the failure of link ij' (for the VLT system);

$u_{r_k,e,\lambda}^{sd,ij'}$ a candidate restoration route e of node pair sd occupying wavelength λ for multicast demand r_k upon the failure of link ij' (for the LT and PVLT systems);

$W_{r_k,\lambda}$ wavelength channel λ occupied by multicast demand r_k (only for the LT system).

5.3 ILP formulations to Solve Joint Optimization of Working and Spare Fibers (Network Problem A)

For network design problem A, we divide the presentation into two parts. In the first part, *i.e.*, sections 5.3.1-5.3.6, we introduce the ILP formulations for the multicast protection strategies as a class of light-tree protection as shown in Figure 4.9. For the latter part *i.e.*, sections 5.3.7-5.3.11, the ILP formulations for the point-to-point protections are presented. Note that although ILP programs are different for different wavelength assignment approaches, the meanings of constraints used to model the ILP programs of three wavelength assignment approaches are quite similar; see the ILP formulations of in chapter 2 for example. Hence, in the following, we shall provide the explanation of constraints only in the case of VLT wavelength allocation. The constraint meanings of the VLT mathematical model can be well applied to those of the PVLT and LT models.

5.3.1 LR Protection Formulations

Due to the light-tree reconfiguration in restoration process of the LR protection, the spare capacity placement technique that appropriately matches with the LR protection is the SW+WW+SR technique. Hence, the LR mathematical model can be formulated as follows.

- **VLT wavelength allocation case**

$$\min : \sum_{ij \in L} f_{ij} \,, \tag{5.1}$$

subject to the constraints (2.2)-(2.5), (2.7)-(2.9) and:

$$\sum_{ij \in A_k} xf^{ij}_{r_k, ij'} = \left| N_k \right| - 1 \,, \qquad \forall ij' \in L \,, \forall r_k \in R \tag{5.2}$$

$$\sum_{ij \in \vartheta(S)} xf^{ij}_{r_k, ij'} \geq 1 \,, \qquad \forall S \subset N_k \,, S \neq \phi, N \,,\ \forall ij' \in L \,, \forall r_k \in R \tag{5.3}$$

$$\sum_{j : ij \in A_k} xf^{ij}_{r_k, ij'} \leq \Delta \,, \qquad \forall i \in N_k \,, \forall ij' \in L \,, \forall r_k \in R \tag{5.4}$$

$$xf^{ij}_{r_k, ij'} \in \{0,1\} \,, \qquad \forall ij \in A_k \,, \forall ij' \in L \,, \forall r_k \in R \tag{5.5}$$

$$\sum_{e \in E^{ij'}_{sd}} u^{sd, ij'}_{r_k, e} = t_{r_k} \times xf^{sd}_{r_k, ij'} \,, \qquad \forall sd \in A_k \,, \forall r_k \in R \,, \forall ij' \in L \tag{5.6}$$

$$M \times f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E^{ij'}_{sd}} u^{sd, ij'}_{r_k, e} \, \mu^{sd, ij'}_{ij, e} \geq 0 \,, \qquad \forall ij \in L - \{ij'\} \,, \forall ij' \in L \tag{5.7}$$

$$u^{sd, ij'}_{r_k, e} \in Z^{+} \,, \qquad \forall e \in E^{ij'}_{sd} \,, \forall sd \in A_k \,, \forall r_k \in R \,, \forall ij' \in L \tag{5.8}$$

$$f_{ij} \in Z^{+} \,, \qquad \forall ij \in L \,. \tag{5.9}$$

The objective function (5.1) is to minimize the total number of fibers of a network with the LR protection. Under network normal operation, constraints (2.2)-(2.5) and (2.7)-(2.9) are contained in the model to find the working light-tree structures and also their routing characteristic. Likewise, constraints (5.2)-(5.5) are provided to the model to ensure that in an event of link ij' failure, all light-trees of the network are able to reconfigure to avoid the failure. Constraints (5.7) ensure that upon the link ij' failure, the number of fibers assigned to link ij is high enough to accommodate the restoration routes of all reconfigured light-trees. Finally, constraints

(5.8) and (5.9) express that the variables of restoration routes of light-trees and the number of fibers of each network link must be nonnegative integers.

- **PVLT wavelength allocation case**

$$\min : \sum_{ij \in L} f_{ij} \,, \tag{5.10}$$

subject to the constraints (2.2)-(2.5), (2.12)-(2.14) and:

$$\sum_{ij \in A_k} xf^{ij}_{r_k,ij'} = \left|N_k\right| - 1 \,, \qquad \forall ij' \in L \,, \forall r_k \in R \tag{5.11}$$

$$\sum_{ij \in \vartheta(S)} xf^{ij}_{r_k,ij'} \geq 1 \,, \qquad \forall S \subset N_k \,, S \neq \phi, N \,, \forall ij' \in L \,, \forall r_k \in R \tag{5.12}$$

$$\sum_{j : ij \in A_k} xf^{ij}_{r_k,ij'} \leq \Delta \,, \qquad \forall i \in N_k \,, \forall ij' \in L \,, \forall r_k \in R \tag{5.13}$$

$$xf^{ij}_{r_k,ij'} \in \{0,1\} \,, \qquad \forall ij \in A_k \,, \forall ij' \in L \,, \forall r_k \in R \tag{5.14}$$

$$\sum_{e \in E^{ij'}_{sd}} \sum_{\lambda=1}^{M} u^{sd,ij'}_{r_k,p,\lambda} = t_{r_k} \times xf^{sd}_{r_k,ij'} \,, \quad \forall sd \in A_k \,, \forall r_k \in R \,, \forall ij' \in L \tag{5.15}$$

$$f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda} \mu^{sd,ij'}_{ij,e} \geq 0 \,, \forall \lambda = \{1,2,\ldots, M\}, \ \forall ij \in L - \{ij'\} \,, \forall ij' \in L \tag{5.16}$$

$$u^{sd,ij'}_{r_k,e,\lambda} \in Z^+ \,, \quad \forall \lambda = \{1,2,\ldots, M\}, \quad \forall e \in E^{ij'}_{sd} \,, \forall sd \in A_k \,, \forall r_k \in R \,, \forall ij' \in L \tag{5.17}$$

$$f_{ij} \in Z^+ \,, \qquad \forall ij \in L \,. \tag{5.18}$$

- **LT wavelength allocation case**

$$\min : \sum_{ij \in L} f_{ij} \,, \tag{5.19}$$

subject to the constraints (2.2)-(2.5), (2.17),(2.18), (2.20) and:

$$\sum_{ij \in A_k} xf^{ij}_{r_k,ij'} = \left|N_k\right| - 1 \,, \qquad \forall ij' \in L \,, \forall r_k \in R \tag{5.20}$$

$$\sum_{ij \in \vartheta(S)} xf^{ij}_{r_k,ij'} \geq 1 \,, \qquad \forall S \subset N_k \,, S \neq \phi, N \,, \forall ij' \in L \,, \forall r_k \in R \tag{5.21}$$

$$\sum_{j : ij \in A_k} xf^{ij}_{r_k,ij'} \leq \Delta \,, \qquad \forall i \in N_k \,, \forall ij' \in L \,, \forall r_k \in R \tag{5.22}$$

$$xf^{ij}_{r_k,ij'} \in \{0,1\} \,, \qquad \forall ij \in A_k \,, \forall ij' \in L \,, \forall r_k \in R \tag{5.23}$$

$$\sum_{e\in E_{sd}^{ij'}}\sum_{\lambda=1}^{M} u_{r_k,p,\lambda}^{sd,ij'} = t_{r_k} \times xf_{r_k,ij'}^{sd}\ , \quad \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.24}$$

$$f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E_{sd}^{ij'}} u_{r_k,e,\lambda}^{sd,ij'} \mu_{ij,e}^{sd,ij'} \geq 0, \forall\lambda = \{1,2,\dots,M\},\ \forall ij \in L - \{ij'\}, \forall ij' \in L \tag{5.25}$$

$$u_{r_k,e,\lambda}^{sd,ij'} \in Z^+, \quad \forall\lambda = \{1,2,\dots,M\}, \quad \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.26}$$

$$\sum_{\lambda=1}^{M} W_{r_k,\lambda} = t_{r_k}, \qquad \forall r_k \in R \tag{5.27}$$

$$u_{r_k,e,\lambda}^{sd,ij'} \leq I_\infty \times W_{r_k,\lambda}, \quad \forall\lambda = \{1,2,\dots,M\},\ \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.28}$$

$$W_{r_k,\lambda} \in Z^+, \qquad \forall\lambda = \{1,2,\dots,M\}, \forall r_k \in R \tag{5.29}$$

$$f_{ij} \in Z^+, \qquad \forall ij \in L. \tag{5.30}$$

5.3.2 LIR Protection Formulations

As the same reason in the LR protection, the LIR protection is studied only with the SW+WW+SR technique.

- **VLT wavelength allocation**

$$\min : \sum_{ij\in L} f_{ij}\ , \tag{5.31}$$

subject to the constraints (2.2)- (2.5), (2.7)-(2.9) and:

$$\sum_{sd}\sum_{p\in P_{sd}} a_{r_k,p}^{sd} \delta_{ij',p}^{sd} \leq I_\infty \times G_{r_k}^{ij'}, \quad \forall r_k \in R, \forall ij' \in L \tag{5.32}$$

$$\sum_{ij\in A_k} xf_{r_k,ij'}^{ij} = (|N_k| - 1) \times G_{r_k}^{ij'}, \qquad \forall ij' \in L, \forall r_k \in R \tag{5.33}$$

$$\sum_{ij\in\vartheta(S)} xf_{r_k,ij'}^{ij} \geq G_{r_k}^{ij'}, \quad \forall S \subset N_k, S \neq \phi, N\ , \forall ij' \in L\ , \forall r_k \in R \tag{5.34}$$

$$\sum_{j:ij\in A_k} xf_{r_k,ij'}^{ij} \leq \Delta \times G_{r_k}^{ij'}, \qquad \forall i \in N_k, \forall ij' \in L, \forall r_k \in R \tag{5.35}$$

$$xf_{r_k,ij'}^{ij} \in \{0,1\}, \qquad \forall ij \in A_k, \forall ij' \in L, \forall r_k \in R \tag{5.36}$$

$$\sum_{e\in E_{sd}^{ij'}} u_{r_k,e}^{sd,ij'} = t_{r_k} \times xf_{r_k,ij'}^{sd}\ , \quad \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.37}$$

$$(\sum_{sd}\sum_{p\in P_{sd}} a_{r_k,p}^{sd}\delta_{ij,p}^{sd} - C_{r_k,ij}^{ij'}) \le I_\infty G_{r_k}^{ij'}, \quad \forall r_k \in R, \forall ij \in L-\{ij'\}, \forall ij' \in L \qquad (5.38)$$

$$C_{r_k,ij}^{ij'} \le I_\infty(1-G_{r_k}^{ij'}), \quad \forall r_k \in R, \forall ij \in L-\{ij'\}, \forall ij' \in L \qquad (5.39)$$

$$C_{r_k,ij}^{ij'} \in Z^+, \quad \forall r_k \in R, \forall ij \in L-\{ij'\}, \forall ij' \in L \qquad (5.40)$$

$$G_{r_k}^{ij'} \in \{0,1\}, \quad \forall r_k \in R, \forall ij' \in L \qquad (5.41)$$

$$M \times f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E_{sd}^{ij'}} u_{r_k,e}^{sd,ij'}\mu_{ij,e}^{sd,ij'} - \sum_{r_k\in R} C_{r_k,ij}^{ij'} \ge 0, \quad \forall ij \in L-\{ij'\}, \forall ij' \in L \qquad (5.42)$$

$$u_{r_k,e}^{sd,ij'} \in Z^+, \quad \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \qquad (5.43)$$

$$f_{ij} \in Z^+, \quad \forall ij \in L. \qquad (5.44)$$

In the formulation, the objective function (5.31) is to minimize the fiber requirement in a network with the LIR protection. As in the LR formulation, constraint sets (2.2)-(2.5) and (2.7)-(2.9) are used to obtain an optimal service light-tree routing pattern. For constraints (5.32), they determine which service light-trees are corrupted by failed link ij' by employing Boolean variables $G_{r_k}^{ij'}$ as formulated in constraints (5.41). In constraints (5.32), if multicast demand r_k is disrupted by failed link ij', the value of $G_{r_k}^{ij'}$ is one. Otherwise, it becomes zero. Again, I_∞ in constraints (5.32) represents a highly arbitrary integer constant. For constraints (5.33)-(5.37), they compute a restoration light-tree for multicast demand r_k when $G_{r_k}^{ij'}$=1. Since in the LIR protection, the option of stub release is applied, constraints (5.38)-(5.40) are used to determine capacity needed for restoration. In constraints (5.38), when $G_{r_k}^{ij'}$=0, the $C_{r_k,ij}^{ij'}$ equals to the wavelength capacity at link ij of light-tree r_k which is not interrupted by failed link ij. Meanwhile, constraints (5.39) enforce that the value of $C_{r_k,ij}^{ij'}$ should be zero if $G_{r_k}^{ij'}$=1. For constraints (5.42), they assure that the number of fibers placed at link ij is sufficient to support all multicast demands in the network state of link ij' failure. Finally, constraints (5.43) and (5.44) limit the network variables to be only nonnegative integers.

- **PVLT wavelength allocation case**

$$\min: \sum_{ij \in L} f_{ij} \,, \tag{5.45}$$

subject to the constraints (2.2)- (2.5), (2.12)-(2.14) and:

$$\sum_{sd} \sum_{p \in P_{sd}} \sum_{\lambda=1}^{M} a_{r_k,p,\lambda}^{sd} \delta_{ij',p}^{sd} \le I_{\infty} \times G_{r_k}^{ij'}, \quad \forall r_k \in R, \forall ij' \in L \tag{5.46}$$

$$\sum_{ij \in A_k} xf_{r_k,ij'}^{ij} = (|N_k| - 1) \times G_{r_k}^{ij'}, \qquad \forall ij' \in L, \forall r_k \in R \tag{5.47}$$

$$\sum_{ij \in \vartheta(S)} xf_{r_k,ij'}^{ij} \ge G_{r_k}^{ij'}, \qquad \forall S \subset N_k, S \ne \phi, N \;, \forall ij' \in L \;, \forall r_k \in R \tag{5.48}$$

$$\sum_{j: ij \in A_k} xf_{r_k,ij'}^{ij} \le \Delta \times G_{r_k}^{ij'}, \qquad \forall i \in N_k, \forall ij' \in L, \forall r_k \in R \tag{5.49}$$

$$xf_{r_k,ij'}^{ij} \in \{0,1\}, \qquad \forall ij \in A_k, \forall ij' \in L, \forall r_k \in R \tag{5.50}$$

$$(\sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij,p}^{sd} - C_{r_k,ij,\lambda}^{ij'}) \le I_{\infty} G_{r_k}^{ij'}, \quad \forall \lambda = \{1,2,..., M\}, \forall r_k \in R$$

$$, \forall ij \in L - \{ij'\}, \forall ij' \in L \tag{5.51}$$

$$C_{r_k,ij,\lambda}^{ij'} \le I_{\infty} (1 - G_{r_k}^{ij'}), \quad \forall \lambda = \{1,2,..., M\}, \forall r_k \in R, \forall ij \in L - \{ij'\}, \forall ij' \in L \tag{5.52}$$

$$C_{r_k,ij.\lambda}^{ij'} \in Z^{+}, \quad \forall \lambda = \{1,2,..., M\}, \forall r_k \in R, \forall ij \in L - \{ij'\}, \forall ij' \in L \tag{5.53}$$

$$G_{r_k}^{ij'} \in \{0,1\}, \qquad \forall r_k \in R, \forall ij' \in L \tag{5.54}$$

$$\sum_{e \in E_{sd}^{ij'}} \sum_{\lambda=1}^{M} u_{r_k,e,\lambda}^{sd,ij'} = t_{r_k} \times xf_{r_k,ij'}^{sd}, \quad \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.55}$$

$$f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e,\lambda}^{sd,ij'} \mu_{ij,e}^{sd,ij'} - \sum_{r_k \in R} C_{r_k,ij,\lambda}^{ij'} \ge 0,$$

$$\forall \lambda = \{1,2,..., M\}, \forall ij \in L - \{ij'\}, \forall ij' \in L \tag{5.56}$$

$$u_{r_k,e,\lambda}^{sd,ij'} \in Z^{+}, \quad \forall \lambda = \{1,2,..., M\}, \quad \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.57}$$

$$f_{ij} \in Z^{+}, \qquad \forall ij \in L. \tag{5.58}$$

- **LT wavelength allocation case**

$$\min: \sum_{ij \in L} f_{ij} \,, \tag{5.59}$$

subject to the constraints (2.2)- (2.5), (2.17),(2.18), (2.20) and:

$$\sum_{sd}\sum_{p\in P_{sd}}\sum_{\lambda=1}^{M} a_{r_k,p,\lambda}^{sd}\delta_{ij',p}^{sd} \le I_\infty \times G_{r_k}^{ij'}, \quad \forall r_k \in R, \forall ij' \in L \tag{5.60}$$

$$\sum_{ij\in A_k} xf_{r_k,ij'}^{ij} = (|N_k|-1)\times G_{r_k}^{ij'}, \qquad \forall ij' \in L, \forall r_k \in R \tag{5.61}$$

$$\sum_{ij\in \vartheta(S)} xf_{r_k,ij'}^{ij} \ge G_{r_k}^{ij'}, \qquad \forall S \subset N_k, S \ne \phi, N \;, \forall ij' \in L \;, \forall r_k \in R \tag{5.62}$$

$$\sum_{j:ij\in A_k} xf_{r_k,ij'}^{ij} \le \Delta \times G_{r_k}^{ij'}, \qquad \forall i \in N_k, \forall ij' \in L, \forall r_k \in R \tag{5.63}$$

$$xf_{r_k,ij'}^{ij} \in \{0,1\}, \qquad \forall ij \in A_k, \forall ij' \in L, \forall r_k \in R \tag{5.64}$$

$$(\sum_{sd}\sum_{p\in P_{sd}} a_{r_k,p,\lambda}^{sd}\delta_{ij,p}^{sd} - C_{r_k,ij,\lambda}^{ij'}) \le I_\infty G_{r_k}^{ij'}, \quad \forall \lambda = \{1,2,...,M\}, \forall r_k \in R$$

$$, \forall ij \in L - \{ij'\}, \forall ij' \in L \tag{5.65}$$

$$C_{r_k,ij,\lambda}^{ij'} \le I_\infty (1 - G_{r_k}^{ij'}), \quad \forall \lambda = \{1,2,...,M\}, \forall r_k \in R, \forall ij \in L - \{ij'\}, \forall ij' \in L \tag{5.66}$$

$$C_{r_k,ij.\lambda}^{ij'} \in Z^+, \quad \forall \lambda = \{1,2,...,M\}, \forall r_k \in R, \forall ij \in L - \{ij'\}, \forall ij' \in L \tag{5.67}$$

$$G_{r_k}^{ij'} \in \{0,1\}, \qquad \forall r_k \in R, \forall ij' \in L \tag{5.68}$$

$$\sum_{e\in E_{sd}^{ij'}}\sum_{\lambda=1}^{M} u_{r_k,e,\lambda}^{sd,ij'} = t_{r_k} \times xf_{r_k,ij'}^{sd}, \quad \forall sd \in A_k, \forall r_k \in R \;\forall ij' \in L \tag{5.69}$$

$$f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E_{sd}^{ij'}} u_{r_k,e,\lambda}^{sd,ij'}\mu_{ij,e}^{sd,ij'} - \sum_{r_k\in R} C_{r_k,ij,\lambda}^{ij'} \ge 0,$$

$$\forall \lambda = \{1,2,...,M\}, \forall ij \in L - \{ij'\}, \forall ij' \in L \tag{5.70}$$

$$u_{r_k,e,\lambda}^{sd,ij'} \in Z^+, \quad \forall \lambda = \{1,2,...,M\}, \quad \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.71}$$

$$\sum_{\lambda=1}^{M} W_{r_k,\lambda} = t_{r_k}, \qquad \forall r_k \in R \tag{5.72}$$

$$u_{r_k,e,\lambda}^{sd,ij'} \le I_\infty \times W_{r_k,\lambda}, \forall \lambda = \{1,2,...,M\}, \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.73}$$

$$W_{r_k,\lambda} \in Z^+, \qquad \forall \lambda = \{1,2,...,M\}, \forall r_k \in R \tag{5.74}$$

$$f_{ij} \in Z^+, \qquad \forall ij \in L. \tag{5.75}$$

5.3.3 OB Protection Formulations

In the OB protection, the backup optical branches are utilized for restoration. Hence, based on the restoration mechanism, ILP programs of the OB protection can be formulated as follows.

- **VLT wavelength allocation case**

$$\min : \sum_{ij \in L} (f_{ij} + s_{ij}) , \tag{5.76}$$

subject to the constraints (2.2)- (2.5), (2.7)-(2.9) and:

$$\sum_{p \in P_{sd}} a_{r_k,p}^{sd} \delta_{ij',p}^{sd} \leq I_{\infty} \times \Omega_{r_k}^{sd,ij'} , \quad \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.77}$$

$$\sum_{ab \in A_k} V_{r_k,ab}^{sd,ij'} - \sum_{bc \in A_k} V_{r_k,bc}^{sd,ij'} = \begin{cases} \Omega_{r_k}^{sd,ij'} , s = b \\ -\Omega_{r_k}^{sd,ij'} , d = b \\ 0, \quad b \in N_k - \{s,d\} \end{cases}$$

$$\forall b \in N_k , \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.78}$$

$$V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} \leq 1 , \qquad \forall \{sd,ab\} \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.79}$$

$$V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} - x_{r_k}^{ab} \leq \begin{cases} y_{r_k,ab}^{sd,ij'} - \Omega_{r_k}^{sd,ij} , sd = ab \\ y_{r_k,ab}^{sd,ij'} , sd \neq ab \end{cases}$$

$$, \forall \{sd,ab\} \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.80}$$

$$(\sum_{p \in P_{sd}} a_{r_k,p}^{sd} \delta_{ij',p}^{sd} - \sum_{e \in E_{sd}^{ij'}} u_{r_k,e}^{ab,ij'}) \leq I_{\infty} (1 - y_{r_k,ab}^{sd,ij'}) , \quad \forall \{sd,ab\} \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.81}$$

$$\sum_{e \in E_{sd}^{ij'}} u_{r_k,e}^{ab,ij'} \leq I_{\infty} y_{r_k,ab}^{sd,ij'} , \quad \forall \{sd,ab\} \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.82}$$

$$\Omega_{r_k}^{sd,ij'} \in \{0,1\} \ \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.83}$$

$$y_{r_k,ab}^{sd,ij'} , V_{r_k,ab}^{sd,ij'} \in \{0,1\} , \quad \forall \{sd,ab\} \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.84}$$

$$M \times s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e}^{sd,ij'} \mu_{ij,e}^{sd,ij'} \geq 0 , \ \forall ij \in L - \{ij'\} , \forall ij' \in L \ \text{ for the SF+WF case} \tag{5.85}$$

$$M \times s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e}^{sd,ij'} \mu_{ij,e}^{sd,ij'} + (M \times f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p}^{sd} \delta_{ij,p}^{sd}) \geq 0 ,$$

$$\forall ij \in L - \{ij'\} , \forall ij' \in L \quad \text{for the SW+WW case} \tag{5.86}$$

$$M \times s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e}^{sd,ij'} \mu_{ij,e}^{sd,ij'} + (M \times f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p}^{sd} \delta_{ij,p}^{sd}) +$$

$$\sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p}^{sd} \delta_{ij',p}^{sd} \delta_{ij,p}^{sd} \geq 0 , \ \forall ij \in L - \{ij'\} , \forall ij' \in L \quad \text{for the SW+WW+SR case} \tag{5.87}$$

$$u_{r_k,e}^{sd,ij'} \in Z^{+} , \qquad \forall e \in E_{sd}^{ij'} , \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.88}$$

$$f_{ij}, s_{ij} \in Z^{+}, \qquad \forall ij \in L. \tag{5.89}$$

In the OB formulation, the objective function (5.76) is the minimization of the number of working and spare fibers required by a designed network. Given the multicast demands, constraints (2.2)-(2.5) and (2.7)-(2.9) determine optimal light-tree structures and their routing used in the normal network condition. In order to know which optical branches of light-tree r_k are affected by failed link $ij^{'}$, Boolean variables $\Omega_{r_k}^{sd,ij^{'}}$ as in constraints (5.83) are introduced and also employed in constraints (5.77). For constraints (5.77), $\Omega_{r_k}^{sd,ij^{'}}$ will be one if optical branch *sd* of light-tree r_k are disturbed by failed link $ij^{'}$; otherwise, it will be zero. In the next step, if $\Omega_{r_k}^{sd,ij^{'}}$=1, we have to find backup optical branches to restore disturbed optical branch *sd* of light-tree r_k. To achieve this, the logical graph $G_k = (N_k, A_k)$ of multicast r_k as defined in chapter 2 is utilized together with new Boolean variables, $V_{r_k,ab}^{sd,ij'}$. Let $V_{r_k,ab}^{sd,ij'}$ denote a possible backup optical branch *ab* when working optical branch *sd* of multicast r_k is affected by failed link $ij^{'}$. The possible backup optical branch *ab* is here defined as an logical link in set A_k of graph $G_k = (N_k, A_k)$. With Boolean variables $V_{r_k,ab}^{sd,ij'}$ and $\Omega_{r_k}^{sd,ij^{'}}$, constraint sets (5.78) and (5.79) express the flow conservation constraints for finding the optimal backup optical branches to replace interrupted optical branch *sd* of light-tree r_k.

In constraints (5.78), and (5.79), it is possible that more than one backup optical branch, $V_{r_k,ab}^{sd,ij'}$ are equal to one and all are selected as the results of these constraints. Thus, constraints (5.80) are derived to select which backup optical branches of constraints (5.78), and (5.79) we can use to restore interrupted optical branch *sd* of light-tree r_k. As we can see, Boolean variables $y_{r_k,ab}^{sd,ij'}$ are formulated as the results of constraints (5.80). By using constraints (5.80), if they provides $y_{r_k,ab}^{sd,ij'}$=1, it means that the corresponding backup optical branch, $V_{r_k,ab}^{sd,ij'}$ is finally selected for restoration. Otherwise, if $y_{r_k,ab}^{sd,ij'}$=0, it implies that the network does not use the corresponding backup optical branch, $V_{r_k,ab}^{sd,ij'}$ for protecting light-tree r_k. In constraints (5.80), if $V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} = 1$, there will exist three possible cases.

– $V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} = 1$, $x_{r_k}^{ab}$=0, and $sd \neq ab$: under this case, $y_{r_k,ab}^{ab,ij'}$=1 and the network use backup branch *ab*, which is not identical to interrupted branch *sd*, to restore light-tree r_k.

– $V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} = 1$, $x_{r_k}^{ab}$=1, and $sd = ab$: under this case, $y_{r_k,ab}^{ab,ij'}$=1 and for restoration, the network selects backup branch *ab* coinciding with interrupted branch *sd* for restoration. Consequently, the network only reroutes working physical paths of interrupted branch *sd* to new physical paths to avoid failed link ij'. Note that such new restoration physical paths have their source and destination as same as those working physical paths.

– $V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} = 1$, $x_{r_k}^{ab}$=1, and $sd \neq ab$: under this case, $y_{r_k,ab}^{ab,ij'}$=0. This arises from the fact that it is trivial to use the backup branch *ab* to restore disturbed branch *sd* because we can employ the working optical branch *ab*, $x_{r_k}^{ab}$=1, to be a part of restoration.

Now, let us explain constraints (5.81) and (5.82). They indicate that if $y_{r_k,ab}^{sd,ij'}$=1, the number of restoration routes of backup optical branch *ab* suffices to restore affected working routes of optical branch *sd*. Hence constraints (5.81) and (5.82) guarantee 100% survivability against any single link failure.

For the last portion of the formulation, constraints (5.85) mean that in the SF+WF spare capacity placement, the number of spare fibers of link *ij* is high enough to serve all backup optical branches routed on it. Similar to constraints (5.85), constraints (5.86) are formulated for the SW+WW technique so as to compute the spare fiber requirement. Note that the third term of constraints (5.86) expresses the remainder wavelength capacity of working fibers, which in SW+WW the network can use this capacity for serving backup optical branches. For the SW+WW+SR technique, constraints (5.86) of SW+WW are also applicable to determine the spare fiber requirement as represented in constraints (5.87). However, due to the stub release in SW+WW+SR, the fourth term of constraints (5.87) are additionally introduced and signifies that the working wavelength capacity of interrupted light-trees can be available for backup optical branches. Finally, to complete the OB formulation, the last constraints (5.88) and (5.89) ensure that the variables of restoration routes and the number of fibers are nonnegative integers.

