Development of Large Capacity Photonic Network Technologies

by

Zhishu SHEN

Doctoral Dissertation

Department of Electrical Engineering and Computer Science
Nagoya University

2015

GLOSSARY OF ACRONYMS

BXC	Waveband Cross-connect
BV-	Bandwidth Variable-
C/D/C	Colorless/Directionless/Contentionless
CO-OFDM	Coherent Optical - Orthogonal Frequency Division Multiplexing
DEMUX	Demultiplexer
EDFA	Erbium Doped Fiber Amplifier
HOXC	Hierarchical Optical Cross-connect
ILP	Integer Linear Programming
ITU-T	International Telecommunication Union Telecommunication Standardization Sector
MBBR	Make Before Break Rerouting
MLR	Mixed Line Rate
MUX	Multiplexer
NNI	Network Network Interface
OXC	Optical Cross-connect
PLC	Planar Lightwave Circuit
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RWA	Routing and Wavelength Assignment
RSA	Routing and Spectrum Assignment
SDN	Software Defined Networking
SLR	Single Line Rate
UNI	User Network Interface
WB	Waveband
WBC	Waveband Convertor
WBSS	Waveband Selective Switch
WC	Wavelength Convertor
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch
WXC	Wavelength Cross-connect

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1
INTRODUCTION

1.1 Background

The rapid deployment of broadband access including ADSL (Asymmetric Digital Subscriber Line) and FTTH (Fiber To The Home) is driving the exponential increase in communication traffic in the currently backbone networks in the world. Moreover, this rapid traffic expansion will be further enhanced with the adoption of advanced video distribution services requiring large bandwidth [1-1]-[1-2] such as real-time transmission of UHDTV (Ultra-High Definition Television), which requires 72/144 Gbps/ch for uncompressed transmission [1-3]. The IP (Internet Protocol) traffic forecast released by Cisco shows that the broadband video and file sharing services will be dominated in the near future, and from 2013-2018, the annual growth rate of the global IP traffic is estimated about 21% (in developing countries, this rate is closer to 50%). Following this trend, the global IP traffic is expected to surpass 1 ZB (10^{21} bytes) in 2016 [1-4]. This rapid traffic growth increases the capacity requirement of the networks, which is associated with CAPEX (capital expenditure)/OPEX (operating expense). Meanwhile, with the increase of traffic volume, the energy consumption imposed by the emerging ICT (Information and Communication Technologies) also becomes a crucial issue where ICT is estimated to be accountable for 2-4% of worldwide carbon emissions, and 40~60% of the ICT carbon emissions is caused by the use of related equipment [1-5]. The development of photonic network technology is expected to satisfy the aforementioned high requests.

Currently, a typical backbone network topology mainly composes of two elements: node (switch/cross-connect equipment), and link (logical adjacent between each equipment). For the current backbone networks, optical fibers are laid on transmission links. To provide a high-capacity network infrastructure to cope with the rapid annual traffic increases, WDM (Wavelength Division Multiplexing, Fig. 1-1) transmission has already been commercially introduced to optical fibers at links since 1997. This technology enables the transmission of multiple optical signals with different optical (wavelength) channels simultaneously in a single optical fiber by using the optical multiplexing (MUX) /demultiplexing (DEMUX) filters. On the other hand, in the currently backbone networks, exchange equipment such as IP router and DXC (digital cross-connect) are deployed at nodes. For this type of node, the packet forwarding operation is based on the electrical processing; therefore, at each interface of the node, O-E-O (Optical-Electrical-Optical) conversions are required as shown in Fig. 1-2. The details of different O-E-O architectures can be found in [1-6]. However, with the growth of network transmission capacity, electrical forwarding and O-E-O operation consume more and more electrical power. For example, in Japan, the annual energy consumption of IP routers has already accounted for approximately 1% of Japan’s total electricity generation in 2006 [1-7].

This ratio will raise more with the traffic expansion expected in the near future. The high power consumption caused by the electrical processing will become bottlenecks that hinder the construction of large-scale cost-effective networks.