- **PVLT wavelength allocation case**

$$\min : \sum_{ij \in L} (f_{ij} + s_{ij}) , \tag{5.90}$$

subject to the constraints (2.2)- (2.5), (2.12)-(2.14) and:

$$\sum_{p \in P_{sd}} \sum_{\lambda=1}^{M} a_{r_k,p,\lambda}^{sd} \delta_{ij',p}^{sd} \le I_\infty \times \Omega_{r_k}^{sd,ij'} , \quad \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.91}$$

$$\sum_{ab \in A_k} V_{r_k,ab}^{sd,ij'} - \sum_{bc \in A_k} V_{r_k,bc}^{sd,ij'} = \begin{cases} \Omega_{r_k}^{sd,ij'} , s = b \\ -\Omega_{r_k}^{sd,ij'} , d = b \\ 0, \quad b \in N_k - \{s,d\} \end{cases}$$

$$\forall b \in N_k , \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.92}$$

$$V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} \le 1 , \quad \forall \{sd,ab\} \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.93}$$

$$V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} - x_{r_k}^{ab} \le \begin{cases} y_{r_k,ab}^{sd,ij'} - \Omega_{r_k}^{sd,ij} , sd = ab \\ y_{r_k,ab}^{sd,ij'} , sd \ne ab \end{cases}$$

$$, \forall \{sd,ab\} \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.94}$$

$$\left(\sum_{p \in P_{sd}} \sum_{\lambda=1}^{M} a_{r_k,p,\lambda}^{sd} \delta_{ij',p}^{sd} - \sum_{e \in E_{sd}^{ij'}} \sum_{\lambda=1}^{M} u_{r_k,e,\lambda}^{ab,ij'} \right) \le I_\infty (1 - y_{r_k,ab}^{sd,ij'}) ,$$

$$\forall \{sd,ab\} \in A_k , \forall r_k \in R \ \forall ij' \in L \tag{5.95}$$

$$\sum_{e \in E_{sd}^{ij'}} \sum_{\lambda=1}^{M} u_{r_k,e,\lambda}^{ab,ij'} \le I_\infty y_{r_k,ab}^{sd,ij'} , \quad \forall \{sd,ab\} \in A_k , \forall r_k \in R \ \forall ij' \in L \tag{5.96}$$

$$\Omega_{r_k}^{sd,ij'} \in \{0,1\} \ \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.97}$$

$$y_{r_k,ab}^{sd,ij'} , V_{r_k,ab}^{sd,ij'} \in \{0,1\} , \quad \forall \{sd,ab\} \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.98}$$

$$s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e,\lambda}^{sd,ij'} \mu_{ij,e}^{sd,ij'} \ge 0 , \ \forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\}$$

$$, \forall ij' \in L \text{ for the SF+WF case} \tag{5.99}$$

$$s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e,\lambda}^{sd,ij'} \mu_{ij,e}^{sd,ij'} + \left(f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij,p}^{sd} \right) \ge 0$$

$$, \forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\} , \forall ij' \in L \quad \text{for the SW+WW case} \tag{5.100}$$

$$s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e,\lambda}^{sd,ij'} \mu_{ij,e}^{sd,ij'} + (f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij,p}^{sd}) + \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij',p}^{sd} \delta_{ij,p}^{sd} \geq 0,$$

$$\forall \lambda = \{1,2,...,M\},\ \forall ij \in L - \{ij'\}, \forall ij' \in L \quad \text{for the SW+WW+SR case} \quad (5.101)$$

$$u_{r_k,e,\lambda}^{sd,ij'} \in Z^+, \quad \forall \lambda = \{1,2,...,M\}, \quad \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R\ \forall ij' \in L \quad (5.102)$$

$$f_{ij}, s_{ij} \in Z^+, \qquad \forall ij \in L. \quad (5.103)$$

- **LT wavelength allocation case**

$$\min: \sum_{ij \in L} (f_{ij} + s_{ij}), \quad (5.104)$$

subject to the constraints (2.2)- (2.5), (2.17),(2.18),(2.20) and:

$$\sum_{p \in P_{sd}} \sum_{\lambda=1}^{M} a_{r_k,p,\lambda}^{sd} \delta_{ij',p}^{sd} \leq I_\infty \times \Omega_{r_k}^{sd,ij'}, \quad \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.105)$$

$$\sum_{ab \in A_k} V_{r_k,ab}^{sd,ij'} - \sum_{bc \in A_k} V_{r_k,bc}^{sd,ij'} = \begin{cases} \Omega_{r_k}^{sd,ij'}, s = b \\ -\Omega_{r_k}^{sd,ij'}, d = b \\ 0, \quad b \in N_k - \{s,d\} \end{cases}$$

$$\forall b \in N_k, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.106)$$

$$V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} \leq 1, \quad \forall \{sd,ab\} \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.107)$$

$$V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} - x_{r_k}^{ab} \leq \begin{cases} y_{r_k,ab}^{sd,ij'} - \Omega_{r_k}^{sd,ij}, sd = ab \\ y_{r_k,ab}^{sd,ij'}, sd \neq ab \end{cases}$$

$$, \forall \{sd,ab\} \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.108)$$

$$(\sum_{p \in P_{sd}} \sum_{\lambda=1}^{M} a_{r_k,p,\lambda}^{sd} \delta_{ij',p}^{sd} - \sum_{e \in E_{sd}^{ij'}} \sum_{\lambda=1}^{M} u_{r_k,e,\lambda}^{ab,ij'}) \leq I_\infty (1 - y_{r_k,ab}^{sd,ij'}),$$

$$\forall \{sd,ab\} \in A_k, \forall r_k \in R\ \forall ij' \in L \quad (5.109)$$

$$\sum_{e \in E_{sd}^{ij'}} \sum_{\lambda=1}^{M} u_{r_k,e,\lambda}^{ab,ij'} \leq I_\infty y_{r_k,ab}^{sd,ij'}, \quad \forall \{sd,ab\} \in A_k, \forall r_k \in R\ \forall ij' \in L \quad (5.110)$$

$$\Omega_{r_k}^{sd,ij'} \in \{0,1\}\ \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.111)$$

$$y_{r_k,ab}^{sd,ij'}, V_{r_k,ab}^{sd,ij'} \in \{0,1\}, \quad \forall \{sd,ab\} \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.112)$$

$$s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e,\lambda}^{sd,ij'} \mu_{ij,e}^{sd,ij'} \geq 0, \ \forall \lambda = \{1,2,...,M\},\ \forall ij \in L - \{ij'\}$$

$$, \forall ij^{'} \in L \text{ for the SF+WF case} \quad (5.113)$$

$$s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij^{'}}} u_{r_k,e,\lambda}^{sd,ij^{'}} \mu_{ij,e}^{sd,ij^{'}} + (f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij,p}^{sd}) \geq 0 ,$$

$$\forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij^{'}\} , \forall ij^{'} \in L \quad \text{for the SW+WW case} \quad (5.114)$$

$$s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij^{'}}} u_{r_k,e,\lambda}^{sd,ij^{'}} \mu_{ij,e,\lambda}^{sd,ij^{'}} + (f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij,p}^{sd}) + \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij^{'},p}^{sd} \delta_{ij,p}^{sd} \geq 0 ,$$

$$\forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij^{'}\} , \forall ij^{'} \in L \quad \text{for the SW+WW+SR case} \quad (5.115)$$

$$u_{r_k,e,\lambda}^{sd,ij^{'}} \in Z^{+}, \ \forall \lambda = \{1,2,..., M\}, \quad \forall e \in E_{sd}^{ij^{'}} , \forall sd \in A_k , \forall r_k \in R , \forall ij^{'} \in L \quad (5.116)$$

$$\sum_{\lambda=1}^{M} W_{r_k,\lambda} = t_{r_k} , \qquad \forall r_k \in R \quad (5.117)$$

$$u_{r_k,e,\lambda}^{sd,ij^{'}} \leq I_{\infty} \times W_{r_k,\lambda} , \quad \forall \lambda = \{1,2,..., M\}, \ \forall e \in E_{sd}^{ij^{'}} , \forall sd \in A_k , \forall r_k \in R , \forall ij^{'} \in L \quad (5.118)$$

$$W_{r_k,\lambda} \in Z^{+} , \qquad \forall \lambda = \{1,2,..., M\}, \forall r_k \in R \quad (5.119)$$

$$f_{ij} , s_{ij} \in Z^{+} , \qquad \forall ij \in L . \quad (5.120)$$

5.3.4 OBF Protection Formulations

As described in chapter 4, the OBF protection is a limited version of the OB protection. Thus, the basic idea to develop the OB formulation can be also adopted to develop the OBF formulation. The OBF formulation can be formulated as below.

- **VLT wavelength allocation case**

$$\min : \sum_{ij \in L} (f_{ij} + s_{ij}) , \quad (5.121)$$

subject to the constraints (2.2)- (2.5), (2.7)-(2.9) and:

$$\sum_{p \in P_{sd}} a_{r_k,p}^{sd} \delta_{ij^{'},p}^{sd} \leq I_{\infty} \times \Omega_{r_k}^{sd,ij^{'}} , \quad \forall sd \in A_k , \forall r_k \in R , \forall ij^{'} \in L \quad (5.122)$$

$$\sum_{ij \in A_k} \Theta_{r_k}^{ij} \leq Br , \qquad \forall r_k \in R \quad (5.123)$$

$$\Theta_{r_k}^{ij} \in \{0,1\} , \qquad \forall ij \in A_k , \forall r_k \in R , \forall ij^{'} \in L \quad (5.124)$$

$$\sum_{ab\in A_k} V_{r_k,ab}^{sd,ij'} - \sum_{bc\in A_k} V_{r_k,bc}^{sd,ij'} = \begin{cases} \Omega_{r_k}^{sd,ij'}, s=b \\ -\Omega_{r_k}^{sd,ij'}, d=b \\ 0, \quad b\in N_k - \{s,d\} \end{cases}$$

$$\forall b \in N_k, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.125)$$

$$V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} \le 1, \qquad \forall\{sd,ab\} \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.126)$$

$$V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} - x_{r_k}^{ab} \le \begin{cases} y_{r_k,ab}^{sd,ij'} - \Omega_{r_k}^{sd,ij}, sd=ab \\ y_{r_k,ab}^{sd,ij'}, sd \ne ab \end{cases}$$

$$, \forall\{sd,ab\} \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.127)$$

$$\left(\sum_{p\in P_{sd}} a_{r_k,p}^{sd}\delta_{ij',p}^{sd} - \sum_{e\in E_{sd}^{ij'}} u_{r_k,e}^{ab,ij'}\right) \le I_\infty(1-y_{r_k,ab}^{sd,ij'}), \quad \forall\{sd,ab\} \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.128)$$

$$\sum_{e\in E_{sd}^{ij'}} u_{r_k,e}^{ab,ij'} \le I_\infty y_{r_k,ab}^{sd,ij'}, \quad \forall\{sd,ab\} \in A_k, \forall r_k \in R \ \forall ij' \in L \quad (5.129)$$

$$\Theta_{r_k}^{ab} \ge y_{r_k,ab}^{sd,ij'}, \quad \forall\{sd,ab\} \in A_k, \forall r_k \in R \ \forall ij' \in L \quad (5.130)$$

$$\Omega_{r_k}^{sd,ij'} \in \{0,1\} \ \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.131)$$

$$y_{r_k,ab}^{sd,ij'}, V_{r_k,ab}^{sd,ij'} \in \{0,1\}, \quad \forall\{sd,ab\} \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.132)$$

$$M \times s_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E_{sd}^{ij'}} u_{r_k,e}^{sd,ij'}\mu_{ij,e}^{sd,ij'} \ge 0, \forall ij \in L - \{ij'\} \ \forall ij' \in L \ \text{ for the SF+WF case} \quad (5.133)$$

$$M \times s_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E_{sd}^{ij'}} u_{r_k,e}^{sd,ij'}\mu_{ij,e}^{sd,ij'} + (M \times f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a_{r_k,p}^{sd}\delta_{ij,p}^{sd}) \ge 0,$$

$$\forall ij \in L - \{ij'\} \ \forall ij' \in L \quad \text{for the SW+WW case} \quad (5.134)$$

$$M \times s_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E_{sd}^{ij'}} u_{r_k,e}^{sd,ij'}\mu_{ij,e}^{sd,ij'} + (M \times f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a_{r_k,p}^{sd}\delta_{ij,p}^{sd}) +$$

$$\sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a_{r_k,p}^{sd}\delta_{ij',p}^{sd}\delta_{ij,p}^{sd} \ge 0, \ \forall ij \in L - \{ij'\} \ \forall ij' \in L \ \text{ for the SW+WW+SR case} \quad (5.135)$$

$$u_{r_k,e}^{sd,ij'} \in Z^+, \quad \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R \ \forall ij' \in L \quad (5.136)$$

$$f_{ij}, s_{ij} \in Z^+, \qquad \forall ij \in L. \quad (5.137)$$

Comparing with the OB formulation, most of OBF constraints are identical to the OB constraints, except constraints (5.123), (5.124), and (5.130) that are exclusive for the OBF formulation. With this comparison, in the following, we hence explain only the meanings of constraints (5.123), (5.124), and (5.130), while for other constraints, the previous explanation of the OB formulation can be applied directly.

Since in the OBF protection, each light-tree of multicast session will only have a limited number of backup optical branches to restore a multicast session from all possible failures. To put this restoration mechanism to the ILP model, constraints (5.123) should be included in the model. As we can see constraints (5.123), we define a parameter, Br as the number of backup optical branches given for multicast demand r_k of a considered network. With the parameter, Br, constraints (5.123) state that a set of backup optical branches ($\Theta_{r_k}^{ij}$) will be selected for protecting multicast demand r_k and this selected set is also utilized for all cases of single link failure. Moreover, constraints (5.123) state that the total number of backup optical branches in the selected set must be not more than a given value of Br. For constraints (5.124), they are employed to limit the variables of the backup branch $\Theta_{r_k}^{ij}$ to be Boolean. Finally, constraints (5.130) express that in the situation in which working optical branch *sd* of multicast demand r_k is interrupted by failed link ij', the backup branch *ab* of $y_{r_k,ab}^{sd,ij'}$ can be chosen to restore against failed link ij' only if backup branch *ab*, $\Theta_{r_k}^{ab}$ was already chosen by constraints (5.123), *i.e.*, $\Theta_{r_k}^{ab}$ =1.

- **PVLT wavelength allocation case**

$$\min: \sum_{ij \in L} (f_{ij} + s_{ij}), \qquad (5.138)$$

subject to the constraints (2.2)- (2.5), (2.12)-(2.14) and:

$$\sum_{p \in P_{sd}} \sum_{\lambda=1}^{M} a_{r_k,p,\lambda}^{sd} \delta_{ij',p}^{sd} \le I_\infty \times \Omega_{r_k}^{sd,ij'}, \quad \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \qquad (5.139)$$

$$\sum_{ij \in A_k} \Theta_{r_k}^{ij} \le Br, \qquad \forall r_k \in R \qquad (5.140)$$

$$\Theta_{r_k}^{ij} \in \{0,1\}, \qquad \forall ij \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.141)$$

$$\sum_{ab \in A_k} V_{r_k,ab}^{sd,ij'} - \sum_{bc \in A_k} V_{r_k,bc}^{sd,ij'} = \begin{cases} \Omega_{r_k}^{sd,ij'}, s = b \\ -\Omega_{r_k}^{sd,ij'}, d = b \\ 0, \quad b \in N_k - \{s,d\} \end{cases}$$

$$\forall b \in N_k, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.142)$$

$$V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} \le 1, \quad \forall \{sd,ab\} \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.143)$$

$$V_{r_k,ab}^{sd,ij'} + V_{r_k,ba}^{sd,ij'} - x_{r_k}^{ab} \le \begin{cases} y_{r_k,ab}^{sd,ij'} - \Omega_{r_k}^{sd,ij}, sd = ab \\ y_{r_k,ab}^{sd,ij'}, sd \ne ab \end{cases}$$

$$, \forall \{sd,ab\} \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.144)$$

$$\left(\sum_{p \in P_{sd}} \sum_{\lambda=1}^{M} a_{r_k,p,\lambda}^{sd} \delta_{ij',p}^{sd} - \sum_{e \in E_{sd}^{ij'}} \sum_{\lambda=1}^{M} u_{r_k,e}^{ab,ij'}\right) \le I_\infty (1 - y_{r_k,ab}^{sd,ij'})$$

$$, \forall \{sd,ab\} \in A_k, \forall r_k \in R \ \forall ij' \in L \quad (5.145)$$

$$\sum_{e \in E_{sd}^{ij'}} \sum_{\lambda=1}^{M} u_{r_k,e,\lambda}^{ab,ij'} \le I_\infty y_{r_k,ab}^{sd,ij'}, \quad \forall \{sd,ab\} \in A_k, \forall r_k \in R \ \forall ij' \in L \quad (5.146)$$

$$\Theta_{r_k}^{ab} \ge y_{r_k,ab}^{sd,ij'}, \quad \forall \{sd,ab\} \in A_k, \forall r_k \in R \ \forall ij' \in L \quad (5.147)$$

$$\Omega_{r_k}^{sd,ij'} \in \{0,1\} \ \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.148)$$

$$y_{r_k,ab}^{sd,ij'}, V_{r_k,ab}^{sd,ij'} \in \{0,1\}, \quad \forall \{sd,ab\} \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.149)$$

$$s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e,\lambda}^{sd,ij'} \mu_{ij,e}^{sd,ij'} \ge 0, \ \forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\}$$

$$, \forall ij' \in L \ \text{ for the SF+WF case} \quad (5.150)$$

$$s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e,\lambda}^{sd,ij'} \mu_{ij,e}^{sd,ij'} + \left(f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij,p}^{sd}\right) \ge 0,$$

$$\forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\}, \forall ij' \in L \quad \text{for the SW+WW case} \quad (5.151)$$

$$s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e,\lambda}^{sd,ij'} \mu_{ij,e}^{sd,ij'} + \left(f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij,p}^{sd}\right) + \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij',p}^{sd} \delta_{ij,p}^{sd} \ge 0,$$

$$\forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\}, \forall ij' \in L \quad \text{for the SW+WW+SR case} \quad (5.152)$$

$$u_{r_k,e,\lambda}^{sd,ij'} \in Z^+, \quad \forall \lambda = \{1,2,..., M\}, \quad \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R \ \forall ij' \in L \quad (5.153)$$

$$f_{ij}, s_{ij} \in Z^+, \qquad \forall ij \in L. \quad (5.154)$$

- **LT wavelength allocation case**

$$\min: \sum_{ij \in L} (f_{ij} + s_{ij}), \quad (5.155)$$

subject to the constraints (2.2)- (2.5), (2.17), (2.18), (2.20) and:

$$\sum_{p\in P_{sd}} \sum_{\lambda=1}^{M} a^{sd}_{r_k,p,\lambda}\delta^{sd}_{ij',p} \le I_\infty \times \Omega^{sd,ij'}_{r_k}, \quad \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.156}$$

$$\sum_{ij\in A_k}\Theta^{ij}_{r_k} \le Br, \qquad \forall r_k \in R \tag{5.157}$$

$$\Theta^{ij}_{r_k} \in \{0,1\}, \qquad \forall ij \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.158}$$

$$\sum_{ab\in A_k} V^{sd,ij'}_{r_k,ab} - \sum_{bc\in A_k} V^{sd,ij'}_{r_k,bc} = \begin{cases} \Omega^{sd,ij'}_{r_k}, s=b \\ -\Omega^{sd,ij'}_{r_k}, d=b \\ 0, \quad b\in N_k-\{s,d\} \end{cases}$$

$$\forall b \in N_k, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.159}$$

$$V^{sd,ij'}_{r_k,ab} + V^{sd,ij'}_{r_k,ba} \le 1, \qquad \forall \{sd,ab\} \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.160}$$

$$V^{sd,ij'}_{r_k,ab} + V^{sd,ij'}_{r_k,ba} - x^{ab}_{r_k} \le \begin{cases} y^{sd,ij'}_{r_k,ab} - \Omega^{sd,ij}_{r_k}, sd=ab \\ y^{sd,ij'}_{r_k,ab}, sd\neq ab \end{cases}$$

$$, \forall \{sd,ab\} \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.161}$$

$$\left(\sum_{p\in P_{sd}} \sum_{\lambda=1}^{M} a^{sd}_{r_k,p,\lambda}\delta^{sd}_{ij',p} - \sum_{e\in E^{ij'}_{sd}} \sum_{\lambda=1}^{M} u^{ab,ij'}_{r_k,e}\right) \le I_\infty (1 - y^{sd,ij'}_{r_k,ab})$$

$$, \forall \{sd,ab\} \in A_k, \forall r_k \in R \ \forall ij' \in L \tag{5.162}$$

$$\sum_{e\in E^{ij'}_{sd}} \sum_{\lambda=1}^{M} u^{ab,ij'}_{r_k,e,\lambda} \le I_\infty y^{sd,ij'}_{r_k,ab}, \quad \forall \{sd,ab\} \in A_k, \forall r_k \in R \ \forall ij' \in L \tag{5.163}$$

$$\Theta^{ab}_{r_k,ij'} \ge y^{sd,ij'}_{r_k,ab}, \quad \forall \{sd,ab\} \in A_k, \forall r_k \in R \ \forall ij' \in L \tag{5.164}$$

$$\Omega^{sd,ij'}_{r_k} \in \{0,1\} \ \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.165}$$

$$y^{sd,ij'}_{r_k,ab}, V^{sd,ij'}_{r_k,ab} \in \{0,1\}, \quad \forall \{sd,ab\} \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.166}$$

$$s_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda}\mu^{sd,ij'}_{ij,e} \ge 0, \ \forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\}$$

$$, \forall ij' \in L \text{ for the SF+WF case} \tag{5.167}$$

$$s_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda}\mu^{sd,ij'}_{ij,e} + \left(f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda}\delta^{sd}_{ij,p}\right) \ge 0$$

$$, \forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\}, \forall ij' \in L \quad \text{for the SW+WW case} \tag{5.168}$$

$$s_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda}\mu^{sd,ij'}_{ij,e} + \left(f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda}\delta^{sd}_{ij,p}\right) + \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda}\delta^{sd}_{ij',p}\delta^{sd}_{ij,p} \ge 0,$$

$$\forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\}, \forall ij' \in L \quad \text{for the SW+WW+SR case} \tag{5.169}$$

$$u_{r_k,e,\lambda}^{sd,ij'} \in Z^+, \quad \forall \lambda = \{1,2,...,M\}, \quad \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.170}$$

$$\sum_{\lambda=1}^{M} W_{r_k,\lambda} = t_{r_k}, \qquad \forall r_k \in R \tag{5.171}$$

$$u_{r_k,e,\lambda}^{sd,ij'} \leq I_\infty \times W_{r_k,\lambda}, \quad \forall \lambda = \{1,2,...,M\}, \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.172}$$

$$W_{r_k,\lambda} \in Z^+, \qquad \forall \lambda = \{1,2,...,M\}, \forall r_k \in R \tag{5.173}$$

$$f_{ij}, s_{ij} \in Z^+, \qquad \forall ij \in L. \tag{5.174}$$

5.3.5 PBF Protection Formulations

Although the PBF protection is developed from the OBF protection, the basic idea to formulate the PBF mathematical models is quite different from that of the OBF models. Before presenting the PBF models, we shall describe the basic idea to formulate the PBF models.

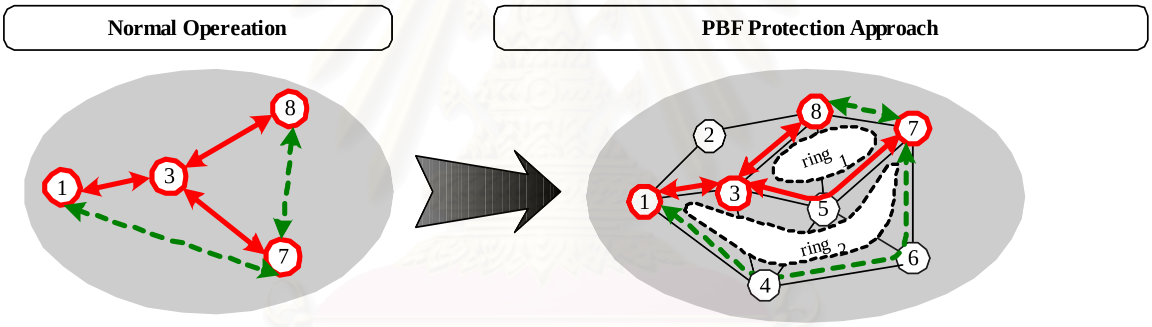


Figure 5.1: Multi-ring concept to derive PBF mathematical formulations.

Observing a light-tree structure together with physical restoration routes that the PBF protection assigns to the light-tree, it can be seen as a view composed of a set of rings. Rings in the set cover all nodes of the light-tree and also cover all physical links of restoration routes. To clearly understand, an illustrative example is given in Figure 5.1. As shown, the light-tree and its restoration routes based on the PBF protection are constructed from two rings, *i.e.*, ring 1 and 2.

Therefore, under this scenario, we can formulate the PBF mathematical models by using the above concept. Note that this concept is usually applied to design multi-ring networks [27, 36]. To derive the PBF formulations, let us define some new parameters and variables.

Network parameters:

Q a set of possible rings to form the network;

n_q total number of physical links of ring $q \in Q$;

π_q^{ij} takes the value of one if ring q passes through link ij and zero, otherwise;

Network variables:

$b_{r_k,q}^{ij}$ number of working wavelength channels occupied by ring q on physical link ij for multicast demand r_k;

$Sw_{r_k,ij}^{q}$ number of spare wavelength channels occupied by ring q on physical link ij for multicast demand r_k upon any single link failure.

From the new parameters and variables, the PBF formulation can be developed as follows.

- **VLT wavelength allocation case**

$$\min : \sum_{ij \in L} (f_{ij} + s_{ij}) , \tag{5.175}$$

subject to the constraints (2.2)-(2.5), (2.7)-(2.9) and:

$$\sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p}^{sd} \delta_{ij,p}^{sd} = \sum_{q \in Q} b_{r_k,q}^{ij} \pi_q^{ij} , \quad \forall r_k \in R , \forall ij \in L \tag{5.176}$$

$$(Sw_{r_k,ij}^{q} + b_{r_k,q}^{ij}) \pi_q^{ij} \geq b_{r_k,q}^{ij'} \pi_q^{ij'} , \quad \forall r_k \in R , \forall q \in Q , \forall ij \in L - \{ij'\} , \forall ij' \in L \tag{5.177}$$

$$M \times s_{ij} - \sum_{r_k \in R} \sum_{q \in Q} Sw_{r_k,ij}^{q} \pi_q^{ij} \geq 0$$

$$, \forall ij \in L - \{ij'\} , \forall ij' \in L \quad \text{for the SF+WF case} \tag{5.178}$$

$$M \times s_{ij} - \sum_{r_k \in R} \sum_{q \in Q} Sw_{r_k,ij}^{q} \pi_q^{ij} - (M \times f_{ij} - \sum_{r_k \in R} \sum_{q \in Q} b_{r_k,q}^{ij} \pi_q^{ij}) \geq 0 ,$$

$$\forall ij \in L - \{ij'\} , \forall ij' \in L \quad \text{for the SW+WW case} \tag{5.179}$$

$$b_{r_k,q}^{ij} \in Z^{+} , \qquad \forall r_k \in R , \forall q \in Q \ \forall ij \in L \tag{5.180}$$

$$Sw_{r_k,ij}^{q} \in Z^{+} , \qquad \forall r_k \in R , \forall q \in Q , \forall ij \in L - \{ij'\} , \forall ij' \in L \tag{5.181}$$

$$f_{ij}, s_{ij} \in Z^{+}, \qquad \forall ij \in L. \tag{5.182}$$

As formulated, the objective function (5.175) is to minimize the total number of working and spare fibers for a network with the PBF protection. As same as the previous formulations, constraints (2.2)-(2.5) and (2.7) compute the working routing pattern for each multicast demand of the network. For constraints (5.176), they express that active routes of light-tree r_k which pass through link ij are assigned to occupy the wavelength channels of ring q which also cover link ij. As considered, constraints (5.176) additionally imply the selection of rings to cover light-tree r_k. Upon any single link failure, constraints (5.177) are employed to determine the spare wavelength channels of each link of ring q. Note that in the determination, the number of spare wavelength channels must be high enough to restore all interrupted working routes of light-trees which is on ring q in any possible events of failure. For constraints (5.178) and (5.179), they calculate the spare fibers needed for restoration corresponding to the SF+WF and SW+WW spare capacity placement techniques, respectively. Finally, constraints (5.180)-(5.182) ensure that the network design solution is in the nonnegative integer set.