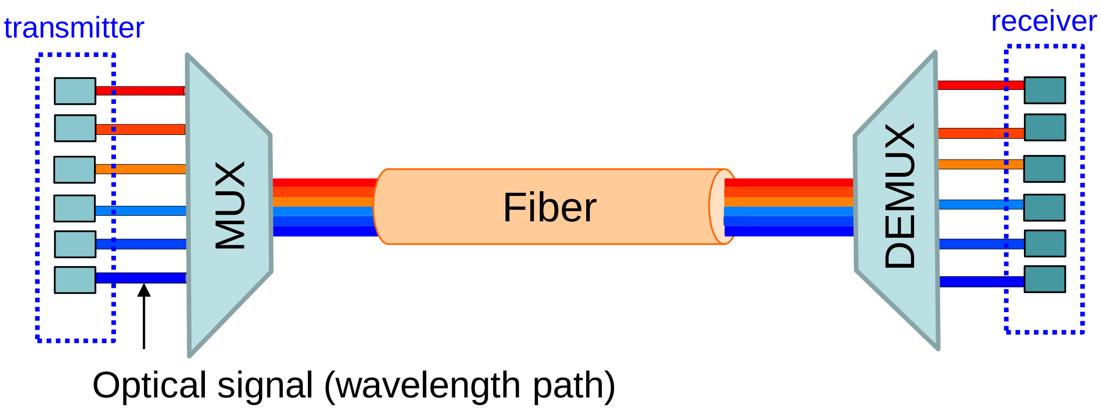


Figure 1-1. Basic WDM transmission technology concept.

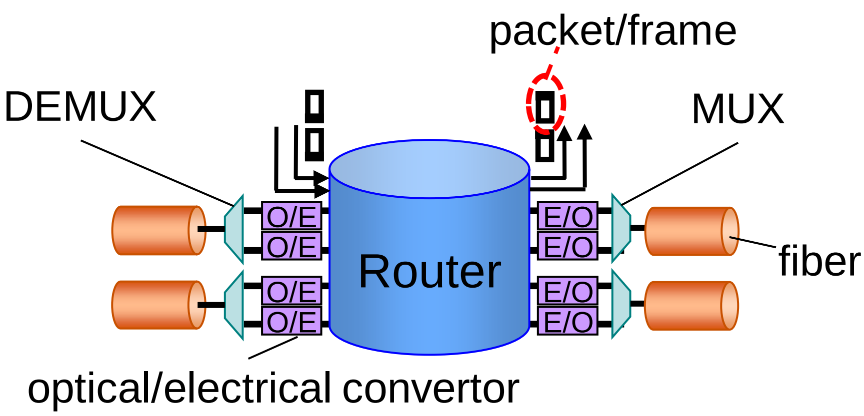


Figure 1-2. An example of an electrical node system.

In order to solve the aforementioned problem, photonic networks that utilize wavelength routing (In this thesis, the photonic networks offering only wavelength path routing is referred as single-layer optical path networks) made possible with ROADMs (Reconfigurable Optical Add-Drop Multiplexers) [1-1][1-8][1-9] have already been extensively introduced in Japan and North America. ROADMs enable the all optical conversion by utilizing optical switching, while the unnecessary O-E-O conversion can be eliminated as much as possible. Figure 1-3 shows a simple example of a photonic node system. For each node, the optical signals are switched in the optical layer, and these optical signals connect the source and destination node pairs are called as wavelength paths. The photonic node shown in Fig. 1-3 is also called as single-layer

OXC (Optical Cross-Connect). It should be noted that, in the related literatures, the technologies/networks performing in the optical domain are named as "optical" or "photonic" while the definition of these two words differs case by case. For example, in [1-10], the authors defined the O-E-O system as an optical switching system (Figure 1-3), while the system based on all-optical switching and control as the photonic switching. However, this argument is outside of the scope of this thesis and this classification does not impact the description in this thesis. Therefore, for simplicity, in this thesis, the words "optical" and "photonic" can be considered equivalent. Compared with the conventional (all) electrical node system, the optical/photonic node system can reduce the power consumption significantly by reducing the required number of O-E-O convertors. For example, in the aspect of energy consumption for 1000 ports × 1 Tbps, the consumption of the optical node is less than 1 kW, while the electrical node (IP router) consumes approximately 6000 kW [1-7].

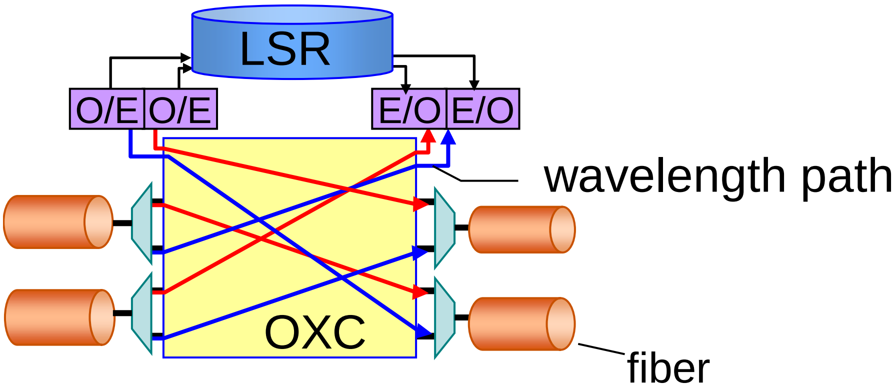


Figure 1-3. An example of a photonic node system.

Photonics networks can be expected to realize energy-efficient communication from access to the backbone networks. However, there are still challenges in creating future photonics networks cost-effectively. The first challenge is how to realize and utilize high capacity transmission system cost-effectively to cope with future traffic expansion [1-11]. The transmission capacity of fiber is approaching its estimated fundamental limits rapidly, and it may lead to a capacity shortage in decade [1-9]. Research on increasing fiber transmission capacity has been actively studied to alleviate this problem: the transmission capacity of 1 Pbps (=1015 Mbps, 12 cores × 380 Gbps × 222 channels) has already been achieved [1-12] by introducing coherent detection ([1-13]) and SDM (Space Division Multiplexing, i.e., multicore/multi-mode fiber which supports multiple independent cores/modes in a single fiber [1-14]). Moreover, a high-capacity transmission (140 Tbps, 7 cores × 100 Gbps × 201 channels) with a long transmission distance (7326 km) was also experimentally demonstrated in [1-15]. These multi-core fibers are expected to be deployed in the future. Meanwhile, to improve the transmission efficiency, in the future, telecom carriers will replace old lower bitrate transmission systems with higher ones (e.g., 400 Gbps) [1-11] which can be realized by coherent transmission technology [1-12]. However, due to the limitation of the currently photonics networks where all the channels are spaced with an equally channel distance (e.g., 50 GHz) in the fiber's available spectrum, it is a critical issue to improve the fiber utilization efficiency while accommodating the high bitrate signal (e.g., the required frequency bandwidth for a 400 Gbps signal is much broader than 50 GHz). Elastic optical path networks (in this thesis, it also referred to "flexible grid optical path networks") can maximize the fiber utilization efficiency since they utilize a minimum frequency slot granularity (e.g., 12.5 GHz) and can allocate multiple frequency slots as needed [1-16]-[1-17]. One of the focuses of this thesis is the flexible grid networks, and its detailed overview will be summarized in Chapter 3.

On the other hand, constructing large scale optical switches (nodes) is also an important challenge to cope with future traffic expansion. Unfortunately, the scale of optical switches currently used in OXCs/ROADMs for single-layer optical path networks increases in proportion to the square of the wavelength numbers, and unfortunately, by nowadays technologies, the large-scale optical switch is still extremely difficult to be realized (the port size of currently commercially available optical switch is only 32×32 [1-18]). The hierarchical optical path networks utilizing two different optical path routing granularity, waveband routing (bundle of multiple wavelength paths), and the conventional wavelength routing, have been widely investigated since the significantly effectiveness in reducing the node cost compared with the conventional single-layer optical path networks [1-19]-[1-21]. This type of network is also tackled by this thesis, and the overview of hierarchical optical path networks will be summarized in Chapter 2.

1.2 Purpose of this study

Hierarchical optical path networks and elastic optical path networks are the stronger candidates to create the next generation bandwidth-abundant photonic network cost-effectively. Previous studies have verified their effectiveness in achieving node/link cost reduction; however, the following challenges still need to be resolved:

(1) Topic on the hierarchical optical path networks

Research problem: the wavelength/waveband continuity constraint prevents from improving fiber utilization, and as a result, it hinders the cost reduction effectiveness achieved by introducing waveband routing.

Hierarchical optical path networks that utilize wavebands are regarded as an effective architecture to cope with the expected traffic expansion in the future. Unfortunately, the constraints that a same wavelength/waveband cannot be assigned to different wavelength/waveband paths that share a fiber prevent full fiber utilization, which affects the total network cost. Wavelength/waveband convertors can resolve these constraints directly to improve the fiber utilization. However, the trade-off between the convertor cost and the fiber utilization ratio has not been quantitatively evaluated so far. In this thesis, novel optical path network design algorithms for hierarchical optical path networks introducing either or both of wavelength and waveband convertors are proposed to evaluate the impact of wavelength/waveband convertors in hierarchical optical path networks. The short computation time and the sub optimality of solutions make the proposed multi-stage ILPs (Integer Linear Programming) or heuristics (i.e., finding an approximate solution when ILP methods fail to obtain the optimal solution in a realistic calculation time) practical.

(2) Topic on the elastic optical path networks

Research problem: The high hardware requirements and spectral fragmentation caused by the non-uniform bandwidth assignment hiders the introduction effectiveness of elastic optical path networks.

By adaptively allocating the number of contiguous 12.5 GHz width frequency slots as needed by different channel bandwidth demands, flexible grid networks can minimize the total number of allocated frequency slots, which is expected to attain much more higher frequency utilization than is possible with conventional fixed grid systems. Unfortunately, this benefit is obtained at the cost of the high hardware requirement; therefore a viable network solution that can achieve high fiber utilization efficiency without increasing the hardware complexity is highly demanded. In this thesis, a novel semi-flexible grid optical path network is proposed where each specific bitrate signal uses its own dedicated fixed grid and one of the edges of the corresponding different frequency slot widths are anchored at a specific frequency. The proposal can greatly reducing the complexity of devices by using currently cost-effective fixed grid based devices in the transceiver sides. Moreover, to evaluate the network performance of the proposed semi-flexible grid networks, a novel disruption-minimized dynamic rerouting and spectrum defragmentation algorithm that addresses blocking ratio equalization on different bandwidth signals is proposed for both flexible grid networks and proposed semi-flexible grid networks.