- **LT wavelength allocation case**

$$\min : \sum_{ij \in L} (f_{ij} + s_{ij}), \tag{5.183}$$

subject to the constraints (2.2)-(2.5), (2.17), (2.18), (2.20), and:

$$\sum_{sd} \sum_{p \in P_{sd}} a^{sd}_{r_k,p} \delta^{sd}_{ij,p} = \sum_{q \in Q} \sum_{\lambda=1}^{M} b^{ij}_{r_k,q,\lambda} \pi^{ij}_{q}, \quad \forall r_k \in R, \forall ij \in L \tag{5.184}$$

$$(Sw^{q,ij'}_{r_k,ij,\lambda} + b^{ij}_{r_k,q,\lambda}) \pi^{ij}_{q} \geq b^{ij'}_{r_k,q,\lambda} \pi^{ij'}_{q}, \quad \forall \lambda = \{1,2,..., M\}, \quad \forall r_k \in R, \forall q \in Q$$

$$, \forall ij \in L - \{ij'\}, \forall ij' \in L \tag{5.185}$$

$$Sw^{q,ij'}_{r_k,ij,\lambda} \in Z^{+}, \quad \forall \lambda = \{1,2,..., M\}, \forall r_k \in R, \forall q \in Q$$

$$, \forall ij \in L - \{ij'\}, \forall ij' \in L \tag{5.186}$$

$$s_{ij} - \sum_{r_k \in R} \sum_{q \in Q} Sw^{q,ij'}_{r_k,ij,\lambda} \pi^{ij}_{q} \geq 0, \ \forall \lambda = \{1,2,..., M\},$$

$$\forall ij \in L - \{ij'\}, \forall ij' \in L \quad \text{for the SF+WF case} \tag{5.187}$$

$$s_{ij} - \sum_{r_k \in R} \sum_{q \in Q} Sw^{q,ij'}_{r_k,ij,\lambda} \pi^{ij}_{q} - (f_{ij} - \sum_{r_k \in R} \sum_{q \in Q} b^{ij}_{r_k,q,\lambda} \pi^{ij}_{q}) \geq 0,$$

$$\forall \lambda = \{1,2,..., M\},\ \forall ij \in L - \{ij^{'}\},\ \forall ij^{'} \in L \quad \text{for the SW+WW case} \tag{5.188}$$

$$\sum_{\lambda=1}^{M} W_{r_k,\lambda} = t_{r_k}, \qquad \forall r_k \in R \tag{5.189}$$

$$b_{r_k,q,\lambda}^{ij} \le I_{\infty} \times W_{r_k,\lambda}, \quad \forall \lambda = \{1,2,..., M\}, \quad \forall q \in Q, \forall sd \in A_k, \forall r_k \in R \tag{5.190}$$

$$W_{r_k,\lambda} \in Z^{+}, \qquad \forall \lambda = \{1,2,..., M\}, \forall r_k \in R \tag{5.191}$$

$$b_{r_k,q,\lambda}^{ij} \in Z^{+}, \qquad \forall \lambda = \{1,2,..., M\},\ \forall r_k \in R, \forall q \in Q\ \forall ij \in L \tag{5.192}$$

$$f_{ij}, s_{ij} \in Z^{+}, \qquad \forall ij \in L. \tag{5.193}$$

5.3.6 OMP Protection Formulations

Similar to the PBF protection, the OMP formulations can be developed by using the multi-ring concept. The OMP formulation can be formulated as follows.

- **VLT wavelength allocation case**

$$\min : \sum_{ij \in L} f_{ij}, \tag{5.194}$$

subject to the constraints (2.2)-(2.5), (2.7) and:

$$\sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p}^{sd} \delta_{ij,p}^{sd} = \sum_{q \in Q} b_{r_k,q}^{ij} \pi_q^{ij}, \quad \forall r_k \in R, \forall ij \in L \tag{5.195}$$

$$Rw_q^{kl} \pi_q^{kl} \ge b_{r_k}^{ij} \pi_q^{ij}, \forall r_k \in R, \forall q \in Q, \forall ij \in L - \{kl\}, \forall kl \in L \tag{5.196}$$

$$H_{r_k}^{ij} - \sum_{q \in Q} Rw_q^{ij} \pi_q^{ij} \ge 0, \qquad \forall r_k \in R, \forall ij \in L \tag{5.197}$$

$$M \times f_{ij} - \sum_{r_k \in R} H_{r_k}^{ij} \ge 0, \qquad \forall ij \in L \tag{5.198}$$

$$b_{r_k,q}^{ij}, Rw_q^{ij} \in Z^{+}, \qquad \forall r_k \in R, \forall q \in Q\ \forall ij \in L \tag{5.199}$$

$$H_{r_k}^{ij} \in Z^{+}, \qquad \forall r_k \in R, \forall ij \in L \tag{5.200}$$

$$f_{ij} \in Z^{+}, \qquad \forall ij \in L. \tag{5.201}$$

Since in the OMP protection, the network reserves the wavelength channels dedicatedly for each multicast session in both cases of normal and failure events, the network with OMP protection thus has only working fibers on it. Therefore, the objective function (5.194) is to minimize the number of working fibers for the network with OMP protection. As derived, constraints (2.2)-(2.5) and (2.7) are again used to create light-trees. However, in OMP, optical meshes are deployed to serve multicast demands instead of light-trees. Therefore, to transform the structures of light-tree to optical mesh, the following constraints based on the multi-ring concept as employed in PBF are essential.

Like constraints (5.176) in the PBF formulation, constraints (5.195) state that the active routes of light-trees are assigned to reserve the wavelength channels of rings. To convert the light-tree to optical mesh for multicast demand r_k, the network with the OMP reserves the wavelength channels on all physical links of rings that are selected by light-tree r_k as formulated in constraints (5.195). For light-tree r_k, the number of wavelength channels of all physical links of ring q chosen by constraints (5.195) must be identical. Therefore, to compute the wavelength channels, Rw_q^{ij} needed on link ij of ring q, constraints (5.196) are employed. For constraints (5.197), they determine the wavelength channels, $H_{r_k}^{ij}$ required on link ij for the optical mesh of multicast session r_k. Constraints (5.198) compute the fiber requirement of link ij to serve all multicast sessions of the network. Finally, constraints (5.199)-(5.201) guarantee that the values of all network variables in the OMP formulation are nonnegative integers.

- **LT wavelength allocation case**

$$\min : \sum_{ij \in L} f_{ij} , \tag{5.202}$$

subject to the constraints (2.2)-(2.5), (2.17), (2.18), (2.20), and:

$$\sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p}^{sd} \delta_{ij,p}^{sd} = \sum_{q \in Q} \sum_{\lambda=1}^{M} b_{r_k,q,\lambda}^{ij} \pi_q^{ij} , \quad \forall r_k \in R , \forall ij \in L \tag{5.203}$$

$$Rw_{q,\lambda}^{kl} \pi_q^{kl} \geq b_{r_k,\lambda}^{ij} \pi_q^{ij} , \forall \lambda = \{1,2,..., M\}, \forall r_k \in R$$
$$, \forall q \in Q , \forall ij \in L - \{kl\}, \forall kl \in L \tag{5.204}$$

$$H_{r_k,\lambda}^{ij} - \sum_{q \in Q} Rw_{q,\lambda}^{ij} \pi_q^{ij} \geq 0 , \quad \forall \lambda = \{1,2,..., M\}, \forall r_k \in R , \forall ij \in L \tag{5.205}$$

$$f_{ij} - \sum_{r_k \in R} H_{r_k,\lambda}^{ij} \geq 0 , \quad \forall \lambda = \{1,2,..., M\}, \forall ij \in L \tag{5.206}$$

$$\sum_{\lambda=1}^{M} W_{r_k,\lambda} = t_{r_k} , \quad \forall r_k \in R \tag{5.207}$$

$$b^{ij}_{r_k,q,\lambda} \le I_\infty \times W_{r_k,\lambda}, \quad \forall \lambda = \{1,2,...,M\}, \quad \forall q \in Q, \forall sd \in A_k, \forall r_k \in R \tag{5.208}$$

$$W_{r_k,\lambda} \in Z^+, \qquad \forall \lambda = \{1,2,...,M\}, \forall r_k \in R \tag{5.209}$$

$$b^{ij}_{r_k,q,\lambda}, Rw^{ij}_{q,\lambda} \in Z^+, \qquad \forall \lambda = \{1,2,...,M\}, \forall r_k \in R, \forall q \in Q \ \forall ij \in L \tag{5.210}$$

$$H^{ij}_{r_k,\lambda} \in Z^+, \qquad \forall \lambda = \{1,2,...,M\}, \forall r_k \in R, \forall ij \in L \tag{5.211}$$

$$f_{ij} \in Z^+, \qquad \forall ij \in L. \tag{5.212}$$

5.3.7 PRR Protection Formulations

In the PRR protection, the basic restoration is the rearrangement of physical routes of all light-trees working on the network. Thus, we here analyze the PRR protection only with the SW+WW+SR spare capacity placement technique.

- **VLT wavelength allocation case**

$$\min : \sum_{ij \in L} f_{ij}, \tag{5.213}$$

subject to the constraints (2.2)-(2.5), (2.7)-(2.9) and:

$$\sum_{e \in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e} = t_{r_k} \times x^{sd}_{r_k}, \quad \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.214}$$

$$M \times f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e} \, \mu^{sd,ij'}_{ij,e} \ge 0, \qquad \forall ij \in L - \{ij'\}, \forall ij' \in L \tag{5.215}$$

$$u^{sd,ij'}_{r_k,e} \in Z^+, \qquad \forall e \in E^{ij'}_{sd}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \tag{5.216}$$

$$f_{ij} \in Z^+, \qquad \forall ij \in L. \tag{5.217}$$

To minimize the number of fibers as contained in objective function (5.213), constraint sets (2.2)-(2.5) and (2.7)-(2.9) are exploited to find the light-trees to support the given multicast demands at the network state of normal operation. Upon single link failure ij', constraints (5.214) express that the number of restoration routes corresponding to the optical branches of light-trees satisfies the traffic demands. Constraints (5.214) also imply that the network reroutes all physical routes of light-trees against the failure. Constraints (5.215) ensure that for each network physical link, the established wavelength capacity meets the restoration routes flowing on it.

Finally, constraints (5.216) and (5.217) state that all the network variables are nonnegative integers.

- **PVLT wavelength allocation case**

$$\min : \sum_{ij \in L} f_{ij} \ , \qquad (5.218)$$

subject to the constraints (2.2)-(2.5), (2.12)-(2.14) and:

$$\sum_{e \in E_{sd}^{ij'}} \sum_{\lambda=1}^{M} u_{r_k,p,\lambda}^{sd,ij'} = t_{r_k} \times x_{r_k}^{sd} \ , \quad \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \qquad (5.219)$$

$$f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e,\lambda}^{sd,ij'} \mu_{ij,e}^{sd,ij'} \geq 0 , \forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\} , \forall ij' \in L \qquad (5.220)$$

$$u_{r_k,e,\lambda}^{sd,ij'} \in Z^+ , \quad \forall \lambda = \{1,2,..., M\}, \quad \forall e \in E_{sd}^{ij'} , \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \qquad (5.221)$$

$$f_{ij} \in Z^+ , \qquad \forall ij \in L . \qquad (5.222)$$

- **LT wavelength allocation case**

$$\min : \sum_{ij \in L} f_{ij} \ , \qquad (5.223)$$

subject to the constraints (2.2)-(2.5), (2.17), (2.18), (2.20) and:

$$\sum_{e \in E_{sd}^{ij'}} \sum_{\lambda=1}^{M} u_{r_k,p,\lambda}^{sd,ij'} = t_{r_k} \times x_{r_k}^{sd} \ , \quad \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \qquad (5.224)$$

$$f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e,\lambda}^{sd,ij'} \mu_{ij,e}^{sd,ij'} \geq 0 , \forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\} , \forall ij' \in L \qquad (5.225)$$

$$u_{r_k,e,\lambda}^{sd,ij'} \in Z^+ , \quad \forall \lambda = \{1,2,..., M\}, \quad \forall e \in E_{sd}^{ij'} , \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \qquad (5.226)$$

$$\sum_{\lambda=1}^{M} W_{r_k,\lambda} = t_{r_k} \ , \qquad \forall r_k \in R \qquad (5.227)$$

$$u_{r_k,e,\lambda}^{sd,ij'} \leq I_{\infty} \times W_{r_k,\lambda} \ , \quad \forall \lambda = \{1,2,..., M\}, \ \forall e \in E_{sd}^{ij'} , \forall sd \in A_k , \forall r_k \in R \qquad (5.228)$$

$$W_{r_k,\lambda} \in Z^+ , \qquad \forall \lambda = \{1,2,..., M\}, \forall r_k \in R \qquad (5.229)$$

$$f_{ij} \in Z^+ , \qquad \forall ij \in L . \qquad (5.230)$$

5.3.8 SLB Protection Formulations

In the SLB protection, only interrupted physical routes of light-trees are rerouted to corresponding restoration routes when a single link failure occurs. From its protection mechanism, its ILP programs can be constructed as follows.

- **VLT wavelength allocation case**

$$\min : \sum_{ij \in L} (f_{ij} + s_{ij}) , \tag{5.231}$$

subject to the constraints (2.2)-(2.5), (2.7)-(2.9) and:

$$\sum_{p \in P_{sd}} a^{sd}_{r_k,p} \delta^{sd}_{ij',p} - \sum_{e \in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e} = 0 , \quad \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.232}$$

$$M \times s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e} \mu^{sd,ij'}_{ij,e} \geq 0 , \forall ij \in L - \{ij'\} , \forall ij' \in L \text{ for the SF+WF case} \tag{5.233}$$

$$M \times s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e} \mu^{sd,ij'}_{ij,e} + (M \times f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a^{sd}_{r_k,p} \delta^{sd}_{ij,p}) \geq 0 ,$$

$$\forall ij \in L - \{ij'\} , \forall ij' \in L \quad \text{for the SW+WW case} \tag{5.234}$$

$$M \times s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e} \mu^{sd,ij'}_{ij,e} + (M \times f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a^{sd}_{r_k,p} \delta^{sd}_{ij,p}) +$$

$$\sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a^{sd}_{r_k,p} \delta^{sd}_{ij',p} \delta^{sd}_{ij,p} \geq 0 , \forall ij \in L - \{ij'\} \ \forall ij' \in L \quad \text{for the SW+WW+SR case} \tag{5.235}$$

$$u^{sd,ij'}_{r_k,e} \in Z^+ , \quad \forall e \in E^{ij'}_{sd} , \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.236}$$

$$f_{ij}, s_{ij} \in Z^+ , \qquad \forall ij \in L . \tag{5.237}$$

As formulated, the objective function (5.231) is to minimize the total number of working and spare fibers used to serve multicast traffic demands. Again, constraints (2.2)-(2.5) and (2.7)-(2.9) determine the working light-tree routing pattern for all multicast demands. For constraints (5.232), they assure that the working routes corrupted by failed link ij' are rerouted to the restoration routes. To assign the spare capacity, constraints (5.233) state that for the SF+WF case, the restoration paths are allowed to route only on the spare fibers. For the SW+WW case, the third term of constraints (5.234) indicates that the network can use the remainder capacity of working fibers to support the restoration routes. In the same manner, the fourth term of constraints (5.235) states that for the SW+WW+SR case, the stub release option is employed in the network to carry the restoration routes. Finally, constraints (5.236) and (5.237) involve the models to restrict the design outcomes to be in the set of nonnegative integers.

- **PVLT wavelength allocation case**

$$\min : \sum_{ij\in L} (f_{ij} + s_{ij}) , \tag{5.238}$$

subject to the constraints (2.2)-(2.5), (2.12)-(2.14) and:

$$\sum_{\lambda=1}^{M} \sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda} \delta^{sd}_{ij',p} - \sum_{\lambda=1}^{M} \sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda} = 0 , \quad \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.239}$$

$$s_{ij} - \sum_{r_k\in R} \sum_{sd} \sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda} \mu^{sd,ij'}_{ij,e} \geq 0 , \ \forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\}$$

$$, \forall ij' \in L \text{ for the SF+WF case} \tag{5.240}$$

$$s_{ij} - \sum_{r_k\in R} \sum_{sd} \sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda} \mu^{sd,ij'}_{ij,e} + (f_{ij} - \sum_{r_k\in R} \sum_{sd} \sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda} \delta^{sd}_{ij,p}) \geq 0$$

$$, \forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\} , \forall ij' \in L \quad \text{for the SW+WW case} \tag{5.241}$$

$$s_{ij} - \sum_{r_k\in R} \sum_{sd} \sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda} \mu^{sd,ij'}_{ij,e} + (f_{ij} - \sum_{r_k\in R} \sum_{sd} \sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda} \delta^{sd}_{ij,p}) + \sum_{r_k\in R} \sum_{sd} \sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda} \delta^{sd}_{ij',p} \delta^{sd}_{ij,p} \geq 0 ,$$

$$\forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\} , \forall ij' \in L \quad \text{for the SW+WW+SR case} \tag{5.242}$$

$$u^{sd,ij'}_{r_k,e,\lambda} \in Z^{+} , \quad \forall \lambda = \{1,2,..., M\}, \quad \forall e \in E^{ij'}_{sd} , \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.243}$$

$$f_{ij} , s_{ij} \in Z^{+} , \qquad \forall ij \in L . \tag{5.244}$$

- **LT wavelength allocation case**

$$\min : \sum_{ij\in L} (f_{ij} + s_{ij}) , \tag{5.245}$$

subject to the constraints (2.2)-(2.5), (2.17), (2.18), (2.20) and:

$$\sum_{\lambda=1}^{M} \sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda} \delta^{sd}_{ij',p} - \sum_{\lambda=1}^{M} \sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda} = 0 , \quad \forall sd \in A_k , \forall r_k \in R , \forall ij' \in L \tag{5.246}$$

$$s_{ij} - \sum_{r_k\in R} \sum_{sd} \sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda} \mu^{sd,ij'}_{ij,e} \geq 0 , \ \forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij'\}$$

$$, \forall ij^{'} \in L \text{ for the SF+WF case} \quad (5.247)$$

$$s_{ij} - \sum_{r_k \in R}\sum_{sd}\sum_{e \in E_{sd}^{ij^{'}}} u_{r_k,e,\lambda}^{sd,ij^{'}} \mu_{ij,e}^{sd,ij^{'}} + (f_{ij} - \sum_{r_k \in R}\sum_{sd}\sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij,p}^{sd}) \geq 0$$

$$, \forall \lambda = \{1,2,..., M\},\ \forall ij \in L - \{ij^{'}\}, \forall ij^{'} \in L \quad \text{for the SW+WW case} \quad (5.248)$$

$$s_{ij} - \sum_{r_k \in R}\sum_{sd}\sum_{e \in E_{sd}^{ij^{'}}} u_{r_k,e,\lambda}^{sd,ij^{'}} \mu_{ij,e}^{sd,ij^{'}} + (f_{ij} - \sum_{r_k \in R}\sum_{sd}\sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij,p}^{sd}) + \sum_{r_k \in R}\sum_{sd}\sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij^{'},p}^{sd} \delta_{ij,p}^{sd} \geq 0,$$

$$\forall \lambda = \{1,2,..., M\},\ \forall ij \in L - \{ij^{'}\}, \forall ij^{'} \in L \quad \text{for the SW+WW+SR case} \quad (5.249)$$

$$u_{r_k,e,\lambda}^{sd,ij^{'}} \in Z^{+}, \quad \forall \lambda = \{1,2,..., M\}, \quad \forall e \in E_{sd}^{ij^{'}}, \forall sd \in A_k, \forall r_k \in R, \forall ij^{'} \in L \quad (5.250)$$

$$\sum_{\lambda=1}^{M} W_{r_k,\lambda} = t_{r_k}, \qquad \forall r_k \in R \quad (5.251)$$

$$u_{r_k,e,\lambda}^{sd,ij^{'}} \leq I_{\infty} \times W_{r_k,\lambda}, \quad \forall \lambda = \{1,2,..., M\}, \quad \forall e \in E_{sd}^{ij^{'}}, \forall sd \in A_k, \forall r_k \in R \quad (5.252)$$

$$W_{r_k,\lambda} \in Z^{+}, \qquad \forall \lambda = \{1,2,..., M\}, \forall r_k \in R \quad (5.253)$$

$$f_{ij}, s_{ij} \in Z^{+}, \qquad \forall ij \in L. \quad (5.254)$$

5.3.9 DJP Protection Formulations

In the DJP protection, an active route of a light-tree and its restoration route must be selected disjoint. Thus, the ILP programs of the DJP protection can be formulated as follows.

- **VLT wavelength allocation case**

$$\min: \sum_{ij \in L} (f_{ij} + s_{ij}), \quad (5.255)$$

subject to the constraints (2.2)-(2.5), (2.7)-(2.9) and:

$$a_{r_k,p}^{sd} \delta_{ij^{'},p}^{sd} - \sum_{e \in Disj(a_{r_k,p}^{sd})} u_{r_k,e}^{sd,ij^{'}} = 0, \quad \forall p \in P_{sd}, \forall sd \in A_k, \forall r_k \in R, \forall ij^{'} \in L \quad (5.256)$$

$$u_{r_k,e}^{sd,ij^{i}} - u_{r_k,e}^{sd,ij^{''}} = 0, \quad \forall e \in Disj(a_{r_k,p}^{sd}), \forall ij^{'}, ij^{''} \in L \wedge ij^{'} \neq ij^{''} \quad (5.257)$$

$$M \times s_{ij} - \sum_{r_k \in R}\sum_{sd}\sum_{e \in E_{sd}^{ij^{'}}} u_{r_k,e}^{sd,ij^{'}} \mu_{ij,e}^{sd,ij^{'}} \geq 0, \qquad \forall ij \in L - \{ij^{'}\}$$

$$, \forall ij^{'} \in L \text{ for the SF+WF case} \quad (5.258)$$

$$M \times s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e}^{sd,ij'} \mu_{ij,e}^{sd,ij'} + (M \times f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p}^{sd} \delta_{ij,p}^{sd}) \geq 0,$$

$$\forall ij \in L - \{ij'\}, \forall ij' \in L \quad \text{for the SW+WW case} \quad (5.259)$$

$$M \times s_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{e \in E_{sd}^{ij'}} u_{r_k,e}^{sd,ij'} \mu_{ij,e}^{sd,ij'} + (M \times f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p}^{sd} \delta_{ij,p}^{sd}) +$$

$$\sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p}^{sd} \delta_{ij',p}^{sd} \delta_{ij,p}^{sd} \geq 0,$$

$$\forall ij \in L - \{ij'\}, \forall ij' \in L \quad \text{for the SW+WW+SR case} \quad (5.260)$$

$$u_{r_k,e}^{sd,ij'} \in Z^+, \quad \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.261)$$

$$f_{ij}, s_{ij} \in Z^+, \quad \forall ij \in L. \quad (5.262)$$

Like the SLB protection, the objective function (5.255) of the DJP protection is the minimization of the number of working and spare fibers. Constraints (2.2)-(2.5) and (2.7)-(2.9) are used to obtain the working light-tree structures of multicast traffic. Before explaining constraints (5.256) and (5.257), a new terminology has to be introduced. For each active route $a_{r_k,p}^{sd}$ of light-tree r_k, $Disj(a_{r_k,p}^{sd})$ is denoted as a set of candidate node-disjoint restoration paths with respect to route $a_{r_k,p}^{sd}$. $Disj(a_{r_k,p}^{sd})$ set is determined in prior to generating the ILP formulation. With $Disj(a_{r_k,p}^{sd})$ set, constraints (5.256) ensure that upon a failure, the network selects a node-disjoint restoration path for each active path of a light-tree for protection. For constraints (5.257), they guarantee that in all events of failure, one active route per one restoration route system of the DJP protection is satisfied. According to the spare capacity placement techniques, constraints (5.258)-(5.260) are formulated to determine the spare capacity enough to support the restoration paths. Finally, constraints (5.261) and (5.262) are provided to limit the network variables to be only nonnegative integers.

- **PVLT wavelength allocation case**

$$\min : \sum_{ij \in L} (f_{ij} + s_{ij}), \quad (5.263)$$

subject to the constraints (2.2)-(2.5), (2.12)-(2.14) and:

$$\sum_{\lambda=1}^{M} a^{sd}_{r_k,p,\lambda}\delta^{sd}_{ij',p} - \sum_{e\in Disj(a^{sd}_{r_k,p})} u^{sd,ij'}_{r_k,e,\lambda} = 0, \quad \forall p \in P_{sd}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \qquad (5.264)$$

$$\sum_{\lambda=1}^{M} u^{sd,ij'}_{r_k,e,\lambda} - \sum_{\lambda=1}^{M} u^{sd,ij''}_{r_k,e,\lambda} = 0, \quad \forall e \in Disj(a^{sd}_{r_k,p}), \forall ij', ij'' \in L \wedge ij' \neq ij'' \qquad (5.265)$$

$$s_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda}\mu^{sd,ij'}_{ij,e} \geq 0, \quad \forall \lambda = \{1,2,..., M\}, \forall ij \in L - \{ij'\}$$

$$, \forall ij' \in L \quad \text{for the SF+WF case} \qquad (5.266)$$

$$s_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda}\mu^{sd,ij'}_{ij,e} + (f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda}\delta^{sd}_{ij,p}) \geq 0, \ \forall \lambda = \{1,2,..., M\},$$

$$\forall ij \in L - \{ij'\} \ \forall ij' \in L \quad \text{for the SW+WW case} \qquad (5.267)$$

$$s_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda}\mu^{sd,ij'}_{ij,e} + (f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda}\delta^{sd}_{ij,p}) + \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda}\delta^{sd}_{ij',p}\delta^{sd}_{ij,p} \geq 0,$$

$$\forall \lambda = \{1,2,..., M\}, \forall ij \in L - \{ij'\}, \forall ij' \in L \quad \text{for the SW+WW+SR case} \qquad (5.268)$$

$$u^{sd,ij'}_{r_k,e,\lambda} \in Z^+, \quad \forall \lambda = \{1,2,..., M\}, \quad \forall e \in E^{ij'}_{sd}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \qquad (5.269)$$

$$f_{ij}, s_{ij} \in Z^+, \qquad \forall ij \in L. \qquad (5.270)$$

- **LT wavelength allocation case**

$$\min : \sum_{ij\in L}(f_{ij} + s_{ij}), \qquad (5.271)$$

subject to the constraints (2.2)-(2.5), (2.17), (2.18), (2.20) and:

$$\sum_{\lambda=1}^{M} a^{sd}_{r_k,p,\lambda}\delta^{sd}_{ij',p} - \sum_{e\in Disj(a^{sd}_{r_k,p})} u^{sd,ij'}_{r_k,e,\lambda} = 0, \quad \forall p \in P_{sd}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \qquad (5.272)$$

$$\sum_{\lambda=1}^{M} u^{sd,ij'}_{r_k,e,\lambda} - \sum_{\lambda=1}^{M} u^{sd,ij''}_{r_k,\lambda} = 0, \quad \forall e \in Disj(a^{sd}_{r_k,p}), \forall ij', ij'' \in L \wedge ij' \neq ij'' \qquad (5.273)$$

$$s_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda}\mu^{sd,ij'}_{ij,e} \geq 0, \quad \forall \lambda = \{1,2,..., M\}, \forall ij \in L - \{ij'\}$$

$$, \forall ij' \in L \quad \text{for the SF+WF case} \qquad (5.274)$$

$$s_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E^{ij'}_{sd}} u^{sd,ij'}_{r_k,e,\lambda}\mu^{sd,ij'}_{ij,e} + (f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda}\delta^{sd}_{ij,p}) \geq 0, \ \forall \lambda = \{1,2,..., M\},$$

$$\forall ij \in L - \{ij'\}, \forall ij' \in L \quad \text{for the SW+WW case} \qquad (5.275)$$

$$s_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{e\in E_{sd}^{ij'}} u_{r_k,e,\lambda}^{sd,ij'}\mu_{ij,e}^{sd,ij'} + \Big(f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a_{r_k,p,\lambda}^{sd}\delta_{ij,p}^{sd}\Big) + \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a_{r_k,p,\lambda}^{sd}\delta_{ij',p}^{sd}\delta_{ij,p}^{sd} \ge 0,$$

$$\forall\lambda = \{1,2,...,M\},\ \forall ij \in L-\{ij'\},\ \forall ij' \in L \quad \text{for the SW+WW+SR case} \quad (5.276)$$

$$u_{r_k,e,\lambda}^{sd,ij'} \in Z^+, \quad \forall\lambda = \{1,2,...,M\}, \quad \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R, \forall ij' \in L \quad (5.277)$$

$$\sum_{\lambda=1}^{M} W_{r_k,\lambda} = t_{r_k}, \qquad \forall r_k \in R \quad (5.278)$$

$$u_{r_k,e,\lambda}^{sd,ij'} \le I_\infty \times W_{r_k,\lambda}, \ \forall\lambda = \{1,2,...,M\}, \ \forall e \in E_{sd}^{ij'}, \forall sd \in A_k, \forall r_k \in R \quad (5.279)$$

$$W_{r_k,\lambda} \in Z^+, \qquad \forall\lambda = \{1,2,...,M\}, \forall r_k \in R \quad (5.280)$$

$$f_{ij}, s_{ij} \in Z^+, \qquad \forall ij \in L. \quad (5.281)$$

5.3.10 LP Protection Formulations

In the LP protection, the active paths corrupted by the link failure are subject to reroute around the failed link. Therefore, the ILP programs of the LP protection can be modeled as follows.