1.3 Outline of this thesis

This thesis is organized with 7 chapters, and covers a comprehensive overview on the photonic networks, including the two next generation photonic network candidates – hierarchical optical path networks, and elastic optical path networks. This thesis summarizes the research achievement including the development of new photonic network architecture, optical path network design algorithm, also the numerical evaluations and results for verifying the effectiveness of the proposal.

Figure 1-4 illustrates the scope of this thesis, and the thesis is organized as follows:

Chapter 1 – Introduction presents the introduction of the thesis. It gives a brief review on the development trend of currently photonics networks, and clarifies the purpose of this study.

Chapter 2 – Hierarchical Optical Path Networks presents a comprehensive review of the hierarchical optical path networks utilizing wavebands. Firstly, the main concept of waveband switching, including hierarchical optical path network node architectures and associated waveband switching technique is briefly described. Moreover, the benefits of introducing waveband path routing are also discussed. And then, the optical path network design algorithm, including that for conventional single-layer optical path network and hierarchical optical path network, are clarified. Finally, related literatures on the network design problem of hierarchical optical path networks are summarized, and the future issues to be improved are also discussed, motivating the solutions presented in Chapter 4.

Chapter 3 – Elastic Optical Path Networks presents a comprehensive overview of another next generation photonics network – elastic optical path networks (flexible grid optical path networks), which is expected to maximize the fiber resource utilization efficiency. In this chapter, the overview of elastic optical path network, including its enabling technologies, and the introduction benefits are described. The network design problem for elastic optical path networks and related literatures are also summarized.

Chapter 4 – Hierarchical Optical Path Networks with Wavelength/Waveband Conversion presents a comprehensive investigation on the impact of wavelength/waveband convertors in reducing the hierarchical optical path network cost. Firstly, the characteristics of wavelength/waveband convertors, and the network design problem for hierarchal optical path networks introducing these conversions are briefly discussed. Then the proposed network design algorithms that apply either or both wavelength/waveband conversions are summarized. Numerical evaluation testing on various simulation parameters prove that, by employing either of both wavelength/waveband convertors, hierarchical optical path networks can be cost effective over wide traffic demand ranges and a broad convertor cost range.

Chapter 5 – Semi-flexible Grid Optical Path Networks presents a novel semi-flexible grid optical path network where each specific bitrate signal uses its own dedicated fixed grid and one edge of its frequency grid is anchored at a specific frequency. The proposal is expected to retain the high spectral utilization efficiency that can be achieved with the flexible grid networks while utilizing almost the same hardware as the currently cost-effective fixed grid systems. In this chapter, the challenges of actively studied flexible grid networks are explained, and then, the concept of proposed semi-flexible grid networks, including the signal frequency allocation strategy, is described. Finally, the architecture of the proposed semi-flexible grid network is illustrated, and the future tasks (details in Chapter 6) of the proposal are also discussed.

Chapter 6 – Development of Flexible/Semi-flexible Grid Networks Design Algorithm presents a novel disruption-minimized dynamic rerouting and spectrum defragmentation algorithm that addresses blocking ratio equalization on different bandwidth signals in flexible grid networks and the proposed semi-flexible grid networks. Numerical evaluations verify the effectiveness of the proposed algorithm in improving the network performance. The results also confirm that semi-flexible grid networks can achieve almost the same performance as the currently proposed flexible grid solution. Since the former have much relaxed hardware requirements, this novel approach is expected be a viable solution to realizing future flexible bandwidth networks cost-effectively.

Chapter 7 – Conclusions summarizes all the contents presented in this thesis, and the future prospects are also provided.