- **VLT wavelength allocation case**

$$\min : \sum_{ij\in L}(f_{ij} + s_{ij}), \quad (5.282)$$

subject to the constraints (2.2)-(2.5), (2.7)-(2.9) and:

$$\sum_{sd}\sum_{p\in P_{sd}} a_{r_k,p}^{sd}\delta_{ij',p}^{sd} - \sum_{e\in E_{ij'}^{ij'}} u_{r_k,e}^{ij',ij'} = 0, \quad \forall r_k \in R, \forall ij' \in L \quad (5.283)$$

$$M \times s_{ij} - \sum_{r_k\in R}\sum_{e\in E_{ij'}^{ij'}} u_{r_k,e}^{ij',ij'}\,\mu_{ij,e}^{ij',ij'} \ge 0, \quad \forall ij \in L-\{ij'\}, \forall ij' \in L \ \text{ for the SW+SF case} \quad (5.284)$$

$$M \times s_{ij} - \sum_{r_k\in R}\sum_{e\in E_{ij'}^{ij'}} u_{r_k,e}^{ij',ij'}\,\mu_{ij,e}^{ij',ij'} + \Big(M \times f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a_{r_k,p}^{sd}\delta_{ij,p}^{sd}\Big) \ge 0,$$

$$\forall ij \in L-\{ij'\}, \forall ij' \in L \quad \text{for the SW+WW} \quad (5.285)$$

$$u_{r_k,e}^{ij',ij'} \in Z^+, \quad \forall e \in E_{ij'}^{ij'}, \forall r_k \in R, \forall ij' \in L \quad (5.286)$$

$$f_{ij}, s_{ij} \in Z^+, \qquad \forall ij \in L. \quad (5.287)$$

The objective function (5.282) is the minimal number of working and spare fibers employed to support multicast demands. Constraints (2.2)-(2.5) and (2.7)-(2.9) are the formulations to compute the service light-tree routing. Upon a failure of link $ij^{'}$, constraints (5.283) state that disturbed active routes of light-trees are rerouted around the failed link $ij^{'}$. Since in the LP protection the stub release option in SW+WW+SR technique is not useful, two possible cases to provide the spare capacity are thus the SF+WF and SW+WW cases. Accordingly, to determine the spare capacity of each network link, constraints (5.284) and (5.285) are utilized for the cases of SF+WF and SW+WW, respectively. Finally, constraints (5.286) and (5.287) enforce network results to be nonnegative integers.

- **PVLT wavelength allocation case**

$$\min : \sum_{ij \in L} (f_{ij} + s_{ij}) , \tag{5.288}$$

subject to the constraints (2.2)-(2.5), (2.12)-(2.14) and:

$$\sum_{sd} \sum_{\lambda=1}^{M} \sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij^{'},p}^{sd} - \sum_{\lambda=1}^{M} \sum_{e \in E_{ij^{'}}^{ij^{'}}} u_{r_k,e,\lambda}^{ij^{'},ij^{'}} = 0 , \quad \forall r_k \in R , \forall ij^{'} \in L \tag{5.289}$$

$$s_{ij} - \sum_{r_k \in R} \sum_{e \in E_{ij^{'}}^{ij^{'}}} u_{r_k,e,\lambda}^{ij^{'},ij^{'}} \mu_{ij,e}^{ij^{'},ij^{'}} \geq 0 , \quad \forall \lambda = \{1,2,..., M\}, \ \forall ij \in L - \{ij^{'}\}$$

$$, \forall ij^{'} \in L \text{ for the SF+WF case} \tag{5.290}$$

$$s_{ij} - \sum_{r_k \in R} \sum_{e \in E_{ij^{'}}^{ij^{'}}} u_{r_k,e,\lambda}^{ij^{'},ij^{'}} \mu_{ij,e}^{ij^{'},ij^{'}} + (f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a_{r_k,p,\lambda}^{sd} \delta_{ij,p}^{sd}) \geq 0 , \ \forall \lambda = \{1,2,..., M\},$$

$$\forall ij \in L - \{ij^{'}\} , \forall ij^{'} \in L \text{ for the SW+WW case} \tag{5.291}$$

$$u_{r_k,e,\lambda}^{ij^{'},ij^{'}} \in Z^{+} , \quad \forall \lambda = \{1,2,..., M\}, \quad \forall e \in E_{ij^{'}}^{ij^{'}} , \forall sd \in A_k , \forall r_k \in R , \forall ij^{'} \in L \tag{5.292}$$

$$f_{ij} , s_{ij} \in Z^{+} , \qquad \forall ij \in L . \tag{5.293}$$

- **LT wavelength allocation case**

$$\min : \sum_{ij \in L} (f_{ij} + s_{ij}) , \tag{5.294}$$

subject to the constraints (2.2)-(2.5), (2.17), (2.18), (2.20) and:

$$\sum_{sd}\sum_{\lambda=1}^{M}\sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda}\delta^{sd}_{ij',p} - \sum_{\lambda=1}^{M}\sum_{e\in E^{ij'}_{ij'}} u^{ij',ij'}_{r_k,e,\lambda} = 0\,, \quad \forall r_k \in R\,, \forall ij' \in L \qquad (5.295)$$

$$s_{ij} - \sum_{r_k\in R}\sum_{e\in E^{ij'}_{ij'}} u^{ij',ij'}_{r_k,e,\lambda}\mu^{ij',ij'}_{ij,e} \geq 0\,, \quad \forall\lambda = \{1,2,...,M\},\ \forall ij \in L-\{ij'\}$$

$$,\forall ij' \in L \text{ for the SF+WF case} \qquad (5.296)$$

$$s_{ij} - \sum_{r_k\in R}\sum_{e\in E^{ij'}_{ij'}} u^{ij',ij'}_{r_k,e,\lambda}\mu^{ij',ij'}_{ij,e} + (\,f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a^{sd}_{r_k,p,\lambda}\delta^{sd}_{ij,p}) \geq 0\,,\ \forall\lambda = \{1,2,...,M\},$$

$$\forall ij \in L-\{ij'\}\,, \forall ij' \in L \text{ for the SW+WW case} \qquad (5.297)$$

$$u^{ij',ij'}_{r_k,e,\lambda} \in Z^+, \quad \forall\lambda = \{1,2,...,M\}, \quad \forall e \in E^{ij'}_{ij'}, \forall sd \in A_k, \forall r_k \in R\,, \forall ij' \in L \qquad (5.298)$$

$$\sum_{\lambda=1}^{M} W_{r_k,\lambda} = t_{r_k}\,, \qquad \forall r_k \in R \qquad (5.299)$$

$$u^{ij',ij'}_{r_k,e,\lambda} \leq I_\infty \times W_{r_k,\lambda}\,, \quad \forall\lambda = \{1,2,...,M\}, \quad \forall e \in E^{ij'}_{ij'}, \forall sd \in A_k, \forall r_k \in R \qquad (5.300)$$

$$W_{r_k,\lambda} \in Z^+, \qquad \forall\lambda = \{1,2,...,M\}, \forall r_k \in R \qquad (5.301)$$

$$f_{ij}, s_{ij} \in Z^+, \qquad \forall ij \in L\,. \qquad (5.302)$$

5.3.11 1+1 Protection Formulations

In the 1+1 protection, a network sets up two disjoint active routes for each optical branch of a light-tree for protection. Hence, the ILP programs of 1+1 protection can be constructed as below.

- **VLT wavelength allocation case**

$$\min : \sum_{ij\in L} f_{ij}\,, \qquad (5.303)$$

subject to the constraints (2.2)- (2.5) and:

$$\sum_{p\in P_{sd}} a^{sd}_{r_k,p} = 2\times t_{r_k} \times x^{sd}_{r_k}\,, \quad \forall sd \in A_k\,, \forall r_k \in R \qquad (5.304)$$

$$M \times f_{ij} - \sum_{r_k\in R}\sum_{sd}\sum_{p\in P_{sd}} a^{sd}_{r_k,p}\delta^{sd}_{ij,p} \geq 0\,, \qquad \forall ij \in L \qquad (5.305)$$

$$a^{sd}_{r_k,p} \in Z^+, \quad \forall p \in P_{sd}\,, \forall sd \in A_k\,, \forall r_k \in R \qquad (5.306)$$

$$f_{ij} \in Z^+, \qquad \forall ij \in L\,. \qquad (5.307)$$

In the 1+1 protection, two physically disjoint routes of each optical branch of light-tree are set up on working fibers at the same time. Thus, the objective function (5.303) is to minimize the number of working fibers. Again, we use constraints (2.2)-(2.5) to construct a light-tree structure of each traffic demand. Constraints (5.304) express that the network routes two disjoint paths for each optical branch of light-tree on the network. Note that to guarantee the disjointness in routing of the 1+1 protection, in a set of $\{a^{sd}_{r_k,p} : \forall p \in P_{sd}\}$ for each *sd*, each candidate route will be chosen disjoint to all other candidate routes before generating the ILP program. For constraints (5.305), they determine the fiber requirement of each network link. Finally, constraints (5.306) and (5.307) are the nonnegative integer constraints of the network variables.

- **PVLT wavelength allocation case**

$$\min : \sum_{ij \in L} f_{ij} \ , \qquad (5.308)$$

subject to the constraints (2.2)-(2.5) and:

$$\sum_{p \in P_{sd}} \sum_{\lambda=1}^{M} a^{sd}_{r_k,p,\lambda} = 2 \times t_{r_k} \times x^{sd}_{r_k} \ , \qquad \forall sd \in A_k , \forall r_k \in R \qquad (5.309)$$

$$f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a^{sd}_{r_k,p,\lambda} \delta^{sd}_{ij,p} \geq 0 \ , \qquad \forall \lambda = \{1,2,\ldots, M\},\ \forall ij \in L \qquad (5.310)$$

$$a^{sd}_{r_k,p,\lambda} \in Z^{+}, \qquad \forall \lambda = \{1,2,\ldots, M\},$$

$$\forall p \in P_{sd} , \forall sd \in A_k , \forall r_k \in R \qquad (5.311)$$

$$f_{ij} \in Z^{+}, \qquad \forall ij \in L . \qquad (5.312)$$

- **LT wavelength allocation case**

$$\min : \sum_{ij \in L} f_{ij} \ , \qquad (5.313)$$

subject to the constraints (2.2)-(2.5) and:

$$\sum_{p \in P_{sd}} \sum_{\lambda=1}^{M} a^{sd}_{r_k,p,\lambda} = 2 \times t_{r_k} \times x^{sd}_{r_k} \ , \qquad \forall sd \in A_k , \forall r_k \in R \qquad (5.314)$$

$$f_{ij} - \sum_{r_k \in R} \sum_{sd} \sum_{p \in P_{sd}} a^{sd}_{r_k,p,\lambda} \delta^{sd}_{ij,p} \geq 0 \ , \qquad \forall \lambda = \{1,2,\ldots, M\},\ \forall ij \in L \qquad (5.315)$$

$$a^{sd}_{r_k,p,\lambda} \in Z^{+}, \qquad \forall \lambda = \{1,2,\ldots, M\},$$

$$\forall p \in P_{sd}, \forall sd \in A_k, \forall r_k \in R \qquad (5.316)$$

$$\sum_{\lambda=1}^{M} W_{r_k,\lambda} = 2 \times t_{r_k}, \qquad \forall r_k \in R \qquad (5.317)$$

$$a^{sd}_{r_k,p,\lambda} \leq I_{\infty} \times W_{r_k,\lambda}, \qquad \forall \lambda = \{1,2,\ldots, M\},$$

$$\forall p \in P_{sd}, \forall sd \in A_k, \forall r_k \in R \qquad (5.318)$$

$$W_{r_k,\lambda} \in Z^{+}, \qquad \forall \lambda = \{1,2,\ldots, M\}, \forall r_k \in R \qquad (5.319)$$

$$f_{ij} \in Z^{+}, \qquad \forall ij \in L. \qquad (5.320)$$

From all ILP models for all light-tree protection strategies as presented above, we can summarize the number of constraints and variables for each ILP models as in Table 5.1.

Table 5.1: Number of constraints and variables of each ILP programs.

Wavelength Assignment Scheme		Multicast Protection Strategy	
		Light-tree Reconfiguration Strategy (LR)	**Light-tree-interupted Reconfiguration Strategy (LIR)**
VLT	N_C	$\sum_{k=1}^{K}\left(1+(1+L)\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+(1+L)\binom{N_k}{2}+L\times N_k+L\right)+L^2$	$\sum_{k=1}^{K}\left(1+2L\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+(1+L)\binom{N_k}{2}+L\times N_k\right)+\left(2KL+L(2K+1)(L-1)\right)$
	N_v	$(1+P+L+EL)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+L$	$(1+P+L+EL)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+L^2K$
PVLT	N_C	$\sum_{k=1}^{K}\left(1+(1+L)\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+(1+L)\binom{N_k}{2}+L\times N_k+L\right)+ML^2$	$\sum_{k=1}^{K}\left(1+(2+L)\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}+N_k\right)+2KL+2KML(L-1)$
	N_v	$(1+PM+L+ELM)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+L$	$(1+PM+L+ELM)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+L+KML(L-1)+KL$
LT	N_C	$\sum_{k=1}^{K}\left(2+(1+L+ELM)\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+(1+L)\binom{N_k}{2}+L\times N_k+L\right)+ML^2$	$\sum_{k=1}^{K}\left(1+(2+L+ELM)\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}+N_k\right)+2KL+2KML(L-1)+K$
	N_v	$(1+PM+L+ELM)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+KL$	$(1+PM+L+ELM)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+KML(L-1)+LK+MK+L$

Wavelength Assignment Scheme		Multicast Protection Strategy	
		Optical Branch Protection Strategy (OB)	**Optical Branch-fixed Protection Strategy (OBF)**
VLT	N_C	$\sum_{k=1}^{K}\left(1+\left(1+L+N_kL+4L\left(\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}-1\right)\right)\times\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}\right)+L(L+1)$	$\sum_{k=1}^{K}\left(2+\left(1+L+N_kL+5L\left(\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}-1\right)\right)\times\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}\right)+L(L+1)$
	N_v	$\sum_{k=1}^{K}\left((1+P)\binom{N_k}{2}+\left(L+EL+2L\left(\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}-1\right)\right)\right)+2L$	$\sum_{k=1}^{K}\left((1+P)\binom{N_k}{2}+\left(L+EL+2L+2L\left(\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}-1\right)\right)\right)+2L$
PVLT	N_C	$\sum_{k=1}^{K}\left(1+\left(1+L+N_kL+4L\left(\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}-1\right)\right)\times\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}\right)+LM(L+1)$	$\sum_{k=1}^{K}\left(1+\left(1+L+N_kL+5L\left(\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}-1\right)\right)\times\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}\right)+LM(L+1)$
	N_v	$\sum_{k=1}^{K}\left((1+PM)\binom{N_k}{2}+\left(L+ELM+2L\left(\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}-1\right)\right)\right)+2L$	$\sum_{k=1}^{K}\left((1+PM)\binom{N_k}{2}+\left(L+ELM+2L+2L\left(\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}-1\right)\right)\right)+2L$
LT	N_C	$\sum_{k=1}^{K}\left(1+\left(1+L+N_kL+EL+4L\left(\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}-1\right)\right)\times\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}\right)+LM(L+1)$	$\sum_{k=1}^{K}\left(1+\left(1+L+N_kL+EL+5L\left(\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}-1\right)\right)\times\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}\right)+LM(L+1)$
	N_v	$\sum_{k=1}^{K}\left((1+PM)\binom{N_k}{2}+\left(L+ELM+2L\left(\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}-1\right)\right)\right)+2L+MK$	$\sum_{k=1}^{K}\left((1+PM)\binom{N_k}{2}+\left(L+ELM+2L+2L\left(\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}-1\right)\right)\right)+2L+MK$

Table 5.1 (continued): Number of constraints and variables of each ILP programs.

Wavelength Assignment Scheme		Multicast Protection Strategy	
		Physical Branch-fixed Protection Strategy (PBF)	Optical Mesh Protection Strategy (OMP)
VLT	N_C	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}+N_k\right)+L^2+LK+L(L-1)n_qK$	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}+N_k\right)+L+2LK+L(L-1)n_qK$
	N_v	$(1+P)\sum_{k=1}^{K}\binom{N_k}{2}+2L+L^2n_qK$	$(1+P)\sum_{k=1}^{K}\binom{N_k}{2}+L+LK+Ln_qK$
LT	N_C	$\sum_{k=1}^{K}\left(3+2\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+(MP+1)\binom{N_k}{n}+N_k\right)+L(L-1)(n_qKM+1)+L(M+K)$	$\sum_{k=1}^{K}\left(1+(1+Kn_q)\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}+N_k\right)+K(L+1)+ML(1+K)+L(L-1)n_qKM$
	N_v	$(1+PM)\sum_{k=1}^{K}\binom{N_k}{2}+L+KM(1+L+n_qL)$	$(1+PM)\sum_{k=1}^{K}\binom{N_k}{2}+2L+KM(1+Ln_q)$

Wavelength Assignment Scheme		Point-to-Point Protection Strategy	
		Physical-Route Reconfiguration Strategy (PRR)	Single Link Basis and Link Protection Strategies (SLB, LP)
VLT	N_C	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}+N_k+L\right)+L^2$	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}+N_k+L\right)+L^2$
	N_v	$\sum_{k=1}^{K}\left((1+P)\binom{N_k}{2}+EL\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}\right)+L$	$\sum_{k=1}^{K}\left((1+P)\binom{N_k}{2}+EL\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}\right)+2L$
PVLT	N_C	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}+N_k+L\right)+L^2M$	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}+N_k+L\right)+L^2M$
	N_v	$\sum_{k=1}^{K}\left((1+PM)\binom{N_k}{2}+ELM\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}\right)+L$	$\sum_{k=1}^{K}\left((1+PM)\binom{N_k}{2}+ELM\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}\right)+2L$
LT	N_C	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+(1+PM+L+EM)\binom{N_k}{2}+N_k\right)+L^2M+K$	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+(1+PM+L+EM)\binom{N_k}{2}+N_k\right)+L^2M+K$
	N_v	$\sum_{k=1}^{K}\left((1+PM)\binom{N_k}{2}+ELM\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}\right)+L+KM$	$\sum_{k=1}^{K}\left((1+PM)\binom{N_k}{2}+ELM\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}\right)+2L+KM$

Wavelength Assignment Scheme		Point-to-Point Protection Strategy	
		Disjoint Path Protection Strategy (DJP)	1+1 Protection Strategy
VLT	N_C	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}+N_k+L\right)+L^2+EL(L\text{-}1)$	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+N_k\right)+\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+L$
	N_v	$\sum_{k=1}^{K}\left((1+P)\binom{N_k}{2}+EL\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}\right)+2L$	$(P+1)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+L$
PVLT	N_C	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+\binom{N_k}{2}+N_k+L\right)+L^2M+EL(L\text{-}1)$	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+N_k\right)+\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+(L\times M)$
	N_v	$\sum_{k=1}^{K}\left((1+PM)\binom{N_k}{2}+ELM\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}\right)+2L$	$(P\times M+1)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+L$
LT	N_C	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+(1+PM+L+EM)\binom{N_k}{2}+N_k\right)+L^2M+K+EL(L\text{-}1)$	$\sum_{k=1}^{K}\left(1+\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}+N_k\right)+(M\times P+1)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+(L\times M)+K$
	N_v	$\sum_{k=1}^{K}\left((1+PM)\binom{N_k}{2}+ELM\sum_{n=1}^{\lfloor N_k/2\rfloor}\binom{N_k}{n}\right)+2L+KM$	$(P\times M+1)\sum_{k=1}^{K}\frac{N_k(N_k-1)}{2}+L+(K\times M)$

5.4 ILP formulations to Solve Optimization of Spare fibers (Network Problem B)

Table 5.2: ILP formulations to solve the minimum spare capacity problem (network problem B).

ILP Program of VLT System						
Protection Strategy	**LR**	**LIR**	**OB**	**OBF**	**PBF**	**OMP**
Constraint	**(5.1)-(5.9)**	**(5.31)-(5.44)**	**(5.77)-(5.89)**	**(5.122) -(5.137)**	**(5.176)-(5.182)**	**(5.194)-(5.201)**
Protection Strategy	**PRR**	**SLB**	**DJP**	**LP**	**1+1**	
Constraint	**(5.213)-(5.217)**	**(5.232)-(5.237)**	**(5.256)-(5.262)**	**(5.283)-(5.287)**	**(5.303)-(5.307)**	

ILP Program of PVLT System						
Protection Strategy	**LR**	**LIR**	**OB**	**OBF**	**PRR**	**SLB**
Constraint	**(5.10)-(5.18)**	**(5.45)-(5.58)**	**(5.91)-(5.103)**	**(5.139)-(5.154)**	**(5.218)-(5.222)**	**(5.239)-(5.244)**
Protection Strategy	**DJP**	**LP**	**1+1**			
Constraint	**(5.264)-(5.270)**	**(5.289)-(5.293)**	**(5.308)-(5.312)**			

ILP Program of LT System						
Protection Strategy	**LR**	**LIR**	**OB**	**OBF**	**PBF**	**OMP**
Constraint	**(5.19)-(5.30)**	**(5.59)-(5.75)**	**(5.105)-(5.120)**	**(5.156)-(5.174)**	**(5.184)-(5.193)**	**(5.202)-(5.212)**
Protection Strategy	**PRR**	**SLB**	**DJP**	**LP**	**1+1**	
Constraint	**(5.223)-(5.230)**	**(5.246)-(5.254)**	**(5.272)-(5.281)**	**(5.295)-(5.302)**	**(5.313)-(5.320)**	

As proposed, the ILP formulations for network problem A are applicable for WDM restorable networks where the working and restoration light-tree routing pattern and its wavelength pattern are subject to optimize simultaneously. On the other hand, in network design problem B, the optimization process is exploited to solve only the restoration light-tree routing and wavelength patterns while the working light-tree routing and wavelength patterns are specified in prior to solving the problem. Although the environments of network problems A and B are rather different, the ILP formulations of problem A can be extended to solve problem B.

By dropping a portion of ILP constraints concerned with the working light-tree computation and changing the objective function to minimize only the spare fiber requirement, modified ILP formulations for problem A automatically become ILP formulations for problem B. According to the protection methods, Table 5.2 provides ILP formulations to solve problem B.

It should be noted that in the study of network protection results of problem B, working light-tree routing and wavelength patterns, which are given as inputs to ILP models, are in this thesis obtained by using the ILP programs as already presented in chapter 2.

5.5 Heuristic Algorithm for LT and PVLT Multicast Restorable Networks

As considered in Table 5.1, the proposed ILP formulations of all protection methods turn out to have large numbers of variables and constraints when a designed network gets larger. In particular, for the LT and PVLT wavelength assignment systems, their number of variables and constraints also increases with the number of wavelengths per fiber (M). Therefore, this implies that an optimal solution of network protection problems cannot be obtained in a reasonable time for a large network. In this section, we introduce a heuristic procedure to determine good solutions in cases of the LT and PVLT methods for all proposed protection approaches by using a solution of the ILP model of the VLT method as an input of heuristic procedure.

In development of heuristic procedure, the network protection problem is decomposed into two sub-problems: the working and restoration light-tree routing sub-problem and the wavelength assignment sub-problem. These two sub-problems are considered separately and in sequence.

After a proposed light-tree protection technique is selected to provide in the network, the sequence of steps of the heuristic algorithm is as follows.

- STEP 1: Generate the VLT linear formulation of the protection that we are considering. For instance, if the LR protection is being considered, the corresponding VLT formulation will be the objective function (5.1) and the constraints (2.2)-(2.5), (2.7)-(2.9) and (5.2)-(5.9).

- STEP 2: Solve the linear formulation generated in STEP 1 and record its solution.

  - For the LR protection, its solution is $\{x_{r_k}^{ij}, a_{r_k,p}^{sd}, xf_{r_k,ij'}^{ij}, u_{r_k,e}^{sd,ij'}\}$.

  - For the LIR protection, its solution is $\{x_{r_k}^{ij}, a_{r_k,p}^{sd}, xf_{r_k,ij'}^{ij}, u_{r_k,e}^{sd,ij'}, G_{r_k}^{ij'}, C_{r_k,ij}^{ij'}\}$.

  - For the OB protection, its solution is $\{x_{r_k}^{ij}, a_{r_k,p}^{sd}, u_{r_k,e}^{sd,ij'}, \Omega_{r_k}^{sd,ij'} y_{r_k,ab}^{sd,ij'}, V_{r_k,ab}^{sd,ij'}\}$.

  - For the OBF protection, its solution is $\{x_{r_k}^{ij}, a_{r_k,p}^{sd}, u_{r_k,e}^{sd,ij'}, \Omega_{r_k}^{sd,ij'} y_{r_k,ab}^{sd,ij'}, V_{r_k,ab}^{sd,ij'}, \Theta_{r_k}^{ij}\}$.

  - For the PBF protection, its solution is $\{x_{r_k}^{ij}, a_{r_k,p}^{sd}, b_{r_k,q}^{ij}, Sw_{r_k,ij}^{q}\}$.

  - For the OMP protection, its solution is $\{x_{r_k}^{ij}, a_{r_k,p}^{sd}, b_{r_k,q}^{ij}, Rw_{q}^{ij}, H_{r_k}^{ij}\}$.

  - For the PRR, SLB, DJP and LP protections, its solution is $\{x_{r_k}^{ij}, a_{r_k,p}^{sd}, u_{r_k,e}^{sd,ij'}\}$.

  - For the 1+1 protection, its solution is $\{x_{r_k}^{ij}, a_{r_k,p}^{sd}\}$.

- STEP 3: If the solution of the PVLT system is needed, generate the linear formulation of PVLT corresponding to the protection that we are considering. Otherwise, if the solution of the LT system is needed, generate the linear formulation of LT system instead. For either PVLT or LT, generate the additional following constraints and include them into the model:

$$\sum_{\lambda=1}^{M} a_{r_k,p,\lambda}^{sd} = a_{r_k,p}^{sd} \quad , \forall p \in P_{sd}, \forall sd \in N_k, \forall r_k \in R \qquad (5.321)$$

$$\sum_{\lambda=1}^{M} u_{r_k,e,\lambda}^{sd,ij'} = u_{r_k,e}^{sd,ij'} \quad , \forall p \in P_{sd}, \forall sd \in N_k, \forall r_k \in R \ \forall ij' \in L \qquad (5.322)$$

$$\sum_{\lambda=1}^{M} C^{ij'}_{r_k,ij,\lambda} = C^{ij'}_{r_k,ij} \ ,\forall r_k \in R \ ,\forall ij \in L-\{ij'\} \ ,\forall ij' \in L \text{ only for the LIR protection} \quad (5.323)$$

$$\sum_{\lambda=1}^{M} b^{ij}_{r_k,q,\lambda} = b^{ij}_{r_k,q} \ ,\forall r_k \in R \ ,\forall q \in Q \ ,\forall ij \in L \text{ only for the PBF and OMP protection} \quad (5.324)$$

$$\sum_{\lambda=1}^{M} Rw^{ij}_{q,\lambda} = Rw^{ij}_{q} \ ,\forall r_k \in R \ ,\forall q \in Q \ ,\forall ij \in L \text{ only for the OMP protection} \quad (5.325)$$

$$\sum_{\lambda=1}^{M} H^{ij}_{r_k,\lambda} = H^{ij}_{r_k} \ ,\forall r_k \in R \ ,\forall ij \in L \text{ only for the OMP protection,} \quad (5.326)$$

where the variables in the left side of the above constraints are replaced by the solutions recorded in STEP 2.

- STEP 4: Solve the new linear formulation generated in STEP 3. The network solution obtained from the new formulation combining with the solution recorded in STEP 2 becomes the results of the PVLT and the LT network protection designs.

Chapter 6

Results and Discussion for the Optical Protection Problem

6.1 Introduction

In this chapter, we deploy the ILP mathematical models and the heuristic algorithms as developed in Chapter 5 to study the optical protection problem of optical WDM networks.

With the use of several test networks, in the next section, the numerous experiment results are presented and discussed.

6.2 Results and Discussion

In this section, we present the numerical results obtained from the proposed ILP formulations so as to compare capacity requirements among the different light-tree protection approaches and also evaluate the influences of the limited fanout and the spare fiber placement techniques on spare capacity requirements. To solve the optimization problems formulated by the ILP models, the commercial software CPLEX MIP 6.6 [98] is employed and run on a PC 2.5 GHz Intel Pentium 4 with 1 GB of RAM. In experiments, we solve the optimization problems only in the case of VLT system, while the design outcomes for the PVLT and LT systems are determined by the proposed heuristic procedures as introduced in chapter 5. Thus, design outcomes for the VLT system are confirmed optimal.

Note that to determine active routes for given multicast traffic sessions, only the shortest routes of all node pairs of networks are used when generating ILP models for solving network problems A and B. In addition, the results reported throughout this section are for the VLT system, except in the last subsection.

6.2.1 Comparison of Light-tree Protection Strategies

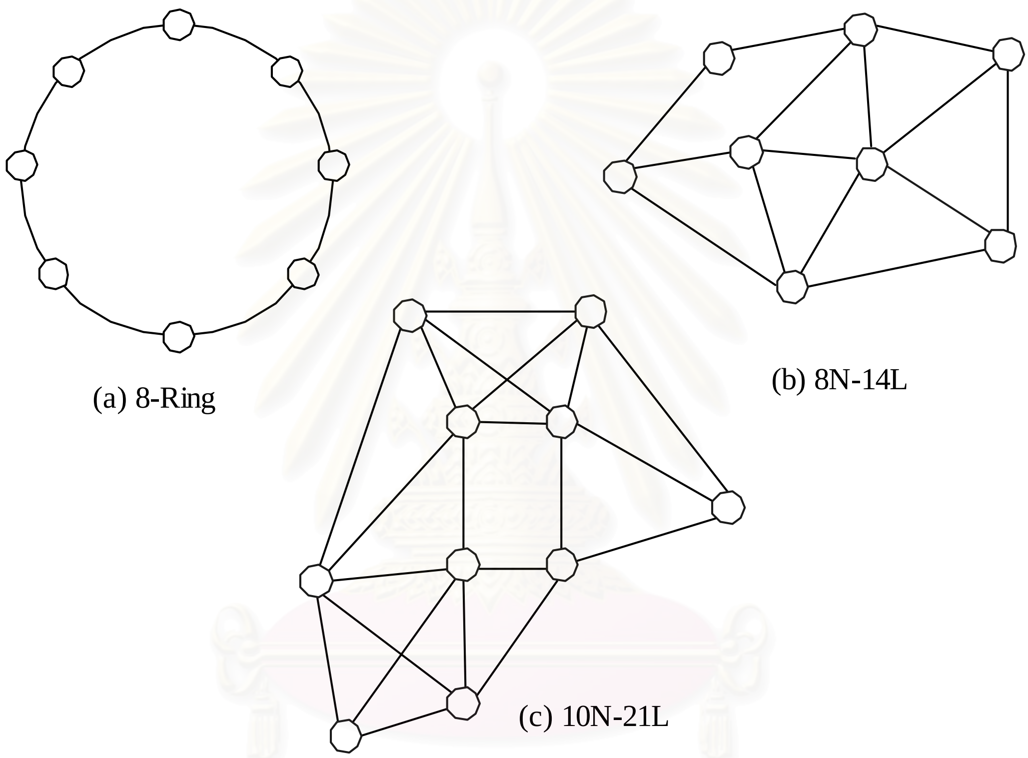


Figure 6.1: Experimental networks.

Here, the light-tree protection strategies as described in chapter 4 are studied and compared in terms of the number of working and spare fibers needed to construct resilient multicast optical networks. The networks used in the experiments are shown in Figure 6.1 and their network characteristics are summarized in Table 6.1.

Table 6.1: Experimental network characteristics.

Network	No. of nodes (N)	No. of links (L)	Avg. nodal degree	No.of candiate restoration routes per node pair	Total number of candidate rings (Q)	No. of destinations per multicast demand (G)	Total amount of multicast demands	Value of fanout (Δ)
8-Ring	8	8	2	1	1	1	5	3
						3	5	
						5	5	
8N-14L	8	14	3.5	10	59	1	5	3
				10	30	3	5	
				5	15	5	5	
10N-21L	10	21	4.2	5	100	1	5	3
				5	40	3	4	
				5	40	4	4	

As shown, the three test networks which are selected for the experiments are 1) the most sparse 8-ring network, 2) the 8N-14L network, and 3) the highly connected 10N-21L network. To set multicast traffic demands for each test network, we initially fix the number of multicast sessions, followed by selecting the source nodes of multicast sessions. Then the nodes of the network are randomly chosen to be the destinations of multicast sessions. The total number of destinations for each session is specified by a fixed value of G as defined in Table 6.1. In the experiments, the value of G for all sessions of each test network is assumed to be equal and all sessions are also assumed to require one wavelength channel for communications. Table 6.1 shows how we set other parameters for test.

In order to determine the fiber requirements, the spare capacity placement techniques applied for light-tree protection strategies have to be selected and summarized as in Table 6.2. As shown, the spare capacity placement schemes are chosen in such a way that each protection method provides the minimal fiber requirement with respect to other possible spare capacity placement schemes that can be applied to it. Hence, this selection guarantees fairness in the comparative study among the different light-tree protection approaches.

Table 6.2: Spare capacity placement techniques used in the experiments.

	Multicast protection	Spare capacity placement technique
Light-Tree protection strategy	LR	SW+WW+SR
	LIR	SW+WW+SR
	OB	SW+WW+SR
	OBF	SW+WW+SR
	PBF	SW+WW
	OMP	Dedicated
	Point-to-Point protection	**Spare capacity placement technique**
	PRR	SW+WW+SR
	SLB	SW+WW+SR
	DJP	SW+WW+SR
	LP	SW+WW
	1+1	Dedicated

For the three test networks, they may be considered not practical-sized optical networks due to their relatively small size. However, we choose these networks because in this section all the results are obtained according to network design problem A (joint optimization). As will be discussed, the computational complexity of problem A is rather time intensive, particularly for large networks. Thus, this results in a limit to select networks for testing with network problem A. Nevertheless, as will be analyzed, the results of these test networks can be used to indicate the fiber requirement differences among the proposed protection strategies.

Table 6.3: Numerical results for the 8-ring network with *G*=3 and 5.

M	Number of Working and Spare Fibers Required											
	NoPro	**LR**	**LIR**	**OB**	**OBF (Br=2)**	**PBF**	**OMP**	**PRR**	**SLB**	**DJP**	**LP**	**1+1**
***G*=3**												
1	22	40	40	40	40	40	40	51	51	51	53	120
2	12	24	24	24	24	24	24	28	28	28	28	64
3	9	16	16	16	16	16	16	20	20	20	20	32
4	8	16	16	16	16	16	16	16	16	16	16	24
5	7	8	8	8	8	8	8	14	15	15	15	24
6	7	8	8	8	8	8	8	12	12	12	12	16
7	7	8	8	8	8	8	8	8	12	12	12	16
8	7	8	8	8	8	8	8	8	8	8	8	8
***G*=5**												
1	25	40	40	40	40	40	40	57	57	57	57	200
2	14	24	24	24	24	24	24	30	30	30	30	104
3	11	16	16	16	16	16	16	22	22	22	22	72
4	8	8	8	16	16	16	16	16	16	16	16	56
5	7	8	8	8	8	8	8	15	15	15	15	40
6	7	8	8	8	8	8	8	14	14	14	14	40
7	7	8	8	8	8	8	8	12	12	12	12	32
8	7	8	8	8	8	8	8	8	8	8	8	32

After calculating the fiber requirements, Table 6.3 shows the results for the 8-ring network in the cases with and without link failure protection. Consider the case without protection where the results are in column “NoPro”. For each *G* analyzed, we found that the number of fibers required for supporting the multicast traffic decreases as the number of wavelengths per fiber, *M*, increases. For example, at *G*=3, the number of fibers can be reduced by around a half when the value of *M* increases from 1 to 2 (from non-WDM to WDM systems). At *M*=4, the number of fibers will approach the number of physical links of the test network, *i.e.*, totaling 8 fibers. A further increment in the value of *M* beyond 4 results in a slight reduction of the fiber requirement; only 7 fibers are needed, meaning that it is not necessary to install fibers at all physical links of the network. It is worth noting that this observation corresponds to the fact that while the amount of traffic is constant, providing more wavelength channels per fiber should lead to lower fiber requirements.

Consider the cases where a protection system is provided. For each value of *G*, we see that with the 8-ring network, a larger number of fibers are required to protect multicast traffic against events of link failure.

At *G*=3 and 5, Table 6.3 shows that the multicast protection strategies, *i.e.*, LR, LIR, OB, OBF, PBF and OMP, typically require fewer fibers to protect the multicast traffic than the point-to-point protection strategies, *i.e.*, PRR, SLB, DJP, LP and 1+1. In particular, for the same dedicated spare capacity reservation, the fiber requirements of the 1+1 protection are on average greater than those of the OMP protection by 131% and 328% for *G*=3 and 5, respectively. These percentages are considered quite large. This observation confirms our expectation that the protection techniques specifically designed for multicast traffic would give better results than adopting the point-to-point protections to protect multicast traffic.

Now, let us examine the capacity difference among the multicast protections or among the point-to-point protections. Table 6.3 shows that the results of all multicast protections or of all point-to-point protections are in most cases identical. By investigating in detail, we found that this equality arises from the two diversity paths of the ring topology of the 8-ring network. Thus, the capacity requirements among light-tree protection approaches are not clear distinguished by testing with the ring topology. Hence, more numerical results for other test networks are needed.

Table 6.4: Numerical results for the 8N-14L network with *G*=3 and 5.

M	Number of Working and Spare Fibers Required											
	NoPro	LR	LIR	OB	OBF (Br=2)	PBF	OMP	PRR	SLB	DJP	LP	1+1
						G=3						
1	16	22	22	24	24	24	29	26	26	26	26	49
2	10	13	13	13	13	14	16	14	14	14	14	27
3	9	10	10	10	10	10	12	11	11	11	11	20
4	8	9	9	9	9	9	10	10	10	10	10	16
5	8	9	9	9	9	9	10	10	10	10	10	13
						G=5						
1	26	31	31	32	32	33	39	38	40	40	40	78
2	13	17	17	18	18	19	23	20	22	22	22	40
3	9	11	11	11	11	13	15	13	14	14	14	27
4	8	10	10	10	10	11	12	11	12	12	12	21
5	7	8	8	8	8	8	9	10	11	11	11	17
6	7	8	8	8	8	8	9	10	10	10	10	15
7	7	8	8	8	8	8	9	10	10	10	10	15

Table 6.5: Numerical results for the 10N-21L network with *G*=3 and 4.

M	Number of Working and Spare Fibers Required											
	NoPro	LR	LIR	OB	OBF (Br=2)	PBF	OMP	PRR	SLB	DJP	LP	1+1
						G=3						
1	12	16	16	17	17	21	23	22	23	23	23	36
2	10	13	13	13	13	14	15	14	15	15	15	20
3	10	13	13	13	13	13	13	14	14	15	15	18
4	10	13	13	13	13	13	13	14	14	15	15	18
5	10	13	13	13	13	13	13	14	14	15	15	17
						G=4						
1	16	20	20	21	21	24	27	26	27	27	27	48
2	10	13	13	13	13	14	15	16	16	16	16	25
3	10	12	12	12	12	13	14	14	14	14	14	20
4	10	12	12	12	12	13	13	14	14	14	14	17

For the more connected 8N-14L and 10N-21L test networks, Tables 6.4 and 6.5 show the network design outcomes. As demonstrated, when comparing with results for no protection, a larger number of fibers are required to provide single link failure restoration for all proposed protection methods. Tables 6.4 and 6.5 also illustrate that the class of multicast protections typically require fewer fibers than the class of point-to-point protections. For instance, 43% and 23% are required on average for 8N-14L at *G*=5 and 10N-21L at *G*=3 to be changed from the multicast to point-to-point protection systems, respectively. This observation is consistent with the results for the 8-ring network.

However, when examining the OMP and PRR protections, the results show that for some *M* values, OMP needs more fibers to guarantee the link restoration than PRR, especially at low values of *M*. This finding signifies that in the test networks, the shared spare capacity reservation of the point-to-point PRR protection can be employed to reduce the capacity better than the dedicated spare capacity reservation of the multicast OMP approach. However, as considered in Tables 6.4 and 6.5, the capacity difference between the OMP and PRR protection techniques is marginal. Note that the capacity comparison between these two methods will be further studied in section 6.2.4.

Next, consider the capacity difference among the multicast protection approaches. The results in Tables 6.4 and 6.5 show that the LR protection leads to the minimal fiber requirement with respect to other multicast protection methods. However, the results for the LR protection can be achieved by those for the LIR protection for all values of *M*. This implies that under the minimum capacity condition, the network prefers to reconfigure only the directly interrupted light-trees when an event of link failure occurs. In addition, this implies that the great flexibility of the LR method to reconfigure entire light-trees does not offer an advantage in fiber savings.

When comparing the capacity difference between OB and OBF at Br=2, we found that the results of both protections are identical for the test networks, meaning that providing only a limited number of backup optical branches for OBF is sufficient to obtain the same results as for OB. Moreover, Tables 6.4 and 6.5 qualitatively show that at *M*=1, there exists only a slight difference in the fiber requirement between the OBF (or OB) and LIR (or LR) approaches and further increasing *M*, no capacity differences can be found. This figure indicates that for multicast traffic served on light-trees, the use of the backup optical branch concept in the OB and OBF protection schemes potentially yields good results for installing the capacity resources on the networks. Furthermore, this restoration concept offers another advantage in that it can simplify the fault management and operation with respect to those of the LR and LIR techniques. Thus, with this observation, we can conclude that OB and OBF are effective candidates for constructing a restoration system for multicast traffic.

Next, let us examine the results for the PBF protection strategy. Tables 6.4 and 6.5 indicate that the fiber differences between PBF and OBF (or OB) can be seen. For example, with the 10N-21L network at G=3, the PBF protection requires more fibers than the OBF protection by 24% and 8% for M=1 and 2, respectively. Such the differences directly arise from the constraint that for the PBF protection, a backup optical branch designed to protect a light-tree has to select only a single corresponding physical path for restoration. However, by the effect of greater wavelength multiplexing, the PBF and OBF (or OB) strategies can lead to identical results. As shown in Tables 6.4 and 6.5, when $M \geq 3$, the results of the PBF and OBF (or OB) schemes are all the same.

Let us now investigate the OMP protection. Tables 6.4 and 6.5 illustrate that the OMP protection requires more fibers than other multicast protection approaches. This is because the OMP protection does not permit sharing of spare wavelength channels among the restoration paths of light-trees in contrast to other multicast protection approaches. However, the rather high number of fibers needed by OMP is compensated by the simple restoration process, thereby simplifying the restoration hardware equipment. Additionally, Tables 6.4 and 6.5 suggest that the extra fibers for OMP with respect to other multicast protections can be diminished by raising the value of M. Thus, from this viewpoint, it is inferred that using a multiple fiber system with high wavelength multiplexing of the network can decrease the capacity differences among the protection techniques. Note that this scenario exclusively exists in networks with a multiple fiber system and cannot be seen in networks with a single fiber system.

Now, let us study another class of light-tree protections, *i.e.,* the point-to-point protection strategies. As shown in Tables 6.4 and 6.5, the results indicate that the 1+1 protection technique provides the maximum fiber requirement to construct a restoration mechanism against link failures. This is because the networks with the 1+1 protection have to assign spare capacity dedicated to each restoration path of each optical branch of the light-trees. For example, 2.61 times the number of fibers for the case of no protection is required on average for the 8N-14L test network with *G*=3 to provide the 1+1 protection system.

In contrast, the experiments also demonstrate that among the point-to-point protection strategies, the minimal capacity requirement occurs in the case of the PRR protection. With respect to the 1+1 protection, the fiber savings of PRR are gained by the spare resource sharing. However, when comparing the results of PRR to those of SLB, the fiber savings of PRR are comparable. Moreover, the capacity differences between these two protection approaches will vanish when the value of *M* becomes larger. Thus, based on the experiments, we can conclude that SLB is more effective and useful than PRR. This is because while SLB provides a fiber capacity close to that of PRR, its restoration process is much less sophisticated than that of PRR.

Further observing the results in Tables 6.4 and 6.5, we found that across the range of *M* values, the SLB, DJP and LP protection schemes typically achieve the same results. Therefore, with the test networks, these three point-to-point protections perform identically in terms of the number of fibers needed to ensure the link restoration.

Finally, throughout this section, we can summarize the light-tree protections in terms of the fiber requirement to provide the link restoration as below:

1) LR=LIR $\leq$ OB=OBF(Br=2) $\leq$ PBF $\leq$ PRR $\leq$ OMP $\leq$ 1+1.

2) PRR $\leq$ SLB=DJP=LP $\leq$ 1+1.

- **Unicast Traffic: A Special Study Case**

To enhance understanding of the restoration mechanism of each proposed light-tree protection, we include a study of the light-tree protections in the case of unicast (point-to-point) traffic given to the test networks. With this study, we can see some equivalences between the multicast and point-to-point protection strategies. Given design parameters as shown in Table 6.1, the numerical results of the three test networks are presented in Table 6.6.

Table 6.6: Numerical results for the three test networks with *G*=1.

M	Number of Working and Spare Fibers Required											
	NoPro	LR	LIR	OB	OBF (Br=2)	PBF	OMP	PRR	SLB	DJP	LP	1+1
8-Ring at *G*=1												
1	10	26	26	26	26	26	40	26	26	26	26	40
2	6	14	14	14	14	14	24	14	14	14	14	24
3	6	12	12	12	12	12	16	12	12	12	12	16
4	6	8	8	8	8	8	8	8	8	8	8	8
5	6	8	8	8	8	8	8	8	8	8	8	8
8N-14L at *G*=1												
1	9	15	15	17	17	17	22	15	17	17	17	22
2	9	10	10	10	10	10	12	10	10	10	10	12
3	9	10	10	10	10	10	10	10	10	10	13	10
4	9	10	10	10	10	10	10	10	10	10	13	10
10N-14L at *G*=1												
1	12	20	20	22	22	22	25	20	22	22	23	25
2	9	15	15	15	15	15	18	15	15	15	17	18
3	9	14	14	14	14	14	17	14	14	14	15	17
4	9	14	14	14	14	14	16	14	14	14	15	16

Consider the results in Table 6.6. With the unicast traffic, we observe that between the classes of multicast and point-to-point protections, the OMP and 1+1 protections are equivalent in all design aspects, such as the capacity requirement and the restoration mechanism. This is because at *G*=1, the light-trees supporting the unicast traffic are automatically reduced to the lightpaths. Thus, with the same concept of dedicated spare capacity reservation, OMP is in effect identical to 1+1. As shown in Table 6.6, this equivalence is represented by the same result of each other. Moreover, for the same reason, three other equivalences can be seen in this experiment, that is, 1) LR=PRR, 2) OB=OBF=SLB, and 3) PBF=DJP. Again, these equivalences are confirmed by the design outcomes shown in Table 6.6.

In addition, for ring networks such as the 8-ring network, an additional equivalence can be noticed, namely, LIR=OB=OBF(Br$\geq$1)=PBF=DJP=SLB. This equivalence arises from the fact that the ring network topology has only a single restoration path for each node pair to recover the disturbed traffic when the failure occurs. Therefore, regardless whether it is LIR, OB, OBF, PBF, DJP or SLB, every protection has only one single candidate restoration route for protection and thereby they provide the same result.

In summary, all the protection equivalences that exclusively occur in the case of the unicast traffic can be concluded as follows:

1) OMP=1+1,

2) LR=PRR,

3) OB=OBF=SLB

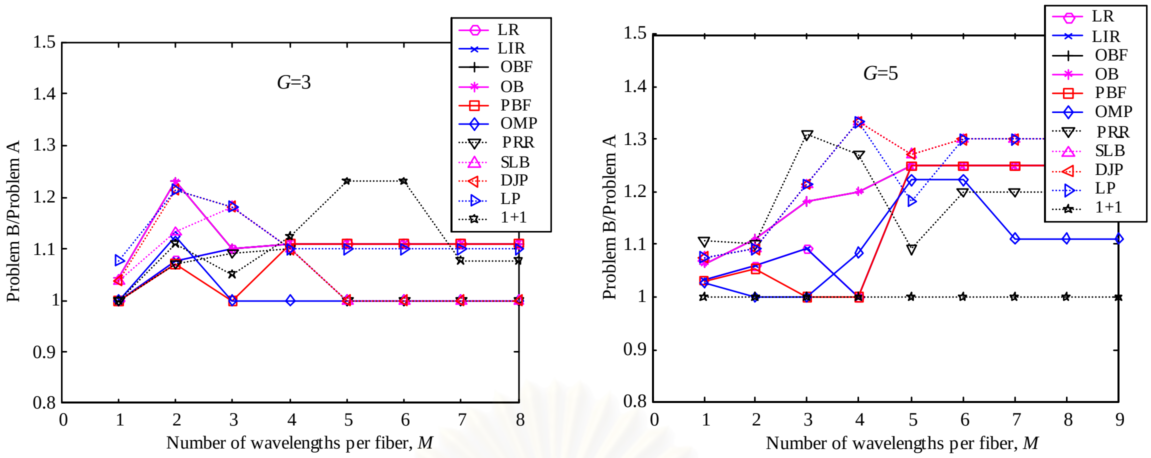
4) PBF=DJP.

Combining with ring topology networks, an extra equivalence must be included as LIR=OB=OBF=PBF=DJP=SLB.

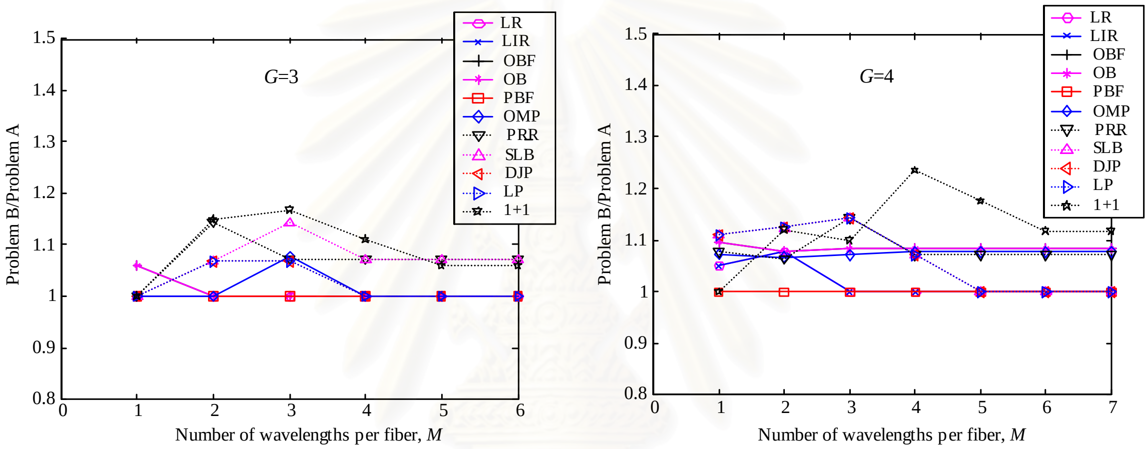
6.2.2 Capacity Comparison of Network Problems A and B

To compare the capacity requirement of network design problem B to that of problem A, Figure 6.2 plots the problem-B to problem-A capacity requirement ratio versus the number of wavelengths per fiber. Using the 8N-14L and 10N-21L test networks, Figure 6.2 shows that for all light-tree protections, the resulting ratios are greater than or equal to one for all values of *M*. This implies that the joint optimization of working and spare fibers can always lead to a better network solution than the optimization of spare fibers alone. As shown in Figure 6.2a), with respect to the results of problem B, we achieve an average of 14% and 17% total capacity savings for the 8N-14L network at *G*= 5 in the cases of the multicast and point-to-point protections in network problem A, respectively. Meanwhile, for the 10N-21L network at *G*=4, the average total capacity reductions are 5% and 8% in the cases of the multicast and point-to-point protection approaches, respectively. From Figure 6.2, it should be noted that the benefit of using the joint optimization tends to be constant for high values of *M*.

Although the joint optimization of working and spare fibers provides the better quality in the capacity requirements than the spare fiber optimization, as will be analyzed in the next section, this better quality of the joint optimization will trade off with the ILP complexity and the computational time to obtain results.



a) Results for the 8N-14L network with *G*=3, 5



b) Results for the 10N-21L network with *G*=3, 4

Figure 6.2: Comparison of the capacity requirements between network design problems A and B.

6.2.3 ILP Complexity and Computation Time

In this section, the computational complexity of ILP formulations and the execution time to solve optimization problems are studied.

Table 6.7: Computational complexity of ILP formulation of network design problem A for 8N-14L with G=5. The computational complexity is represented in terms of the number of constraints (N_c) and variables (N_v) of the ILP formulation. Computational complexity of network design problem B is given in parentheses.

Light-tree Protection	**ILP Complexity of VLT System**	
	N_v	N_c
NoPro	279	164
LR	3751 (3472)	6452 (6288)
LIR	5386 (5107)	7361 (7197)
OB	11392 (11113)	17201 (17037)
OBF	13122 (12843)	17276 (17112)
PBF	1254 (975)	1882 (1718)
OMP	939 (660)	589 (425)
PRR	806 (527)	2069 (1905)
SLB	587 (308)	743 (579)
DJP	4474 (4195)	4378 (4214)
LP	587 (308)	743 (579)
1+1	354 (75)	239 (75)

Table 6.8: Computational complexity of ILP formulation of network design problem A for 10N-21L with G=4. The computational complexity is represented in terms of the number of constraints (N_c) and variables (N_v) of the ILP formulation. Computational complexity of network design problem B is given in parentheses.

Light-tree Protection	ILP Complexity of VLT System	
	N_v	N_c
NoPro	145	101
LR	2749 (2604)	4964 (4863)
LIR	4168 (4023)	5744 (5643)
OB	4307 (4162)	5711 (5610)
OBF	4901 (4756)	5751 (5650)
PBF	2106 (1961)	3493 (3392)
OMP	1515 (1370)	973 (872)
PRR	1515 (1370)	4648 (4547)
SLB	622 (477)	397 (296)
DJP	3742 (3597)	3398 (3297)
LP	622 (477)	397 (296)
1+1	185 (40)	141 (40)

For the 8N-14L network with G=5 and the 10N-21L network with G=4, Tables 6.7 and 6.8 illustrate the complexity of ILP formulations of network problem A in terms of the numbers of constraints (N_c) and variables (N_v), while the ILP complexity of network problem B is given in parentheses.

Tables 6.7 and 6.8 show that N_c and N_v of the case with protection are much greater than those of the case without protection regardless of whether ILP formulations are generated to form network problem A or B. This due to the fact that to guarantee the link restoration, the extra number of constraints and variables associated with the restoration path and spare capacity determination must be included in the formulations.

When the complexities of light-tree protection designs with problem A are considered, Tables 6.7 and 6.8 indicate that the ILP models of multicast protections are more computationally complicated than those of point-to-point protections. Therefore, with this observation we can expect that the computational times to solve the ILP formulations of the multicast protections would be longer than those of the point-to-point protections.