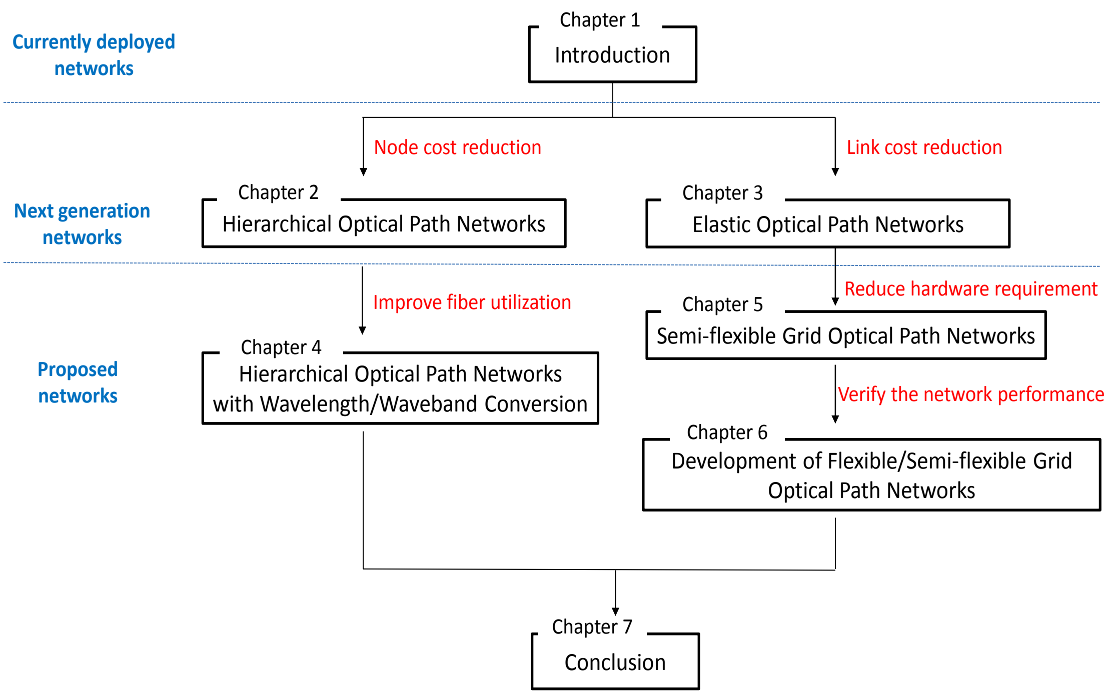


Figure 1-4. Scope of this thesis.

References

[1-1] K. Sato and H. Hasegawa, "Optical networking technologies that will create future bandwidth-abundant networks," *IEEE/OSA Journal of Optical Communications and Networking (JOCN)*, vol. 1, no. 2, pp. A81–A93, July 2009.

[1-2] A. L. Chiu, G. Choudhury, G. Clapp, R. Doverspike, M. Feuer, J. W. Gannett, G. Kim, J. Klincewicz, T. Kwon, G. Li, P. Magill, J. M. Simmons, R. A. Skoog, J. Strand, A. Lehmen, B. J. Wilson, S. L. Woodward, and D. Xu, "Architectures and protocols for capacity efficient, highly dynamic and highly resilient core networks," *IEEE/OSA Journal of Optical Communications and Networking (JOCN)*, vol. 4, no.1, pp. 1–14, January 2012.

[1-3] "Parameter values for ultra-high definition television systems for production and international programme exchange," ITU-R Recommendations BT. 2020-1, June 2014.

[1-4] Cisco Visual Networking Index (VNI): Forecast and Methodology, 2013-2018, Whitepaper, June 2014.

[1-5] W. Vereecken, W. Van Heddeghem, M. Deruyck, B. Puype, B. Lannoo, W. Joseph, D. Colle, L. Martens, and P. Demeester, "Power consumption in telecommunication networks: overview and reduction strategies," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 62-69, June 2011.

[1-6] J. M. Simmons, *Optical network design and planning*, New York, USA: Springer, June 2008.

[1-7] S. Namiki, "Introduction to VICTORIES – challenges for dynamic optical path network," *International Symposium on VICTORIES Project & workshop*, Tsukuba, Japan, October 2014.

[1-8] M. Mezhoudi, R. Feldman, and R. Goudreault, "The value of multiple degree ROADMs on metropolitan network economics," *OSA Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper NThA4, Los Angeles, USA, March 2006.

[1-9] R-J. Essiambre, and R W. Tkach, "Capacity trends and limits of optical communication networks," Proceedings of IEEE, vol. 100, no. 5, pp. 1035-1055, May 2012.

[1-10] T. S. El-Bawab, *Optical switching*, New York, USA: Springer, August 2006.

[1-11] P. Winzer, "Spatial multiplexing in fiber optics: the 10X scaling of metro/core capacities," *Technical Journal of Bell Labs*, vol. 19, pp. 22-30, September 2014.

[1-12] H. Takara, A. Sano, T. Kobayashi, H. Kubota, H. Kawakami, A. Matsuura, Y. Miyamoto, Y. Abe, H. Ono, K. Shikama, Y. Goto, K. Tsujikawa, Y. Sasaki, I. Ishida, K. Takenaga, S. Matsuo, K. Saitoh, M. Koshiba, and T. Morioka, "1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) crosstalk-managed transmission with 91.4-b/s/Hz aggregate spectral efficiency," *OSA European Conference and Exhibition on Optical Communication (ECOC)*, Paper Th.3.C.1, Amsterdam, Netherlands, September 2012.

[1-13] I. Kaminow, T. Li, and A. Willner, *Optical fiber telecommunications Volume VIB - Systems and networks*, Oxford, UK: Elsevier, May 2013.