Figures 6.3 and 6.4 chart the computation times of ILP formulations for the 8N-14L network with G=5 and the 10N-21L network with G=4, respectively. As shown, the computational time of each protection approach is presented by a gray scale. A black square in the charts means that that ILP formulation requires more than 10 hours to obtain the results. In contrast, a white square means that the ILP formulation is completely solved within 5 seconds.

Consider the resulting charts in Figures 6.3 and 6.4. They show that ILP formulations in the cases without protection can be solved almost instantly (within 5 seconds) for all test values of M. This is because the computational complexity of the ILP formulation in a case without protection is very small as illustrated in Tables 6.7 and 6.8. However, Figures 6.3 and 6.4 also demonstrate that the execution time to solve an ILP formulation will be longer when the networks are designed to provide single link protection. Particularly, the ILP formulations of multicast protections generally consume more time to obtain results than the ILP formulations of point-to-point protections. In other words, the chart areas for the multicast protection are

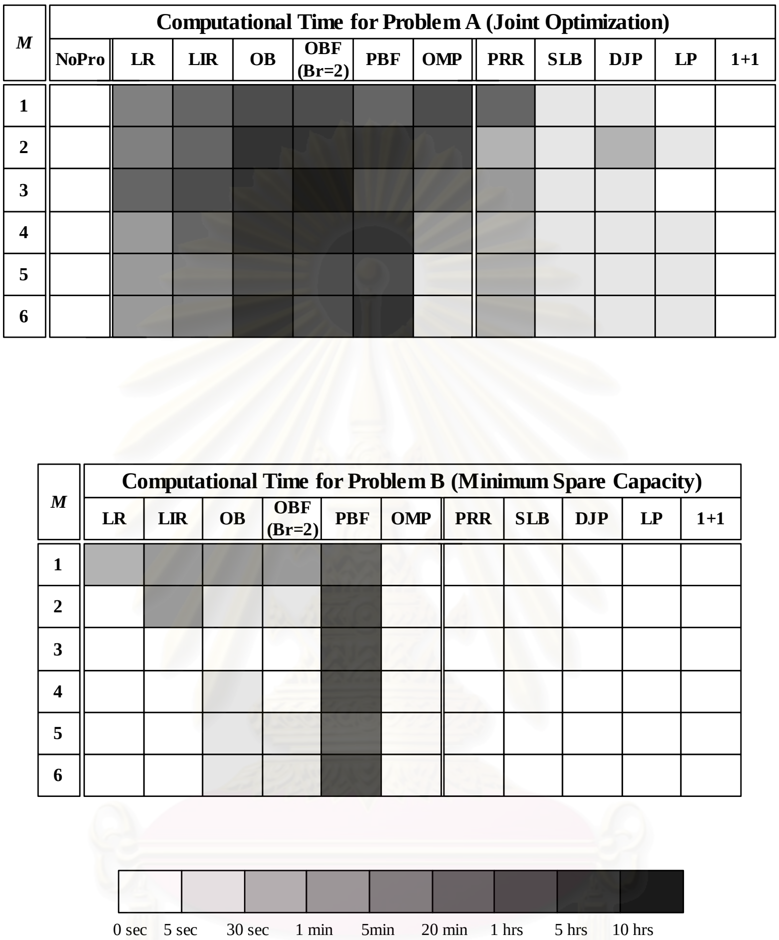


Figure 6.3: Computational time of the ILP formulations for 8N-14L with *G*=5 under network design problems A and B.

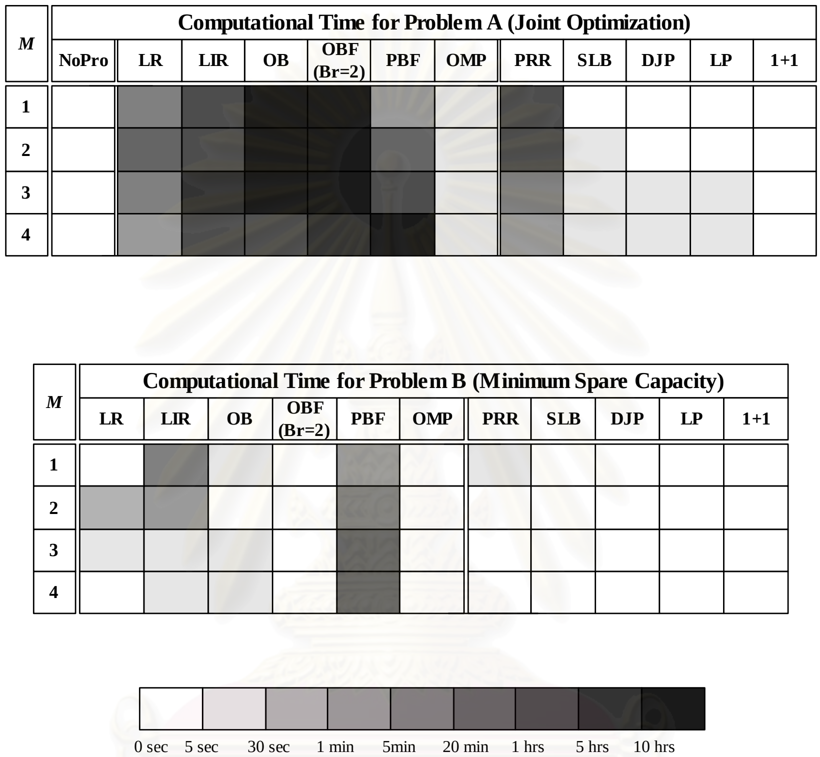


Figure 6.4: Computational time of the ILP formulations for 10N-21L with G=4 under network design problems A and B.

dimmer than those for the point-to-point protections. Note that these observations hold true for both network problems A and B and also correspond to the previous discussion of the ILP complexity shown in Tables 6.7 and 6.8.

Next, let us investigate the computational time difference between network problems A and B. Figures 6.3 and 6.4 demonstrate that the areas in the cases of problem B are generally brighter than those in the cases of problem A. This implies that the time taken to solve network problem B is shorter than that to solve network problem A. In most cases of problem B, Figures 6.3 and 6.4 show that we can obtain the results within 5 minutes. Meanwhile, to solve problem A consumes on average 1 hour. Additionally, in some cases, the execution time to solve problem A is relatively long, *i.e.*, more than 10 hours. However, with respect to problem A, the advantage in the short execution time of problem B will trade off with the quality of network results. This is because, as illustrated in Figure 6.2, the capacity requirements of problem A are always lower than those of problem B.

Since the time to calculate design outcomes of problem B is rather short even for the moderate-sized 10N-21L network, in the next subsection, we shall extend our experiments to study the proposed protection techniques by using a practical-sized NSFNet network [41].

6.2.4 Practical-Sized NSFNet Network

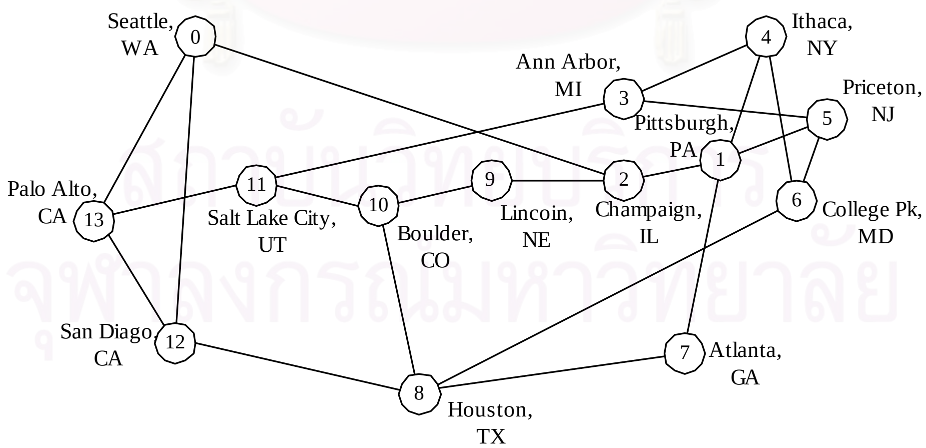


Figure 6.5: NSFNet network topology.

In this section, we extend the comparative study among the proposed light-tree protection methods to cover the more practical-sized NSFNet network. The network topology and the network characteristics are shown in Figure 6.5 and Table 6.9, respectively. As shown in Table 6.9, ten multicast sessions with G= 8 are given to the network. Each multicast session is assumed to require one wavelength channel for communications. In addition, the methodology to assign the spare capacity placement techniques to light-tree protections is shown in Table 6.2.

Table 6.9: NSFNet network characteristics.

Network	No. of nodes (N)	No. of links (L)	Avg. nodal degree	No .of candiate restoration routes per node pair	Total number of candidate rings (Q)	No. of destinations per multicast demand (G)	Total amount of multicast demands	Value of fanout (Δ)
NSFNet	14	21	3	5	40	8	10	3

For network design problem B, Figure 6.6a) plots the total number of working and spare fibers required to guarantee link restoration versus the number of wavelengths per fiber. In the cases with and without protection, Figure 6.6a) shows that the fiber requirement tends to decrease as the value of M increases. For low values of M, the fiber requirement decreases rapidly. When the value of M becomes larger, the rate of decrease of the fiber requirement is reduced. As shown, flatter curves are observed. Furthermore, for $M \geq 12$, no fiber savings can be seen. Therefore, this scenario demonstrates that the increment of $M \geq 12$ leads to an abrupt increment in the system capacity and, in effect, a rapid drop in the fiber utilization can be seen. The system capacity and the fiber utilization for the NSFNet network with and without protection are presented in Figures 6.6b) and 6.6c), respectively.

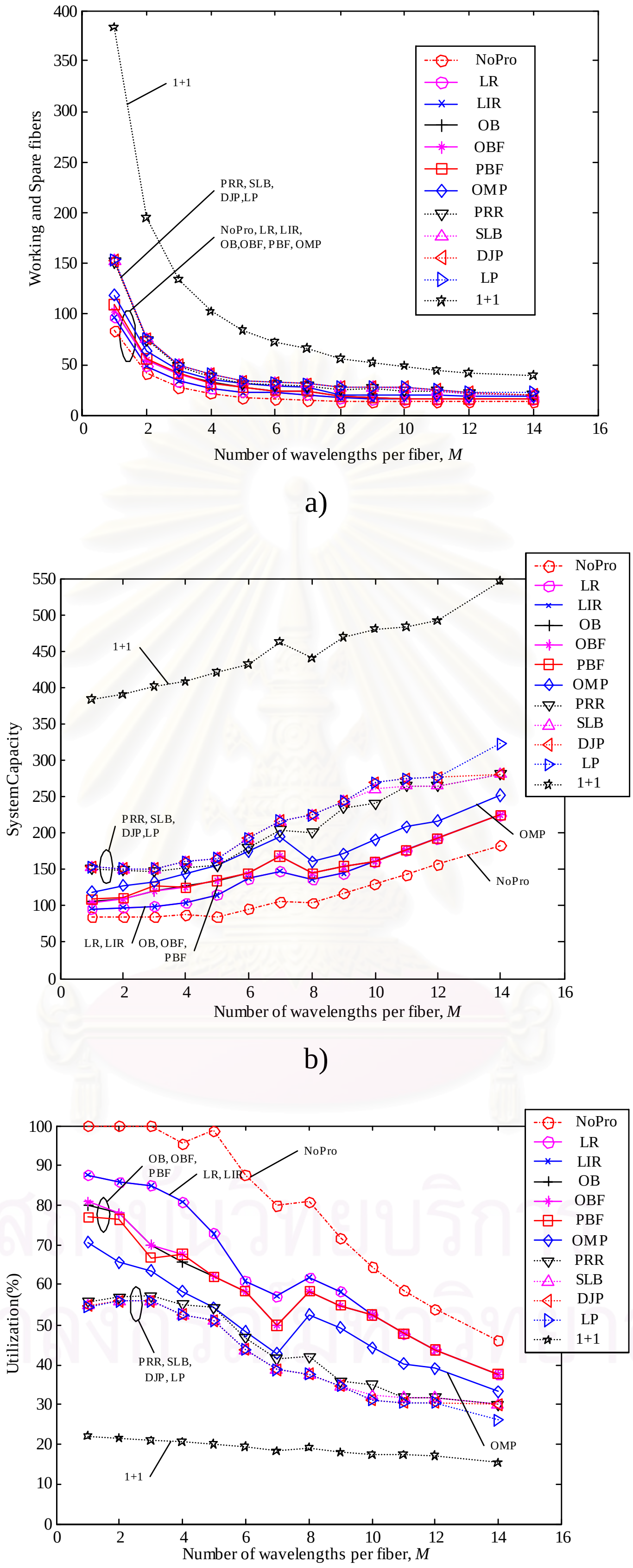


Figure 6.6: Results for the NSFNet network.

Now, consider the results for light-tree protections. Figure 6.6a) shows that among the light-tree protections, 1+1 requires the maximal number of fibers, or on average, 4.15 times the fiber requirement in the case without protection. Note that this observation is consistent with the experiments in section 6.2.1.

Consider the PRR, SLB, DJP, and LP point-to-point protections. The results indicate that PRR, SLB, DJP, and LP always outperform 1+1. This advantage is gained by the sharing of spare wavelength channels on the restoration paths of light-trees. As shown, in the experiments, PRR, SLB, DJP, and LP require less network capacity than 1+1 by about 120%. The benefit of capacity savings of PRR, SLB, DJP, and LP can also be noticed in Figures 6.6b) and 6.6c).

Let us study the capacity differences among the PRR, SLB, DJP, and LP protections. Figure 6.6a) suggests that the NSFNet network seems to require identical network capacity for the PRR, SLB, DJP, and LP protections. The differences among those protections can be observed, but they are comparable. Hence, these results imply that PRR, SLB, DJP, and LP are equal in terms of the fiber requirement. Consequently, to decide which protection is cost-effective, network architects and designers should take other network design factors, such as fault management, into consideration.

Comparing the results between the classes of point-to-point and multicast protections, Figure 6.6a) indicates that for all values of M, the multicast protections always require fewer fibers for single link restoration than the point-to-point protections. This demonstrates that the use of a light-tree as a granularity to make multicast traffic restorable potentially yields better solutions than the use of a lightpath as a granularity for protection. However, Figure 6.6a) also indicates that the results for point-to-point protections can be improved to approach those for multicast protections by increasing the number of wavelengths per fiber.

Now, let us focus on the results of the multicast protection approaches in Figure 6.6a). It is found that the resulting curves of the multicast protections are relatively close, making it difficult to investigate the fiber differences among the multicast protections. Thus, an enlargement of Figure 6.6a) is required and here shown in Figure 6.7.

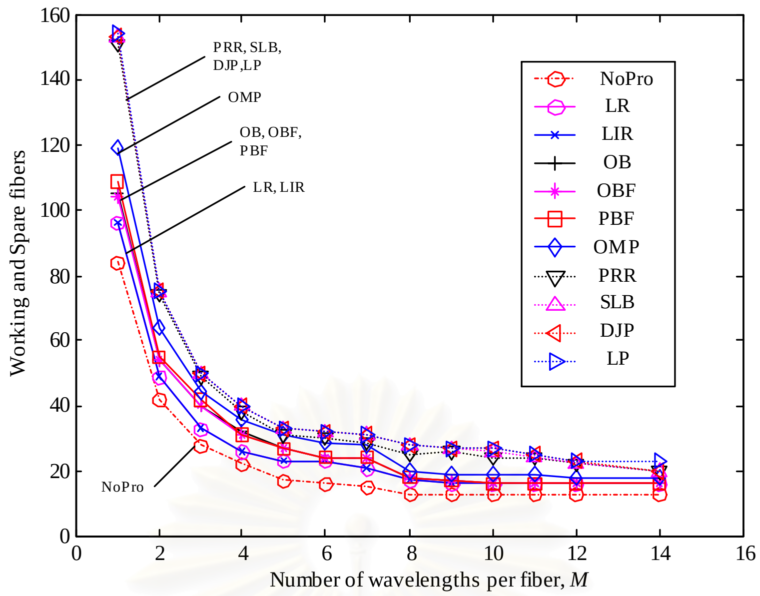


Figure 6.7: Enlarged graph of Figure 6.6a).

The enlarged view shows that the OMP protection always requires the maximum network capacity with respect to other multicast protections. Across the range of *M* values, OMP demands more fibers than the case without protection by 56%. The maximum fiber requirement of the OMP in fact results from the employment of dedicated spare capacity reservation to determine the number of spare fibers. However, with respect to other multicast protections, the extra fibers of the OMP can trade off with a more simplified restoration mechanism.

Next, we investigate the OB, OBF at Br=3, and PBF protections. The results in Figure 6.7 demonstrate that although OB, OBF, and PBF have the different rules to determine the restoration paths for protection, they tend to provide the same design outcomes. Thus, this implies that based on the test network, the OB, OBF, and PBF protections have the same performance in the aspect of fiber requirements.

Now, consider the results for the LR protection. Figure 6.7 shows that LR requires the minimal fiber requirement with respect to other multicast protections. This arises from the great rerouting flexibility of the LR protection. When compared with the case without protection, only 25% extra fibers allow implementation of the LR protection in the test network. However, Figure 6.7 illustrates that the results of LR protection can also be achieved by the LIR protection. This scenario holds true for all values of *M*. Thus, with this observation, we can conclude that the LR and LIR protections perform equally and provide the same fiber cost. However, as discussed in section 6.2.1, we can say that LIR is more attractive than LR. This is because LIR has a much easier restoration mechanism than LR.

Finally, let us examine the fiber differences between OB, OBF, or PBF and LR or LIR. Figure 6.7 shows that there is a gap between these approaches. Thus, these experiments confirm our expectation that the reconfiguration of light-trees after a failure occurs would yield lower network capacity than the use of backup optical braches for restoration. As shown, on average, the capacity difference is 9% between these two approaches. Nevertheless, Figure 6.7 also suggests that the gap between these protections can be decreased. This is done by increasing value of M. As illustrated, when M grows higher, the capacity gap is narrower, and at $M \geq 8$, OB, OBF, or PBF and LR or LIR provide the same network results.

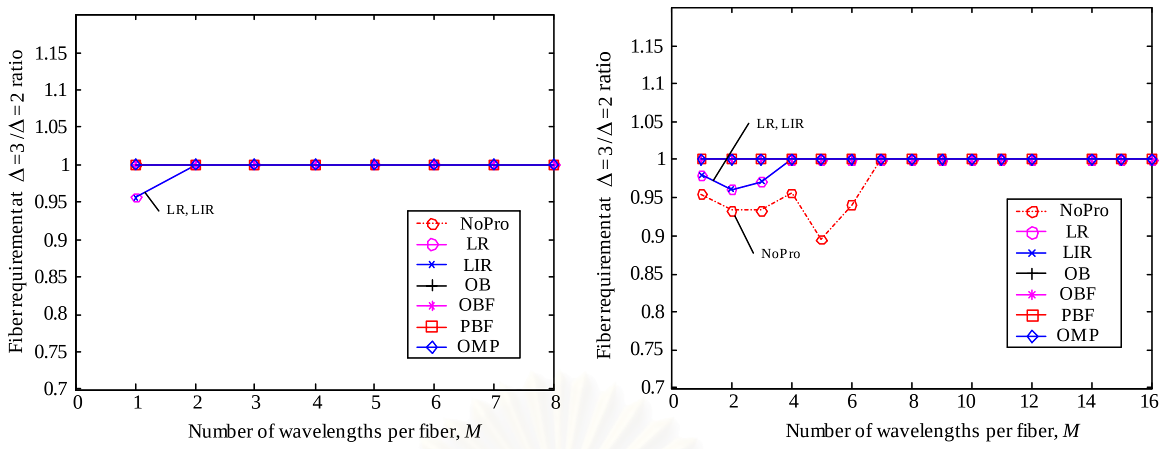
Therefore, to summarize the capacity comparative study with the NSFNet network, it can be concluded that the network capacity required for light-tree protection methods can be ranked as LR=LIR $\leq$ OB=OBF=PBF $\leq$ OMP $\leq$ PRR=SLB=DJP=LP $\leq$ 1+1.

6.2.5 Influence of the Limited Fanout on the Fiber Requirement

As discussed, the limit to replicate and transmit signals of optical power splitters has an impact on the shape of light-trees and also has an impact on fiber requirements of networks. This section will analyze this issue in detail.

First, let us consider the effect of limited fanout in networks with the multicast protection strategies.

Based on the experiments in sections 6.2.1 and 6.2.4, Figures 18a) and 18b) plot the ratio of fiber requirements at $\Delta=3$ and $\Delta=2$ versus the number of wavelengths per fiber for the 8N-14L network with G=3 and the NSFNet network, respectively. Technically, the fanout value at $\Delta=2$ means that networks have to use chain structures instead of light-trees to accommodate multicast traffic, see Figure 4.4 for clarity. Then $\Delta=3$ represents the initial value of optical splitters in employing light-trees to support multicast traffic.



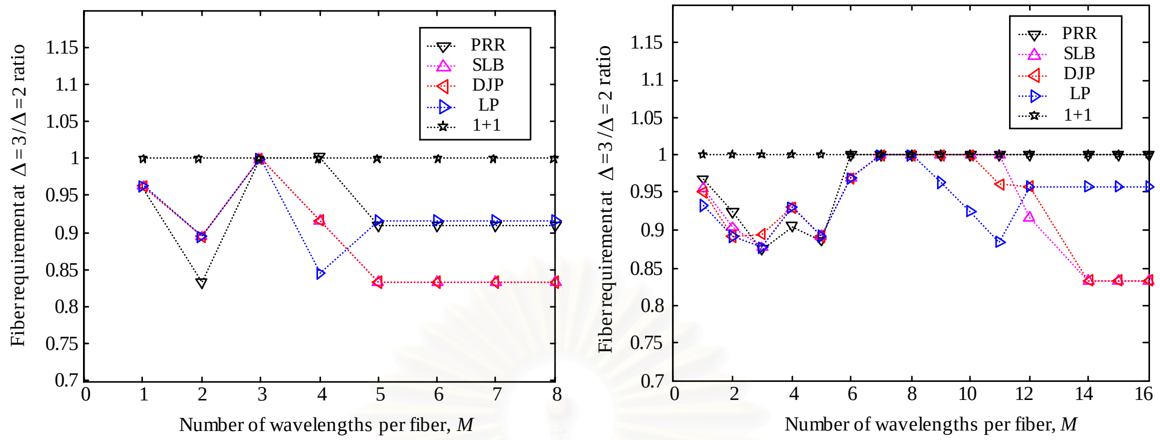
a) 8N-14L network with *G*=3 b) NSFNet network

Figure 6.8: Ratios of fiber requirements at Δ=3 and Δ=2 versus *M* for the cases of multicast protections.

Consider the resulting ratios in Figures 18a) and 18b). They demonstrate that the two test networks have a similar scenario in association with the increment in the fanout value. As shown, among the multicast protections, only the LR and LIR protections are able to use the fanout increment to reduce the network capacity. However, the benefit in fiber reduction is considered restricted and occurs only in cases of low *M*. As shown, in both test networks with the LR or LIR protections, as much as 5% fiber savings can be achieved by increasing the fanout value. This percentage is considered insubstantial. In addition, Figures 18a) and 18b) show that no improvements in network capacity are observed when $M \geq 2$ and $M \geq 4$ for the 8N-14L and NSFNet networks, respectively. Therefore, from the experiments we can conclude that, for multicast protection approaches, the increase of fanout does not significantly improve the fiber reduction.

Now, let us investigate the fiber requirement ratios in the cases of point-to-point protections. Figures 19a) and 19b) demonstrate that excluding the 1+1 protection, the change in the fanout value has a significant influence on the fiber requirements for the point-to-point protections. For example, in Figure 6.9a), when Δ increases from 2 to 3, 17% fiber reduction is possible for the PRR, SLB, and DJP protections. This percentage is considered large. Note that 17% fiber reduction for point-to-point protections is also observed in Figure 6.9b) of the NSFNet network.

Therefore, based on the test networks, we can summarize that while the increment in the fanout from 2 to 3 is not useful to reduce the fibers required for the cases of the multicast protections, this increment will be more attractive in the cases of point-to-point protections.



a) 8N-14L network with *G*=3 b) NSFNet network

Figure 6.9: Ratios of fiber requirements at $\Delta=3$ and $\Delta=2$ versus *M* for the cases of point-to-point protections.

Further increasing fanout values, *i.e.*, $\Delta \geq 4$, were studied with both 8N-14L and NSFNet networks. In the experiments, we found that the fiber requirements for $\Delta \geq 4$ are identical to those for $\Delta = 3$ for all cases of light-tree protections and also for all values of *M*. Hence, this implies that increasing the fanout to more than 3 cannot decrease the network capacity for implementing the restorable optical networks. Here, it is worth noting that this scenario is also found for other test networks.

6.2.6 Influence of the Br design parameter on the Fiber Requirement

In the OBF multicast protection strategy, the number of backup braches (Br) assigned to light-trees is a main design parameter in determination of the network capacity against link failure. In this section, we shall study the effect of the Br value on the fiber requirement.

From the experiment in section 6.2.1, Table 6.10 shows the number of fibers needed for the OBF protection as a functions of Br and Δ values for the 10N-21L network with *G*=4.

Table 6.10: Number of fibers for the OBF protection versus the values of Br and Δ for the 10N-21L network with G=4.

a) M=1

Br \ Δ	2	3	Unlimited
1	25	25	25
2	23	23	23
3	23	23	23
Unlimited (OB)	23	23	23

b) M=2

Br \ Δ	2	3	Unlimited
1	14	14	14
2	14	14	14
3	14	14	14
Unlimited (OB)	14	14	14

c) M=3

Br \ Δ	2	3	Unlimited
1	13	13	13
2	13	13	13
3	13	13	13
Unlimited (OB)	13	13	13

For the case of M=1, Table 6.10a) indicates that the number of fibers required for the OBF protection is not a function of the fanout value. As shown, while fixing a Br value, the fiber requirement is not changed as the fanout value increases.

Now, consider the effect of the Br value. Table 6.10a) suggests that fiber reduction can be realized when the value of Br is increased from 1 to 2. This increment can save fibers by about 9%, which is rather high. This corresponds to our expectation that the greater the value of Br, the more the choices to select backup optical branches for restoration, thereby leading to the reduction in the number of fibers. However, as illustrated, the advantage in reducing the fibers is considered limited. This is because no fiber savings can be seen for Br$\geq$2.

Next, let us investigate the results when the value of M increases from 1 to 2 and 3 in Tables 6.10b) and 6.10c). It is found that at each analyzed M, every combination of Br and Δ values given to the OBF protection provides identical results. As shown, the total numbers of fibers are 14 and 13 fibers for M=2 and 3, respectively. Hence, these results imply that the growth in the M value can efficiently decrease the influence of the Br value on the fiber requirement. Note that for $M\geq 4$, this scenario is also observed.

To further study the effect of the Br value with larger networks, the numerical results for the NSFNet network are reported in Table 6.11.

For the NSFNet network with M=1, Table 6.11a) indicates that like the results in Table 6.10a), the fanout value does not influence the fiber requirement. However, a scenario of fiber reduction can be seen in the case of an increasing Br value. As shown in

Table 6.11a), 11% fiber savings occur when increasing the Br value from 1 to 2. In addition, at Br=3, we still found further fiber reduction with respect to the results for Br=2. However, as we expected, the percentage of fiber savings at Br=3 diminishes with respect to that at Br=2. Finally at Br=4, no fiber reduction can be seen and the results at these points are identical to those of the OB protection.

Table 6.11: Number of fibers for the OBF protection versus the values of Br and Δ for the NSFNet network.

a) *M*=1

Br \ Δ	2	3	4	Unlimited
1	116	116	116	116
2	105	105	105	105
3	104	104	104	104
4	104	104	104	104
Unlimited (OB)	104	104	104	104

b) *M*=2

Br \ Δ	2	3	4	Unlimited
1	65	65	65	65
2	54	54	54	54
3	54	54	54	54
4	54	54	54	54
Unlimited (OB)	54	54	54	54

c) *M*=3

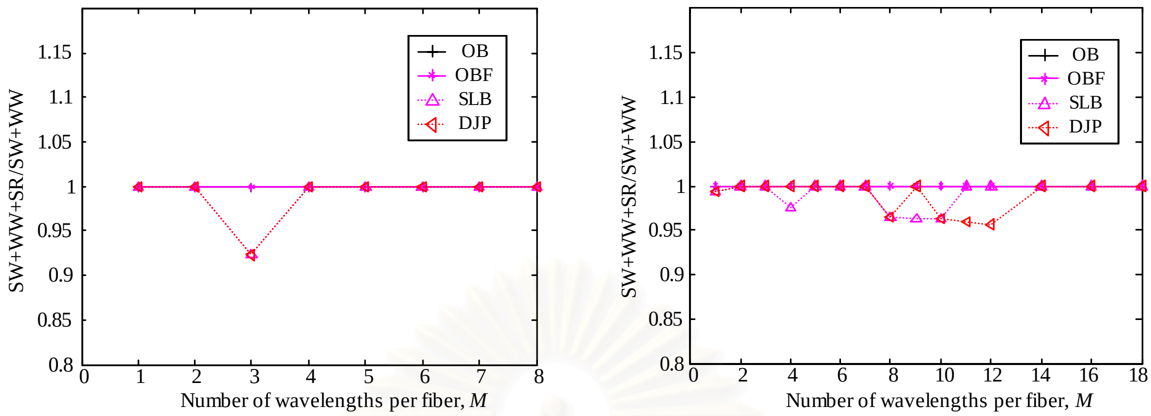
Br \ Δ	2	3	4	Unlimited
1	45	45	45	45
2	40	40	40	40
3	40	40	40	40
4	40	40	40	40
Unlimited (OB)	40	40	40	40

When the value of *M* is increased to 2 and 3, we also found the same scenario as in the case of *M*=1; namely, an increase in the Br value leads to fiber savings. However, unlike the case of *M*=1, Tables 6.11b) and 6.11c) point out that for higher wavelength multiplexing, the results of the OBF protection will converge to the results of OB more quickly. As illustrated, only at the small value of Br=2 are the fiber requirements of OBF and OB identical.

Therefore, analyzing the results for the two test networks, we can summarize that the Br design parameter can reduce the network capacity required for the OBF protection. When the value of Br is increased, the network capacity of OBF will be decreased and also approach closer to that of OB. Moreover, with a large value of *M*, only a small value of Br can yield results for OBF identical to those for OB.

6.2.7 Study of Spare Capacity Placement Techniques

As discussed, one of the main factors that should be considered in implementing resilient multicast WDM networks is the technique to place and use spare capacity. In this section, we shall analyze the spare capacity placement techniques as proposed in chapter 4. Let us first study the SW+WW+SR and SW+WW techniques.



a) 8N-14L network with G=3 b) NSFNet network

Figure 6.10: Ratios of fiber requirements between the SW+WW+SR and SW+WW spare capacity placement techniques.

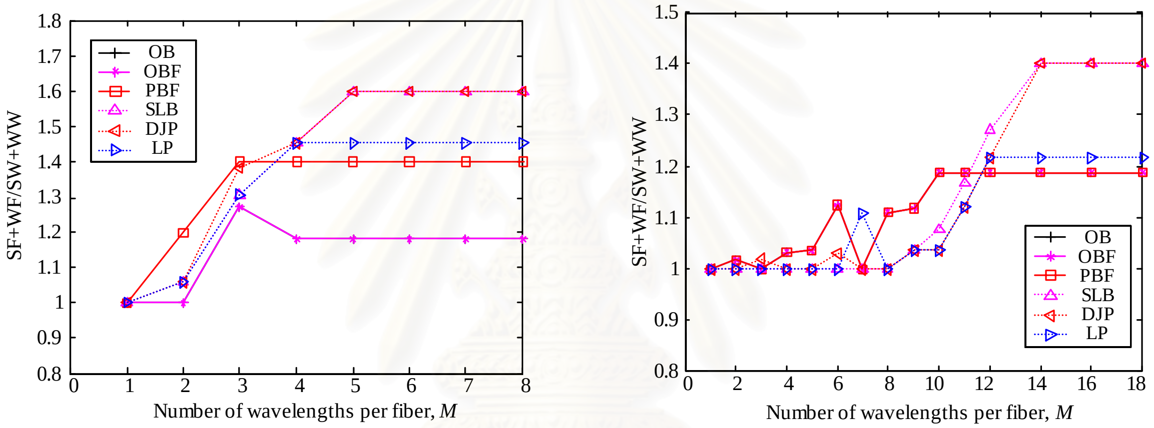
Using the experimental methodology as in the previous section, Figures 6.10a) and 6.10b) plot the SW+WW+SR to SW+WW fiber requirement ratio versus the number of wavelengths per fiber for the 8N-14L network with G=3 and the NSFNet network, respectively.

Considering the resulting ratios in Figure 6.10a), we found that there is a point that the use of SW+WW+SR can reduce the total fiber requirement with respect to the use of SW+WW. As shown, 8% fiber reduction at M=3 can be seen, but this reduction occurs only with the SLB and DJP approaches. Moreover, Figure 6.10a) illustrates that the benefit of using SW+WW+SR instead of SW+WW cannot be observed for $M \geq 4$.

Likewise, Figure 6.10b) shows that the NSFNet network operating only with the SLB or DJP protection can take advantage of SW+WW+SR over SW+WW to reduce the network capacity. As much as 5% fiber savings can be achieved. In addition, the resulting ratios indicate that the advantage of deploying SW+WW+SR over SW+WW exists for some values of M. For $M \geq 14$, the experiments demonstrate that the results of SW+WW+SR and SW+WW are all identical. Hence, SW+WW+SR and SW+WW at these points have a same performance.

Therefore, based on these results, it can be summarized that the SW+WW+SR technique can be used to decrease the fiber requirement with respect to the SW+WW technique. Consequently, the stub release option in SW+WW+SR is useful to reduce the fiber requirement. However, the advantage of SW+WW+SR over SW+WW is rather limited. Whether this advantage is considered cost-effective depends on the value of M and the protection approach that the network employs. Inclusively, one should take the complexity of the restoration signaling system into account. This is because as discussed earlier the restoration signaling system of SW+WW+SR is inherently more intricate than that of SW+WW.

Next, let us compare the results of the SF+WF and SW+WW spare fiber placement techniques. Figure 6.11 plots the SF+WF to SW+WW fiber requirement ratio versus the number of wavelengths per fiber.



a) 8N-14L network with *G*=3 b) NSFNet network

Figure 6.11: Ratios of fiber requirements between the SF+WF and SW+WW spare capacity placement techniques.

For the 8N-14L network with *G*=3, Figure 6.11a) illustrates that with the SF+WF technique, the network requires more network capacity for single link restoration than the SW+WW technique. In addition, with respect to SW+WW, the SF+WF technique tends to requires more fibers as the value of M increases. As shown, for $M \geq 4$, more than 10% extra fibers are needed for SF+WF for all cases of protection methods. In particular, as much as 60% extra fibers are possible for the SLB and DJP protections.

Compared with the results of SW+WW, the extra fibers of SF+WF arise from the fact that a network with SF+WF must allocate spare fibers separately from working fibers and cannot deploy the remaining capacity of the working fibers for restoration as in SW+WW.

Let us now investigate the results for the NSFNet network. Like Figure 6.11a), Figure 6.11b) demonstrates that SF+WF requires more network capacity than SW+WW and the additional fibers for SF+WF have a trend to increase with the value of *M*.

Therefore, based on the results of two test networks, we can conclude that the SF+WF technique typically requires extra network capacity when compared with SW+WW, thus resulting in a higher fiber cost. However, this extra capacity cost for SF+WF leads to simplifying a restoration switching process and a signaling system with respect to those of SW+WW counterpart.

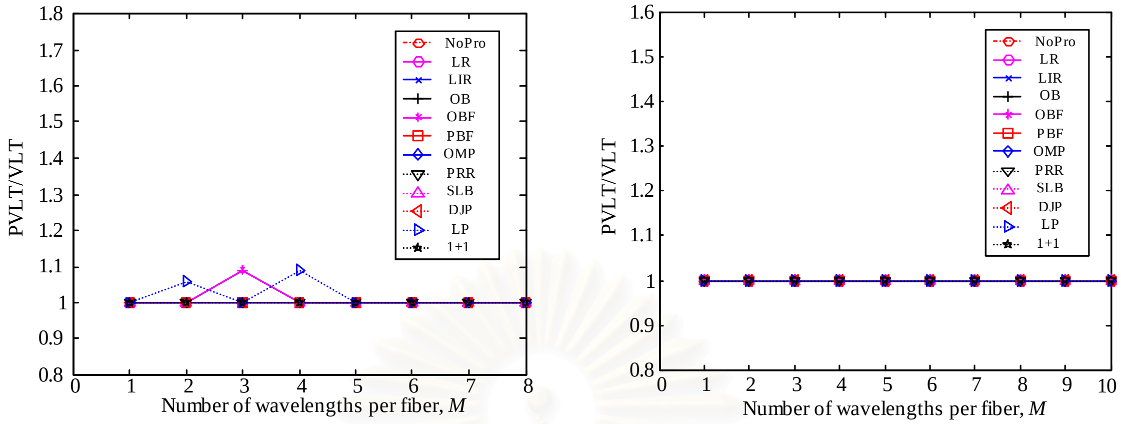
To summarize all the discussion of SW+WW+SR, SW+WW and SF+WF, we can conclude that in terms of the network capacity, we can rank the spare fiber placement techniques in ascending order as SW+WW+SR $\leq$ SW+WW $\leq$ SF+WF. However, in terms of the restoration management complexity, the order is opposite as SW+WW+SR $\geq$ SW+WW $\geq$ SF+WF.

6.2.8 Study of Wavelength Assignment Approaches

One of the main factors that we should examine in designing WDM networks is the wavelength assignment techniques. In this section, the wavelength assignment techniques for restorable light-trees, namely, VLT, PVLT, and LT, are investigated.

Figures 6.12a) and 6.12b) show the ratios of fiber requirements between the PVLT and VLT techniques for the 8N-14L network with *G*=3 and the 10N-21L network with *G*=4, respectively.

First, consider the resulting ratios for the 8N-14L network with *G*=3. Figure 6.12a) demonstrates that the PVLT/VLT fiber requirement ratios are greater than or equal to one for all values of *M*. This implies that the PVLT system typically uses more fibers than the VLT system. This is because for PVLT, the wavelengths assigned to light-trees are more restrictive in comparison with VLT. Namely, for PVLT, each optical branch of a light-tree is permitted to occupy only one wavelength for transmission. However, the increment in the number of fibers for the PVLT system with respect to VLT is rather limited. This is because only three points in Figure 6.12a) show that the fiber requirement of PVLT is greater than that of VLT. Moreover, Figure 6.12a) suggests that no capacity differences between PVLT and LT can be observed for $M \geq 5$.



a) 8N-14L network with *G*=3 b) 10N-21L network with *G*=4

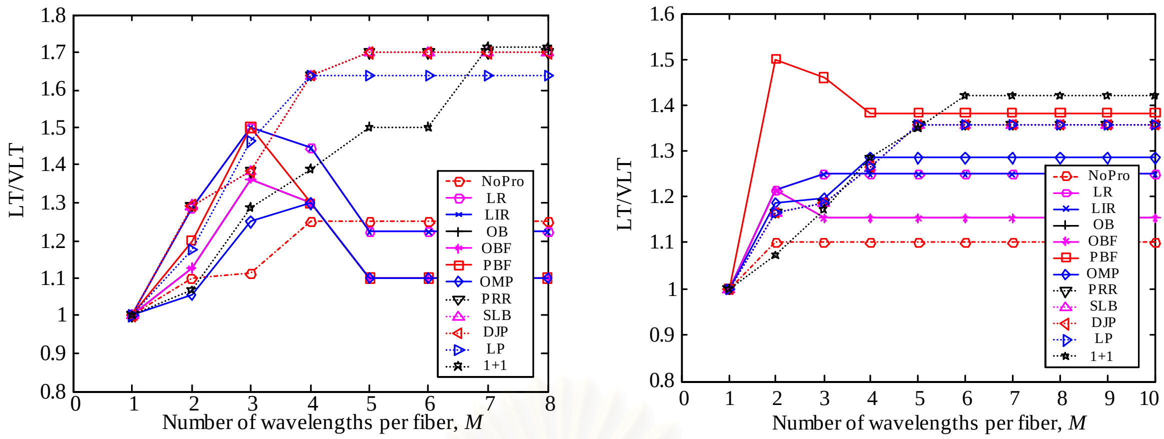
Figure 6.12: Ratios of fiber requirements between the PVLT and VLT wavelength assignment approaches.

Next, consider the results for the 10N-21L network with *G*=4. Figure 6.12b) shows that the results of PVLT and VLT are identical for all cases of protection and all values of *M*. This means that the capacity requirement of VLT can be achieved by PVLT, although PVLT is more limited in terms of wavelength assignments than VLT.

Therefore, based on the experiments, it can be concluded that if the value of *M* is selected properly, the network can use PVLT instead of VLT without increasing the network capacity. The experiments also suggest that the selection of *M* can be relaxed when employing a high value of *M*. It is worth noting that this result is very relevant to WDM network design because PVLT typically requires fewer wavelength converters than VLT, so that switching node cost savings can be realized.

To study the LT wavelength assignment system, Figure 6.13 shows the ratios of fiber requirements between the LT and VLT systems.

For the 8N-14L network with *G*=3, Figure 6.13a) demonstrates that except for *M*=1, deploying the LT system in the network leads to an increase in network capacity with respect to deploying the VLT system. As illustrated, the extra capacity needed for LT is in the range of 10%-70% and also depends on the light-tree protection approach that the network is employing.



a) 8N-14L network with *G*=3   b) 10N-21L network with *G*=4

Figure 6.13: Ratios of fiber requirements between the LT and VLT wavelength assignment approaches.

Consider the resulting ratios for the 10N-21L network with *G*=4 in Figure 6.13b). They again indicate that the network capacity for LT is generally higher than that for VLT. It is also observed that in comparison with VLT, the additional capacity required for LT will be constant for *M* beyond 6. As shown, for $M \geq 6$, 10%-43% extra fibers are needed for LT, depending on the light-tree protection scheme.

Based on the two test networks, these relatively high percentages of extra fibers arising in the LT system are due to the fact that this system assigns only a single wavelength to a light-tree and uses this wavelength under both normal and failure conditions, in contrast with VLT. Hence, the capability to reuse the spare capacity of LT is restricted and less than that of VLT. Accordingly, it is inherent that LT needs more total network capacity than VLT.

In summary, for three wavelength assignment techniques, we can rank the fiber requirement in ascending order as VLT≤PVLT≤LT. However, as discussed in chapter 4, in terms of the number of wavelength converters needed for allocating wavelengths, the order is opposite: LT≤PVLT≤VLT.

Chapter 7

ILP-based Heuristic Algorithm for Multicast WDM Network Design

7.1 Introduction

In the preceding chapter, we have concluded that when protection systems are provided to optical networks, the ILP mathematical formulations used to determine fiber requirements are suitable only for relatively small networks. This is due to the fact that these network design problems are NP-hard; hence the computational time to obtain an optimal solution, even for small networks is expensive.

To extend the analysis to large practical networks, other approaches should be implemented to achieve this aim. In this chapter, we propose a heuristic solution procedure based on the proposed ILP formulations for computing fiber requirements of multicast mesh WDM networks.

The rest of the chapter is organized as follows. In section 7.2, a heuristic algorithm to obtain fiber requirements for large scale networks is proposed in detail. In section 7.3, the presented algorithm is tested with all studied protection approaches to assess the quality of its solutions. To validate the presented algorithm, both small- and large-sized WDM networks are employed. Finally, section 7.4 provides the conclusions as found in this chapter.

7.2 ILP-based Heuristic Procedure

As commonly known, the reason why NP-hard problems are computationally expensive arises from their very high computational complexity not only in terms of the number of constraints but also in terms of the number of unknown variables. In particular, when problems grow larger, the problem complexity will increase exponentially. In order to solve large size NP-hard problems, it is thus imperative to decrease their complexity. One of the possible methods to achieve this is to decompose a NP-hard problem into a sequence of smaller problems [99]. By dividing the problem into a set of small problems, the calculation of each small problem implies making the decision of one part of the whole problem. The heuristic procedure presented here also lies in this scheme. The following is the detail of the heuristic procedure.

Given a set of multicast demands, the heuristic solution procedure that we introduce starts by solving a ILP program of a small network problem of a multicast demand and then we attempt to determine the solution successively for all other multicast demands. To keep the problem complexity at a reasonable level, the heuristic procedure adds the variables and constraints for each multicast demand into the ILP program in each iteration. The network solution for that multicast demand is then kept and fixed in during of all subsequent iterations. At the termination, the heuristic procedure gives a solution of the entire network problem.

Let denote the ILP program generated at iteration t. The formal description of the heuristic procedure is provided as follows and its flow chart is illustrated in Figure 7.1.

- STEP 1: Choose a light-tree protection approach and a wavelength allocation technique that are needed to provide to a WDM network.
- STEP 2: According to the selected light-tree protection approach, let t equal to 1 and P_t be the ILP program that is generated with a multicast demand of a given set of multicast demands of the network. Then, solve P_t.
- STEP 3: Store the solution of P_t, *i.e.*, the resulting values of all routing and wavelength variables.

- STEP 4: Select a certain multicast demand r_k from the multicast demand set that we have not considered so far.
- STEP 5: For multicast demand r_k, add the ILP constraints and variables corresponding to the multicast r_k to P_t. Moreover, fix the solution stored from Step 3 in P_t. Then, solve P_t.
- STEP 6: If all multicast demands were already considered, terminate. The current solution of P_t is the solution of entire network problem. Otherwise, set t=t+1 and go to Step 3.

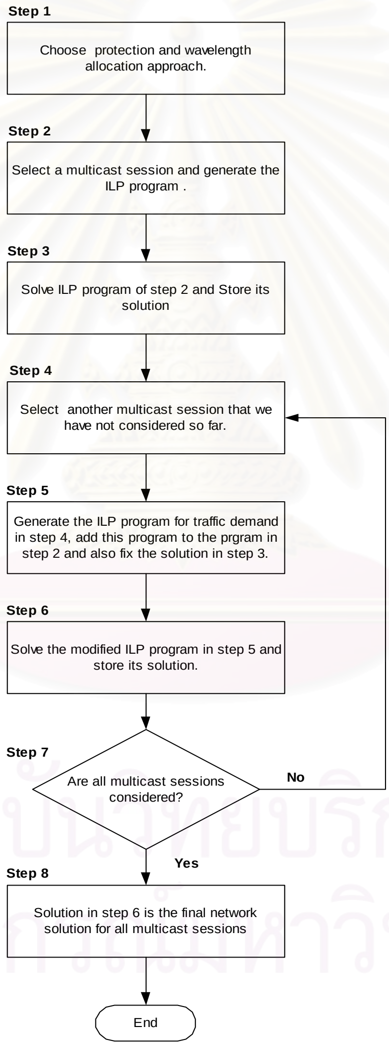


Figure 7.1: Flow chart of the proposed heuristic algorithm.

As presented, we can see that this heuristic procedure can be applied not only optical networks with protection but also optical networks without protection. To clearly understand the proposed heuristic solution procedure, an instance of using this procedure is given as below.

Given a considered network and its set of multicast demands, from step 1 of the heuristic procedure if we select the LR protection and LT wavelength allocation for the network, then the heuristic procedure can perform.

- STEP 1: Choose the LR protection and LT wavelength allocation for the network.
- STEP 2: Set t=1 and select a multicast session from the set of multicast demands. Then, let P_t denote the ILP program that is generated corresponding to a selected multicast demand. Namely, P_t consists of the objective function (24) and constraints (2.2)-(2.5) and (5.20)-(5.30). Then, solve P_t.
- STEP 3: Store the resulting values of variables , and of P_t.
- STEP 4: Select another multicast demands that we have not considered.
- STEP 5: From step 4, add variables and constraints (2.2)-(2.5) and (5.20)-(5.30) of the multicast demand selected at step 4 to P_t. Then, fix the resulting value of variables that we stored in step 3 in P_t. Again, solve P_t.
- STEP 6: If every multicast session in the set of traffic demands was completely considered, terminate and the current solution at step 5 is the solution of the network problem. Otherwise, set t=t+1 and go to step 3. Note that if there are 5 multicast demands in the network, the situation of going back to step 3 of the heuristic procedure totally occurs 4 times.

With the employment of the heuristic algorithm, one important issue that should be addressed is a technique to select a traffic demand in step 2. This is because different selection techniques result in different sequences of sub-problems to be solved; thus it would lead to different network solutions. In this thesis, two criteria to select a traffic demand are proposed and analyzed. The lowest network result obtained from these two criteria is the final design outcome of network problem. The two traffic selection criteria are:

1. Ascending selection criterion (Asc): among multicast demands that have not been considered in the algorithm, the multicast traffic demand with the smallest number of destinations or the group size is first selected to be solved.

2. Descending selection criterion (Desc): as apposed to the ascending selection criterion, in this criterion the multicast traffic demand with the largest group size is subject to solve its solutions first.

Note that for above two criteria, if there is more than one multicast session having the same group size, the uniform random selection is applied to the heuristic procedure for selecting a single multicast session to be taken into account.

7.3 Results and Discussion

In order to assess the performance of the proposed heuristic procedure, small and large size networks are introduced. For the former subsection, an analysis with small size networks is provided and the discussion with large size networks is then addressed in the latter subsection.

7.3.1 Small Scale Optical Networks

With the parameter setting in section 6.2.1 of chapter 6, Tables 7.1 and 7.2 presents numerical design outcomes for the 8N-14L network with G=3 and 10N-14L network with G= 4, respectively. In each table, the first column displays the number of wavelengths multiplexed per fiber (M). The second and third columns show fiber requirements that are optimally calculated from the ILP programs of network problems A and B, respectively. For the last column, it represents the fiber requirements obtained from the proposed heuristic approach. Due to the identical group size of all multicast sessions given to both experimental networks, the results of the heuristic approach as shown here are considered from three traffic demand sequences with random selection manner.

Table 7.1: Numerical design outcomes for 8N-14L network with *G*=3.

No Protection			
M	A	B	Heu
1	16	16	16
2	10	10	11
3	9	9	10
4	8	8	9

LR			
M	A	B	Heu
1	22	22	24
2	13	14	15
3	10	11	12
4	9	10	11
5	9	10	11

LIR			
M	A	B	Heu
1	22	22	24
2	13	14	15
3	10	11	12
4	9	10	11
5	9	10	11

OB			
M	A	B	Heu
1	24	25	25
2	13	16	15
3	10	11	12
4	9	10	11
6	9	10	11

OBF(Br=2)			
M	A	B	Heu
1	24	25	25
2	13	16	15
3	10	11	12
4	9	10	11
6	9	10	11

PBF			
M	A	B	Heu
1	24	24	25
2	14	15	15
3	10	10	13
4	9	10	11
6	9	10	11

OMP			
M	A	B	Heu
1	29	29	29
2	16	18	17
3	12	12	13
4	10	10	11
6	10	10	11

Table 7.1(continued): Numerical design outcomes for 8N-14L network with G=3.

PRR			
M	**A**	**B**	**Heu**
1	26	26	28
2	14	**15**	**16**
3	11	**12**	**12**
4	10	**11**	**12**
6	**10**	**10**	**11**

SLB			
M	**A**	**B**	**Heu**
1	26	27	29
2	14	**17**	**17**
3	11	**13**	**13**
4	10	**11**	**12**
6	**10**	**10**	**11**

DJP			
M	**A**	**B**	**Heu**
1	26	27	29
2	14	**17**	**17**
3	11	**13**	**13**
4	10	**11**	**12**
6	**10**	**10**	**11**

LP			
M	**A**	**B**	**Heu**
1	26	27	29
2	14	**17**	**17**
3	11	**13**	**13**
4	10	**11**	**12**
6	**10**	**11**	**11**

1+1			
M	**A**	**B**	**Heu**
1	**49**	**49**	**49**
2	**27**	30	**28**
3	**20**	**21**	**21**
4	**16**	18	**16**
6	13	**16**	**15**

Table 7.2: Numerical design outcomes for 10N-21L network with *G*=4.

No Protection			
M	A	B	Heu
1	16	16	16
2	10	10	10
3	10	10	10
4	10	10	10

LR			
M	A	B	Heu
1	20	21	22
2	13	14	15
3	12	12	13
4	12	12	13
6	12	12	12

LIR			
M	A	B	Heu
1	20	21	22
2	13	14	15
3	12	12	13
4	12	12	13
6	12	12	12

OB			
M	A	B	Heu
1	21	23	23
2	13	14	15
3	12	13	14
4	12	13	13
6	12	13	13

OBF(Br=2)			
M	A	B	Heu
1	21	23	23
2	13	14	15
3	12	13	14
4	12	13	13
6	12	13	13

PBF			
M	A	B	Heu
1	24	24	26
2	14	14	26
3	13	13	15
4	13	13	25
6	13	13	14

OMP			
M	A	B	Heu
1	27	29	28
2	15	16	18
3	14	15	15
4	13	14	14
6	13	14	14

Table 7.2(continued): Numerical design outcomes for 10N-21L network with G=4.

PRR			
M	**A**	**B**	**Heu**
1	26	28	30
2	**16**	**17**	**17**
3	14	**16**	**16**
4	14	**15**	**16**
6	**14**	**15**	**15**

SLB			
M	**A**	**B**	**Heu**
1	27	**30**	**30**
2	16	**18**	**18**
3	14	**16**	**16**
4	14	**15**	**16**
6	**14**	**14**	**15**

DJP			
M	**A**	**B**	**Heu**
1	27	**30**	**30**
2	16	**18**	**19**
3	14	**16**	**16**
4	14	**15**	**16**
6	**14**	**14**	**15**

LP			
M	**A**	**B**	**Heu**
1	27	**30**	**30**
2	16	**18**	**18**
3	14	**16**	**16**
4	14	**15**	**16**
6	**14**	**14**	**15**

1+1			
M	**A**	**B**	**Heu**
1	**48**	**48**	**48**
2	**25**	28	**25**
3	**20**	**22**	**21**
4	**17**	21	**18**
6	**17**	19	**17**

Consider the design outcomes in Tables 7.1 and 7.2. To ease of consideration, we have bolded the results, where the difference between those results obtained from the heuristic algorithm and network problem A, or network problem B is always less than one.

Examining the results for both experimental networks, we found that in case without protection, the proposed heuristic algorithm provides solutions with the good quality. Namely, the results obtained from the heuristic algorithm are near with the optimal results for both network problems A and B. As shown in Tables 7.1 and 7.2, for all cases of *M* value, the results are all bolded. Therefore, for the test networks we can summarize that the heuristic algorithm potentially yields good design outcomes for the case without protection.

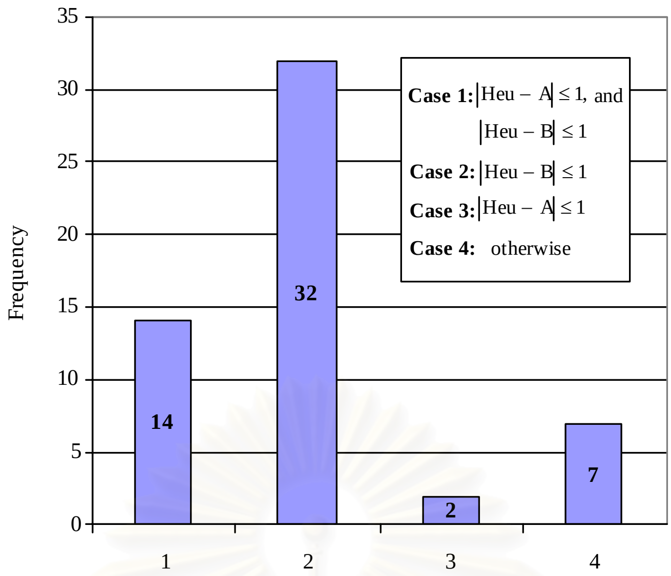
Now, let us investigate the case with protection. The results in Tables 7.1 and 7.2 demonstrate that with the studied protection techniques, the heuristic algorithm typically performs well. In particular, with respect to the results for network problem B, they are, in most experiment cases, close to the results of the heuristic procedure.

To confirm this observation, statistical values obtained from Tables 7.1 and 7.2 are summarized in Figure 7.2.