[1-14] D. Richardson, J. Fini, and L. Nelson, "Space-division multiplexing in optical fibres," *Journal of Nature Photonics*, vol. 7, pp. 354–362, April 2013.

[1-15] K. Igarashi, T. Tsuritani, I. Morita, Y. Tsuchida, K. Maeda, M. Tadakuma, T. Saito, K. Watanabe, K. Imamura, R. Sugizaki, and M. Suzuki, "Super-Nyquist-WDM transmission over 7,326-km seven-core fiber with capacity-distance product of 1.03

Exabit/s·km," *OSA Journal Optics Express*, vol. 22, no. 2, pp. 1220-1228, January 2014.

[1-16] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, "Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies," *IEEE Communications Magazine*, vol. 47, no. 11, pp. 66-73, November 2009.

[1-17] O. Gerstel, M. Jinno, A. Lord, and S. J. B. Yoo, "Elastic optical networking: A new dawn for the optical layer?" *IEEE Communications Magazine*, vol. 50, no. 2, pp. 12-20, February 2012.

[1-18] D. Lucerna, G. Maier, and A. Pattavina, "AWG-based architecture for optical interconnection in asynchronous systems," *Proceeding of IEEE International Conference on High Performance Switching and Routing (HPSR)*, pp. 250-255, Cartagena, Spain, July 2011.

[1-19] X. Cao, V. Anand, Y. Xiong, and C. Qiao, "A study of waveband switching with multi-layer multi-granular optical cross-connects," *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 21, no. 7, pp. 1081–1095, September 2003.

[1-20] P. Torab, V. Hutcheon, D. Walters, and A. Battou, "Waveband switching efficiency in WDM networks: Analysis and case study," *OSA Optical Fiber Communication Conference (OFC)*, paper OTuG3, Anaheim, USA, March 2006.

[1-21] I. Yagyu, H. Hasegawa, and K. Sato, "An efficient hierarchical optical path network design algorithm based on a traffic demand expression in a Cartesian product space," *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 26, no. 6, pp. 22-31, August 2008.

Chapter 2
HIERARCHICAL OPTICAL PATH NETWORKS

This chapter presents a comprehensive review of hierarchical optical path networks utilizing wavebands. This novel network is expected to create future bandwidth abundant networks cost-effectively since its significant advantages in reducing network cost. In this chapter, firstly, fundamental concept of waveband switching, including hierarchical optical path network node architectures and associated waveband switching technique is briefly introduced. Major benefits of hierarchical optical path networks using wavebands are also discussed. And then, the optical path network design algorithm, including that for conventional single-layer optical path network and hierarchical optical path network, is clarified. Finally, related literatures on the network design problem of aforementioned photonics networks are summarized, and the future issues to be improved are also discussed, motivating the solutions presented in the Chapter 4.

2.1 Introduction

Hierarchical optical path networks utilizing wavebands (aggregated wavelength paths) have been recognized as an important technology to cope with the further traffic expansion [2-1]-[2-5]. The basic principle of waveband switching is to group multiple wavelengths as one entity, and the whole group is switched by using a single port as much as possible. By introducing path hierarchy, the network cost is expected to be reduced significantly compared with the currently single-layer optical path network where wavelength of each path is switched individually. Moreover, with the recent development of a waveband cross-connect (BXC) prototype [2-6]-[2-7] which is constructed with waveband selective switches (WBSSs) monolithically integrated on a PLC (Planar Lightwave Circuit) chip, a substantial reduction in node size and cost can be expected. However, from the viewpoint of hierarchical optical path networks design problem, even the routing and wavelength assignment (RWA) problem for the single-layer optical path networks is known to be an NP-complete task [2-8]. The problem of hierarchical optical path network design is much more difficult due to the complexity of establishing optical paths with different granularities while considering the path hierarchy and avoiding wavelength/waveband collisions, as a result, the evaluated cost effectiveness of a waveband network strongly depends on the network design algorithm adopted. The general goal of the hierarchal optical path networks design is to minimize the total network cost to accommodate given traffic demand, and extensive studies have been made to achieve this objective [2-3][2-5][2-9]-[2-13].

In this chapter, the concept of waveband switching is briefly introduced. Then different hierarchical optical path network architectures and technologies enabling the waveband path routing are summarized. The major benefits of using waveband routing compared with the conventional wavelength routing based network are also analyzed. Next, the basic concept of optical path network design algorithm problem is clarified for both conventional single-layer optical path networks and hierarchical optical path networks, and then emphasized the difficulty for the network design problem in obtaining the optimal solutions for a given network condition. Finally, related literatures on the related photonics network design algorithm are reviewed, and future issues are discussed.

2.2 Concept of waveband routing

A "waveband" is defined as a group of several wavelengths that can be switched as one entity as shown in Fig. 2-1. Here, the wavelength path is equivalent to the tradition optical path using a single wavelength unit (See Fig. 1-1). Switching of wavelength paths is only required at two terminating nodes, or the intermediate nodes where waveband grooming operation is required. In contrast, for the conventional single-layer optical path networks, switching of wavelength paths are required at all nodes the paths traverse. Therefore, the hierarchical optical path networks utilizing wavebands can reduce the total network cost (especially the necessary number of port cost), as well as the difficulty associated with the network control. The benefits of introducing wavebands will be discussed in Section 2.4.

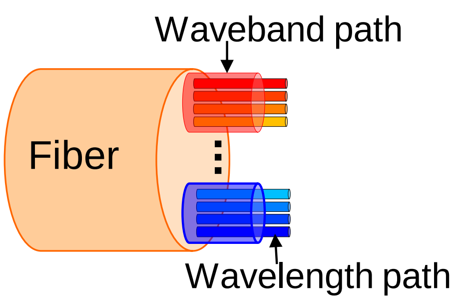


Figure 2-1. Waveband path mechanism.

In this thesis, a continuous waveband arrangement which integrates multiple wavelength paths in sequence is assumed as shown in Fig. 2-2. Another option of waveband arraignment is to integrate multiple wavelength paths in periodic as shown in [2-14], however, in terms of network operation, different waveband arrangement strategies will not affect the network performance.

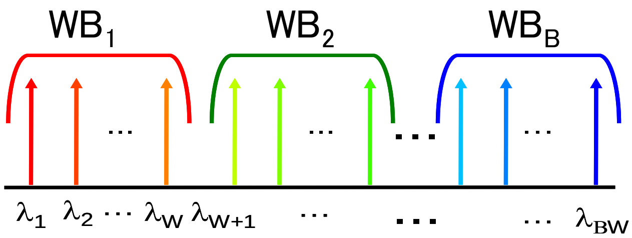


Figure 2-2. Waveband path mechanism.

For the waveband capacity, in [2-9], the authors assume a non-uniform capacity of waveband to evaluate the impact of waveband routing, however, the lack of uniformity increase the complexity in not only the management of different optical paths, especially for the case where the paths are dynamically established or torn down, but also the hardware support. Therefore, in this thesis, a uniform waveband capacity (donated as W) is assumed as shown in Fig. 2-2, while the accommodated number of waveband paths in a fiber is also set at a constant (donated as B in this thesis). The impact of different waveband capacity is evaluated at Chapter 4.5.4.

2.3 Hierarchical optical path networks architecture

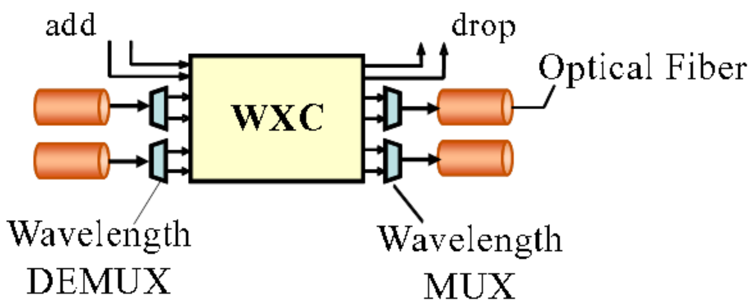
2.3.1 Node architecture of hierarchical optical path networks

Figure 2-3 summarizes the architecture of conventional single-layer OXC and two different types of MG (Multi Granular)-OXC for waveband routing ([2-1][2-3][2-5][2-13]). For the example of single-layer OXC architecture shown in Fig. 2-3(a), this model contains 2 optical channels on each input/output fibers, and 4 wavelength multiplexers (MUXs) and 4 wavelength demultiplexers (DEMUXs). The DEMUXs separate each of the optical channels on an input port, while the MUXs recombine these optical channels from different input ports onto a single output port.