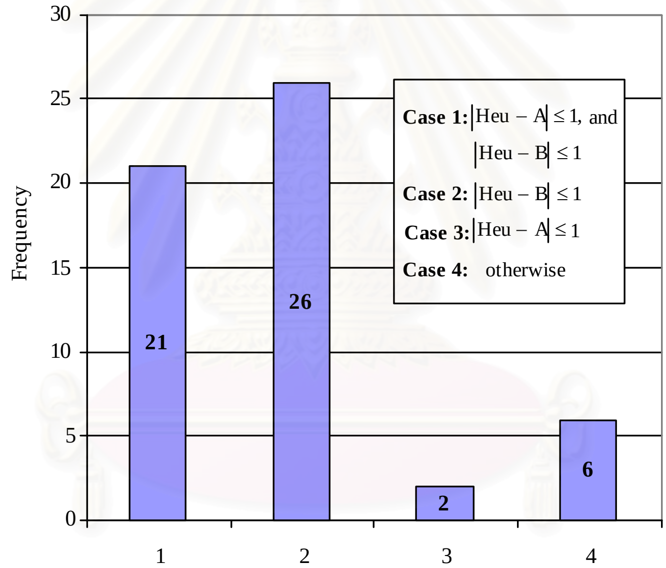
As illustrated in Figure 7.2, for both test networks, the highest frequency occurs in case 2, where the difference between the results of heuristic procedure and of network problem B is less than one. This corresponds to the observation in the previous paragraph.

Furthermore, the statistic in Figure 7.2 illustrate that there are only 7 from 55 and 8 from 55 experimental cases of the 8N-14L and 10N-21L, respectively, which the heuristic algorithm can not lead to near optimal solutions for network problem A or B.

Therefore, with this investigation, we can conclude that, based on test networks, the heuristic algorithm is in general good to estimate optimal network solutions when the studied protection method is provided into networks.



a) 8N-14L network with *G*=3.



b) 10N-21L network with *G*=4.

Figure 7.2: Statistical values summarized from Tables 7.1 and 7.2. The symbol of means the absolute of *x*-*y*.

7.3.2 Large Scale Optical Networks

To extend a conclusion of the heuristic algorithm performance, we test our heuristic algorithm with more practical networks. In the experiments, two optical network infrastructures are employed, *i.e.*, the UK network (UKNet) [41] and Sprint US continental IP backbone (Sprint USNet) [100]. The UKNet has 21 nodes and 39 links and the Sprint USNet has 36 nodes and 55 links. The physical topologies of both test networks are illustrated in Figures 7.3 and 7.4. For setting network experiments, it is shown in Table 7.3.

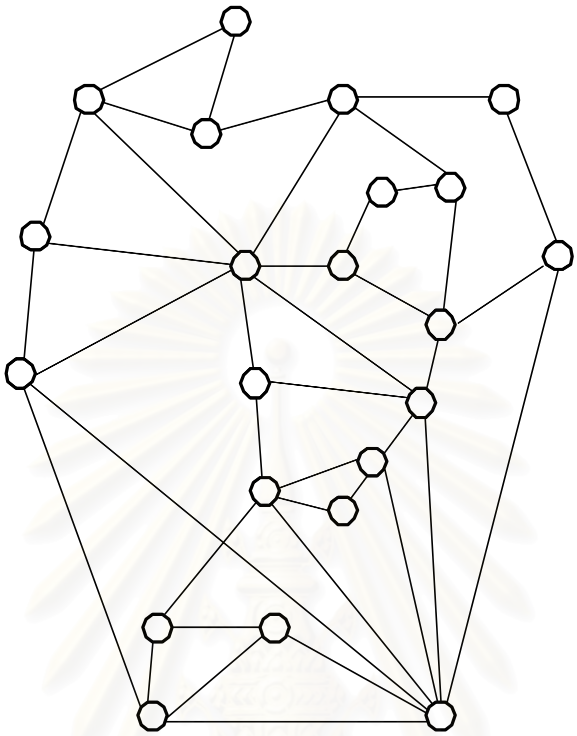


Figure 7.3: UKNet physical topology.

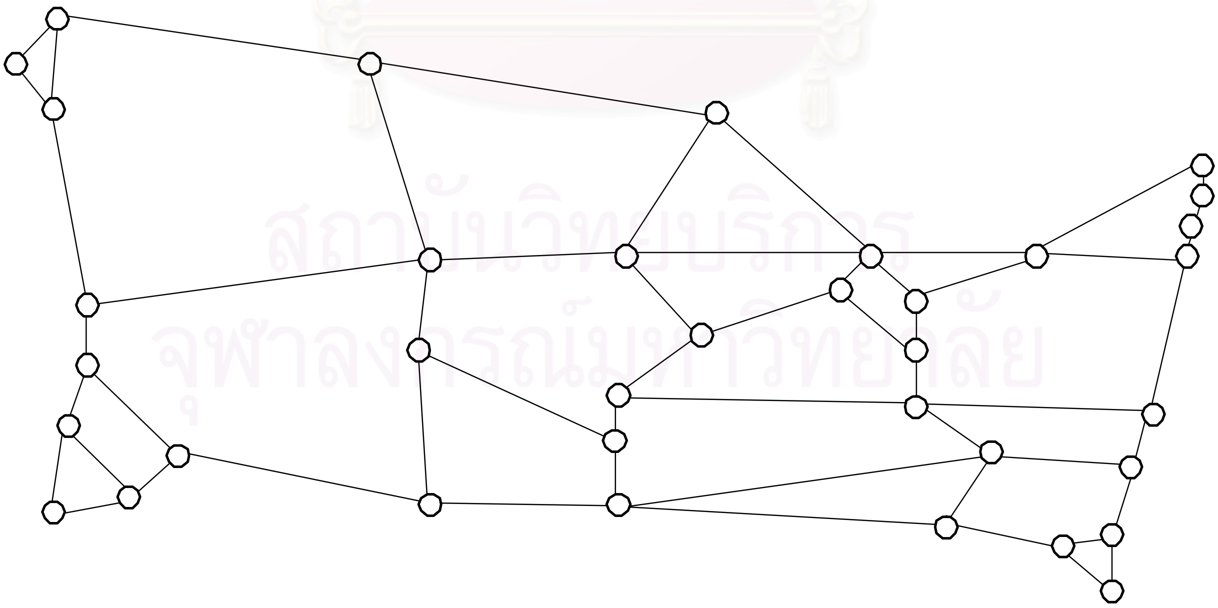


Figure 7.4: Sprint USNet physical topology.

Table 7.3: Experimental network setting.

Network	No. of nodes (*N*)	No. of links (*L*)	Avg. nodal degree	No.of candiate restoration routes per node pair	Total number of candidate rings (*Q*)	Total amount of multicast demands	Value of fanout (Δ)
UKNet	21	39	3.71	3	200	16	3
Sprint USNet	36	55	3.05	3	300	13	3

After employing the ILP models and the heuristic algorithm, Tables 7.4 and 7.5 presents the system capacity requirements of UKNet and Sprint USNet, respectively.

For each studied protection approach, Asc and Desc columns show the system capacity requirements obtained from the heuristic algorithm with the ascending and descending traffic selection criteria, respectively. The Heu column displays the lowest system capacity obtained from the results in Asc and Desc columns. For the next column, the relative gap in percent between the best bounds and the results in the Heu column are presented. Note that the best bound values are determined by using ILP models which are solved by CPLEX and each best bound value is recorded when CPLEX already solved the ILP model for one day. The next two columns show the minimum and maximum time consumed in one iteration of the heuristic algorithm. The last column presents the total computational time required by the heuristic algorithm.

Table 7.4: Numerical design outcomes for the UKNet.

UKNet Backbone								
Protection Strategy	System Capacity							
	Best Bound	Asc.	Desc.	Heu	Gap (%)	t_{min}	t_{max}	t_{tot}
NoPro	112	112	112	112	0	0.01s	0.02s	0.40s
LR	143	150	151	150	4.90	0.05s	4h29m41s	9h42m25s
LIR	143	150	153	150	4.90	0.03s	23h42m40s	52h53m32s
OB	143	152	169	152	6.29	0.13s	3h24m40s	17h2m36s
OBF(Br=2)	143	152	169	152	6.29	1.30s	23h58m44s	84h18m48s
PBF	143	155	175	155	8.39	5.22s	1h23m58s	7h12m15s
OMP	191	191	191	191	0	22.08s	15m41s	1h14m14s
PRR	187	200	202	200	6.95	0.01s	0.09s	0.72s
SLB	187	200	202	200	6.95	0.01s	0.13s	0.69s
DJP	193	200	207	200	2.13	0.02s	0.28s	1.64s
LP	206	214	217	214	3.63	0.01s	0.06s	0.45s
1+1	334	334	334	334	0	0.01s	0.05s	0.28s

Table 7.5: Numerical design outcomes for the Sprint USNet.

Sprint U.S. Network								
Protection Strategy	System Capacity							
	Best Bound	Asc.	Desc.	Heu	Gap (%)	t_{min}	t_{max}	t_{tot}
NoPro	191	191	191	191	0	0.01s	0.02s	0.34s
LR	210	220	224	220	4.76	0.06s	33m44s	1h52m48s
LIR	210	220	227	220	4.76	4.34s	3h42s	32h23m31s
OB	221	236	243	236	6.79	0.17s	10h41m10s	25h10m34s
OBF(Br=2)	223	236	243	236	5.83	0.34s	10h6s	32h31m15s
PBF	223	240	243	240	7.62	2.44s	9h31m45s	30h29m9s
OMP	243	243	243	243	0	0.56s	17m45s	56m30s
PRR	272	281	285	281	3.31	0.01s	0.06s	0.61s
SLB	272	281	285	281	3.31	0.01s	0.11s	0.57s
DJP	281	290	287	287	2.13	0.20s	0.06s	1.65s
LP	296	309	310	309	4.39	0.01s	0.11s	0.44s
1+1	358	358	358	358	0	0.01s	0.02s	0.16s

Consider the design outcomes in Tables 7.4 and 7.5. They indicate that the heuristic algorithm is in general capable of providing good network solutions, where the gaps between the best bounds and the heuristic results are less than 9% for UKNet and less than 8% for Sprint USNet. Thus, based on this observation, we can summarize that the heuristic algorithm is useful in large networks.

Furthermore, Tables 7.4 and 7.5 show that the gaps for the cases of no protection (NoPro), OMP, and 1+1 are zero. As considered in the experimental detail, we found that to minimize the system capacity requirement, the heuristic algorithm with the no protection, OMP, and 1+1 cases prefers to employ the shortest working and restoration paths to achieve this aim. This behavior is the same as that of the ILP approach. Therefore, the results of the ILP approach and the heuristic algorithm are identical and the relative gaps are consequently zero.

Let us now examine the results that are contained in the Asc and Desc columns of Tables 7.4 and 7.5. We found that the different selection techniques results in the different design outcomes. Thus, it can be summarized that the technique to select traffic sessions is an important parameter that should be taken in account when using the heuristic algorithm to design networks. For these experiments, Tables 7.4 and 7.5 demonstrate that the ascending selection technique typically generates better network solutions than the descending selection techniques. Note that this observation in Tables 7.4 and 7.5 is also seen in several other test networks.

Although, the heuristic algorithm yields solutions with good quality, it has a disadvantage. As displayed in Tables 7.4 and 7.5, the disadvantage is the computation effort needed to solve ILP programs of the heuristic algorithm. As we can see, the differences of the minimum and maximum times spent by CPLEX are variable from very small magnitude in the order of second for point-to-point protections to rather large magnitude in the order of hour for multicast protection approaches. For example, Table 7.5 shows that the time difference for the point-to-point SLB protection is only 0.10 second, while the time difference for the multicast OB protection is around as large as 10 hours. Therefore, with this scenario, the total computational time is also quite variable and can not be certainly predicted.

To further illustrate the performance characteristic of the heuristic algorithm, Figures 7.5 and 7.6 plot the algorithm progress in terms of the system capacity and the solution time against the iterations of Sprint USNet. As demonstrated, the value of system capacity in Figure 7.5 is a monotonic increasing function. Meanwhile, Figure 7.6 shows that the graph is rather oscillated. This corresponds to the discussion in the above paragraph.

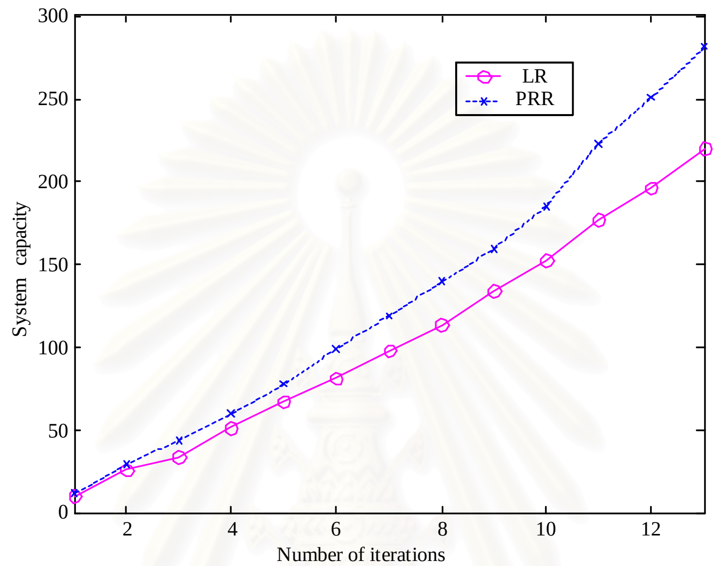


Figure 7.5: Increment of the system capacity versus the number of iterations for the Sprint USNet network.

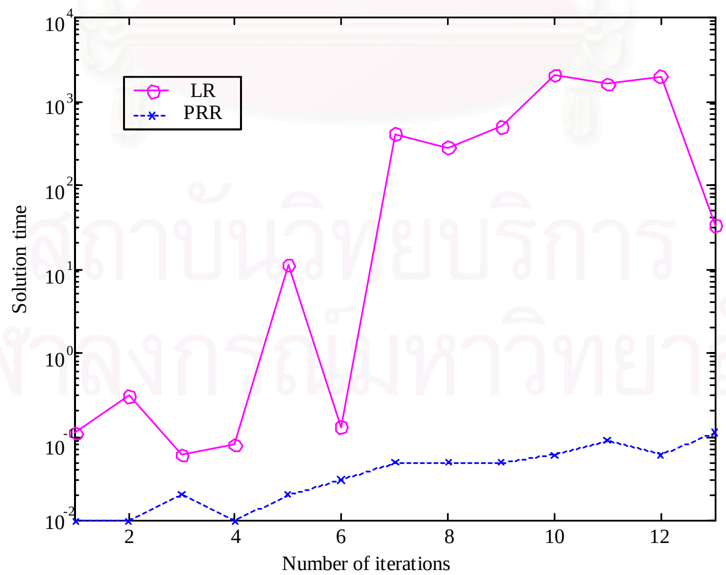


Figure 7.6: Solution time in logarithm scale versus the number of iterations for the Sprint USNet network.

Chapter 8

Conclusions and Future Work

8.1 Conclusions

With the objectives of the thesis to study the problems of MC-RWA and optical protection of optical WDM networks, the thesis is concluded in this chapter.

8.1.1 Conclusions of MC-RWA Problem

In the study of MC-RWA problem, two network design approaches, *i.e.*, mesh and multi-ring designs, are investigated in the thesis to implement WDM networks. Given a set of multicast sessions, the thesis derives ILP mathematical models to solve the MC-RWA problem of mesh and multi-ring WDM networks. These proposed ILP models are very useful because their solutions provide networks not only optimal multicast routing and wavelength assignment patterns but also optimal multicast tree (light-tree) structures that do not exist in solutions of ILP models as proposed in literature. In considering the wavelength assignment, the LT, PVLT, and VLT wavelength assignment methods are presented in the thesis. Apart from ILP formulations used as a tool to study the MC-RWA problem, the thesis also introduces heuristic algorithms and lower bound techniques to determine the total number of fibers required for mesh and multi-ring WDM networks.

The results of two large NSFNet and EON network designs are presented in chapter 3 and we found that for both mesh and multi-ring design techniques, obtained lower bounds are close to optimal VLT results determined from the mathematical models and also close to PVTL and LT results determined from the proposed heuristic algorithms. Therefore, it can be concluded that the proposed lower bound techniques are effective to estimate optimal network design outcomes for mesh and multi-ring WDM networks.

Examining the implications of limited fanout or splitting degree, we found that optical power splitters are very beneficial to reduce the network capacity, thus resulting in fiber-transmission cost savings. However, we also found that providing only a small splitting degree of optical splitters to networks are sufficient to achieve the minimal fiber requirement as in the case of a high splitting degree.

In the study of multiple fiber systems, the experimental results in the thesis indicate that as the number of wavelengths per fiber increases (M), although the total number of fibers required can be decreased, the system capacity will inversely increase, thereby decreasing fiber utilization of networks. Therefore, under these findings, the network implementation seems to be cost-effective at small values of M.

As a comparison of the wavelength capacity between mesh and multi-ring networks in the thesis, the design results show that mesh networks generally require fewer fibers than multi-ring networks. However, additional fibers required by the multi-ring design come hand-in-hand with a simpler control and management with respect to those of mesh networks. Moreover, the experiment shows that a number of extra fibers of the multi-ring design can be diminished by increasing the connectivity of network.

Finally, with the study of the proposed wavelength allocation techniques, the thesis found that LT, PVLT, and VLT results are typically identical, especially for multi-ring networks. Hence, it can be concluded that the benefit to reduce the wavelength capacity achievable by employing the wavelength conversion capability equipped within MC-OXCs may be negligible.

8.1.2 Conclusions of Optical Protection Problem

After studying the MC-RWA problem, this thesis then investigates the problem of optical protection or providing survivability to multicast WDM mesh networks in which a multiple fiber system is employed. This problem is very significant since with the throughput of Tbits/s of WDM networks, some failures of network elements could lead to a large amount of data loss, even in a few seconds. Therefore, with the serious concern, efficient protection systems should be designed and embedded in multicast WDM networks.

Based on the concept of the light-tree to carry multicast traffic, the thesis studies two main categories of protection systems for WDM mesh networks. For the first category, a new set of multicast protection strategies, *i.e.*, the LR, LIR, OB, OBF, PBF, and OMP protection strategies, against single link failures are designed and introduced in the thesis. For another protection category, we present an extension of deploying point-to-point protection techniques, which are generally used for unicast traffic, to protect multicast traffic. Point-to-point protection approaches studied in the thesis are the PRR, SLB, DJP, LR, and 1+1 protection approaches. As all the proposed protection strategies are technically related, the thesis also demonstrates a new simple diagram to describe these investigated protections. The proposed protection diagram is very helpful not only to enhance the understanding of each protection method, but also to systemically anticipate the fiber requirement and the restoration system complexity among the studied light-tree protection strategies.

Moreover, to study the network capacity, the thesis develops and presents ILP formulations of minimizing the total number of spare and/or working fibers needed for building restorable WDM networks. In optimization process, the benefits of joint optimization of working and spare fibers (network problem A) and spare capacity optimization alone (network problem B) are also discussed in the thesis.

Since one of the main problems of restorable WDM networks is the wavelength assignment problem, three new wavelength allocation techniques, that is, the LT, PVLT, and VLT techniques are investigated. In order to reduce the ILP computation complexity, new simple heuristic procedures for wavelength allocation are also introduced in this thesis.

Finally, since a main design factor that we should consider in designing resilient WDM networks is the technique to place or allocate spare capacity, the thesis examines three distinct spare capacity placement techniques, namely, the SF+WF, SW+WW, and SW+WW+SR techniques.

Based on the 8-ring, 8N-14L, and 10N-21L experimental networks, the computational results demonstrate that the multicast protection methods require much fewer fibers than the point-to-point protections. This means that the use of a light-tree as a granularity to design the protection mechanism effectively yields better network solutions than adopting the point-to-point protections for restoring multicast traffic. However, in an environment of networks supporting both unicast and multicast traffic simultaneously, additional fibers required for point-to-point protections can be compensated by a single and simpler protection control plane of networks. This is in contrast to a network using a multicast protection approach that requires an extra control plane for link restoration of multicast traffic.

In a comparison of network capacity among the multicast protections, the experiments in the thesis show that maximal fiber requirements are always for the case of the OMP protection, followed by the PBF, OBF, OB, LIR, and LR methods, respectively. Although LR always provides minimal fiber requirements, the experiments also indicate that the results of LR are identical to those of LIR for every number of wavelengths per fiber assigned to networks. Therefore, it signifies that the great flexibility of the LR method to reconfigure entire light-trees of a network do not offer an advantage in fiber savings. The LIR protection is considered useful to provide minimal fiber requirements for implementing restorable WDM networks.

For the class of point-to-point protections, the design outcomes show that fiber requirements among studied point-to-point protection schemes can be ranked as $\text{PRR} \le \text{SLB=DJP=LP} \le 1+1$. It should be noted that this conclusion is consistent with the previous researches works [26, 63] in literature.

In order to further study the optical protection problem, we investigate a special case, where only unicast demands are given to test networks. The computational results illustrate that there exist four equivalences. Those four protection equivalences are 1) OMP=1+1, 2) LR=PRR, 3) $\text{OB=OBF(Br} \ge 1\text{)=SLB}$, and 4) PBF=DJP. Moreover, when testing with ring topology networks, an extra equivalence that must be included is $\text{LIR=OB=OBF(Br} \ge 1\text{)=PBF=DJP=SLB}$. Note that the equivalences of these protection systems are in terms of not only working and spare fiber requirements, but also the fault management and restoration process.

In the study of the computational ILP complexity, the experiments in the thesis show that network design problem A is much more computationally complicated than network problem B. This results in that the execution times to solve the ILP formulations of the multicast protections are always longer that those for the point-to-point protections. However, the advantage of a short execution time for problem B trades off with the quality of network results. This is because, based on the experiments, the design outcomes for problem A are always better than those for problem B.

Since the time to calculate design outcomes of network problem B is rather short, we extend the comparative study among the proposed light-tree protection methods to cover a more practical-sized NSFNet network. Based on the NSFNet network, we found that the conclusions of the three smaller test networks are also applicable to this network as well.

In the study of the impact of the restricted fanout on the fiber requirement, the network results show that for the multicast protection techniques, the advantage in fiber reduction caused by increasing the fanout value is typically not apparent. As experimented, as much as 5% fiber saving can be achieved. This is in contrast with the point-to-point protection schemes, for which the increment in fanout value is able to reduce the fiber requirement significantly. Therefore, based on the experiments, it can be concluded that optical power splitters are more useful for point-to-point protection systems than for multicast protection systems.

In examining the influence of the Br design parameter on the fiber requirement of the OBF protection, the thesis reaches a conclusion that with all experimental networks, the Br design parameter has an influence to reduce the working and spare capacity of the OBF protection. Moreover, based on network design outcomes, we found that with a large M value, only small value of Br can potentially yield the results of OBF equal to those of OB.

Next, in the investigation of the spare capacity placement techniques, the numerical results in the thesis show that SW+WW+SR can be used to reduce the network capacity with respect to the results of SW+WW. This leads to a conclusion that the stub release option in SW+WW+SR is useful. However, the experiments also demonstrate that the effectiveness of the stub release is rather limited. The fiber reduction of SW+WW+SR with respect to SW+WW occurs in only for some values of *M* and also some protection techniques. For the SF+WF technique, the experiments indicate that the fiber requirement for SF+WF is always greater than that for SW+WW and SW+WW+WR for all values of *M*. Nevertheless, in terms of the spare capacity management, SF+WF outperforms SW+WW and SW+WW+SR.

For the next issue that we study in the thesis, the wavelength allocation is discussed. By using the proposed heuristic algorithms, the thesis found that in most cases, the results of VLT are achieved by the results of PVLT. For the case of an LT system in which no wavelength converters are needed, it appears that the fiber requirement is always greater than those of PVLT and VLT. Therefore, this observation leads to a conclusion that for the multicast traffic environment, the wavelength conversion capability of MC-OXCs is effectively useful for fiber savings of restorable WDM mesh networks.

Apart from the proposed ILP formulations, this thesis finally presents an ILP-based heuristic algorithm as an alternative tool for designing multicast WDM mesh networks in the cases with and without link protection. The objective of introducing the heuristic algorithm is to design large-sized WDM networks, where the proposed ILP mathematical models cannot be completely computed within a reasonable time. With the introduced heuristic algorithm, the derived ILP mathematical model is decomposed into a number of smaller sub-ILP problems and those sub-ILP problems are solved in a sequence manner.

To examine the performance of the ILP-based heuristic algorithm, both small and large optical networks are employed. Based on the experimental results, we found that for small networks, the heuristic procedure generates comparable network solutions with respect to the optimal results of ILP models. For large networks, the experiments demonstrate that the heuristic procedure still provides network design outcomes of good quality when comparing with the best bounds obtained from the ILP models. Therefore, it is conceivable that the proposed heuristic algorithm may be able to offer near-optimal solutions for designing multicast WDM networks with and without link protection.

8.2 Future Work

Although this thesis provides the resulting study of two significant MC-RWA and optical protection problems for WDM networks, there are other research issues that are equally important and we should study them as future research works. A number of examples of future works are as follows.

1. **Traffic Grooming:** since optical WDM networks are expected to be underlying infrastructures of IP networks, a bandwidth requirement of an IP stream that must reserve for communications through optical networks is generally much lower than available wavelength capacity. This results in the ineffective use of network resources. Therefore, with this scenario, a new challenge problem, that is, traffic grooming [101-104], is introduced to networks. Traffic grooming refers to the problem of efficiently combining low-speed traffic streams onto high-speed wavelengths with the aim to maximize network utilization. Hence, possible research works are to design effective algorithms to solve the traffic grooming problem and also study what is the best virtual structure to effectively groom several IP traffic streams. Note that this problem is significant not only for IP networks, but also for MPLS- and GMPLS-based networks [32-34, 103, 104]. As we research in the thesis, a study of the traffic grooming in IP- over-WDM networks is presented in [105].

2. **Scalability:** in the design of modern communication networks, one of important aspects that we should carefully consider is the network scalability. Network scalability refers to as a capability of network to enlarge its service area. This capability is extremely important because as the global economic system grows continuously, a traffic volume of networks is expected to increase dramatically. Therefore, to handle the growth of traffic volume efficiently, network designers should intelligently provide the scalability to networks. Hence, with this importance, one of possible future works is the analysis of network scalability.

3. **Reliability and Availability:** in addition to studying network survivability in this thesis by providing protection systems to optical networks, the network reliability and availability [108, 109] should also be studied for optical networks. This is because these two parameters are very important to guarantee network users and customers that networks are sustainable in service despite of failure

occurrences. Therefore, a further research issue is to find effective approaches in computing the network reliability and availability of WDM networks both in cases with and without link restoration. In addition, one of possible challenge problems of this issue is to answer how the network availability and reliability are improved when efficient protection systems are provided to WDM networks.

4. **Quality of Services (QoS) and Quality of Protections (QoP):** as several business firms are increasingly preferable to use communication networks for transaction purposes, these business firms may require different quality of services and also different quality of protections (QoS and QoP) [110] from network providers. Therefore, under this environment, QoS and QoP should be included in network design in order to implement networks cost-effectively. Consequently, a possible research issue is to analyze and design WDM networks under the considerations of QoS and QoP. This research issue may include the problem of designing QoS and QoP that is suitable for business companies as well as optimized the network design.

5. **Pricing Theory and Economic Analysis:** as studied in this thesis, the network model assumes that we have known traffic demands in advance. However, the thesis does not consider techniques to compute traffic demands of networks. Therefore, a possible research work is to intensively study and analyze such techniques. This work is significant because these techniques could lead to the improvement of the network design both in terms of the installation network cost and the profit return. One of favourite techniques to predict traffic demands of communication networks is the pricing theory [111] that relies on the economic analysis.

6. **Express Route:** as a traffic volume in existing networks, especially in Internet, is expected to increase rapidly, it is possible that some points on networks are bottleneck, thereby degrading the quality of services (*e.g.,* delay, and throughput). Therefore, to solve this problem effectively, WDM optical links are useful and employed as express routes [112] to bypass bottleneck points of networks. Hence, it is crucial to study the concept of express route in existing traditional networks, including circuit-switched, packet-switched, and Internet networks. This crucial problem may include a problem of what are effective combinations of express routes

to decrease every bottleneck point of networks simultaneously. The express route combinations may be ring, bus, star, and/or arbitrarily-connected topologies.

7. **Multi-Granularity Optical Switching:** since implementations of OXCs and MC-OXCs are rather complicated, there are thus several techniques to decrease this complication. One of popular techniques is the multi-granularity optical switching technique [113, 114] that employs several switching levels in stead of purely using wavelength switching level to cross-connect traffic when it passes OXCs or MC-OXCs. Such additional switching levels are fiber and waveband (a group of wavelength channels) levels. Therefore, this technique creates a new challenge research issue of reconsidering the RWA and MC-RWA problems so that RWA and MC-RWA algorithms are designed to be compatible with the multi-granularity switching technique. Note that this switching technique is now included in the GMPLS network design.

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