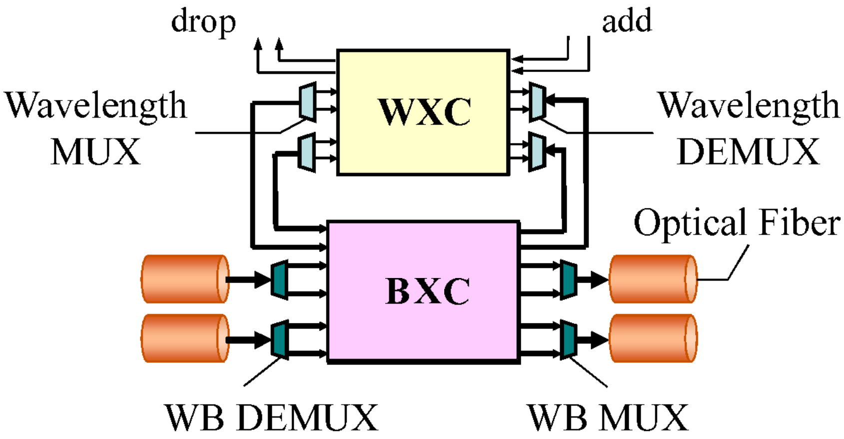
For the hierarchical MG-OXC architecture shown in Fig. 2-3(b), each node consists of two cross-connects with different optical granularity: a BXC with waveband MUXs/DEMUXs for routing higher order waveband paths, and a Wavelength Cross-Connect (WXC) with wavelength MUXs/DEMUXs for routing lower order wavelength paths. Wavelength paths are transported within waveband paths set on links. For this architecture, waveband paths are added from or dropped to WXC only when some wavelength paths accommodated in the respective waveband path requires grooming or terminating operation, and each wavelength paths is processed individually at WXC after demultiplexing from its respective waveband path. On the other hand, wavelength paths are multiplexed to the waveband paths, and then sent to the output fiber through waveband multiplexers. The hierarchical MG-OXC architecture is a feasible approach to deploying large scale networks since its high configurability and flexibility to various network circumstances; the hierarchical (electrical) path approach has been adopted by not only traditional SDH/SONET (Synchronous Optical Network/Synchronous Digital Hierarchy) networks [2-15] but also emerging optical transport networks [2-16].

An alternative architecture for the MG-OXC is the non-hierarchical MG-OXC (Fig. 2-3(c), [2-10],[2-13]) that accommodates a fixed number of wavelength paths and waveband paths simultaneously in the same fiber. Although it can minimize the number of switch ports for a certain fixed traffic demand, WXCs and BXCs cannot collaborate with each other since the grooming of wavelength paths at intermediate OXCs is not possible in the non-hierarchical MG-OXC. As a result, its effectiveness degrades greatly when the traffic pattern or traffic demand changes since the optimum wavelength path and waveband path configuration changes.

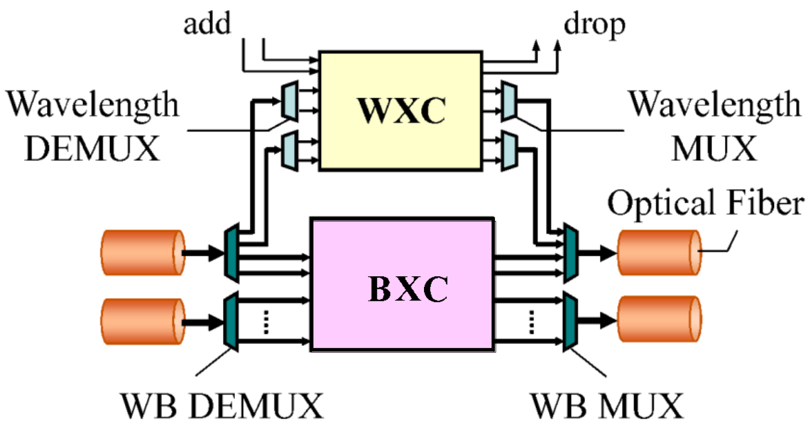
In this thesis, the hierarchical MG-OXC is adopted and it is called as hierarchical optical cross-connect (HOXC).



(a) Single-layer OXC architecture



(b) Hierarchical MG-OXC architecture



(c) Non-hierarchical MG-OXC

Figure 2-3. Configurations of different optical path network architecture.

2.3.2 Technologies enabling waveband path routing

To construct cost-effective hieratical optical path networks, the development of new photonics device technology for waveband routing is essential. The key components including the WBSS that can switch any of waveband paths from one input fiber to any desired output fiber. This function is similar with the wavelength selective switch (WSS) where switching granularity is wavelength optical path. A compact BXC can be realized cost effectively by using PLC technologies [2-6]-[2-7], and in the future, further cost reduction will be expected by using silicon photonics technologies. Indeed, a 1x8 WBSS that processes 96 wavelengths with 50 GHz spacing was developed. It was monolithically integrated on a 74.6 mm × 48.4 mm PLC chip. Its transmission performance has been verified [2-7]. Moreover, the module size of WBSS is much smaller than that of comparable WSS as shown in Fig. 2-4. It should be noted that the hardware scale reduction yielded by the introduction of wavebands also depends on the switch technologies adopted, such as matrix switch-based, 3D micro-electro-mechanical-system (3D-MEMS)-based WSSs, and liquid-crystal-on-silicon (LCoS)-based WSSs as is detailed in [2-17]. The efficient devices related to the waveband routing can be exploited in the hierarchical architecture to create comprehensive cost effectiveness, i.e., substantial reduction in node size and cost can be expected.

Meanwhile, waveband convertor, which is capable of converting any input waveband index into any desired output waveband index, is expected to improve network performance of hierarchical optical path networks. A low-crosstalk waveband conversion based on quasi-phase-matched $LiNbO_3$ devices have been already experimentally demonstrated [2-18]. The introduction effectiveness of waveband convertor will be discussed in Chapter 4.

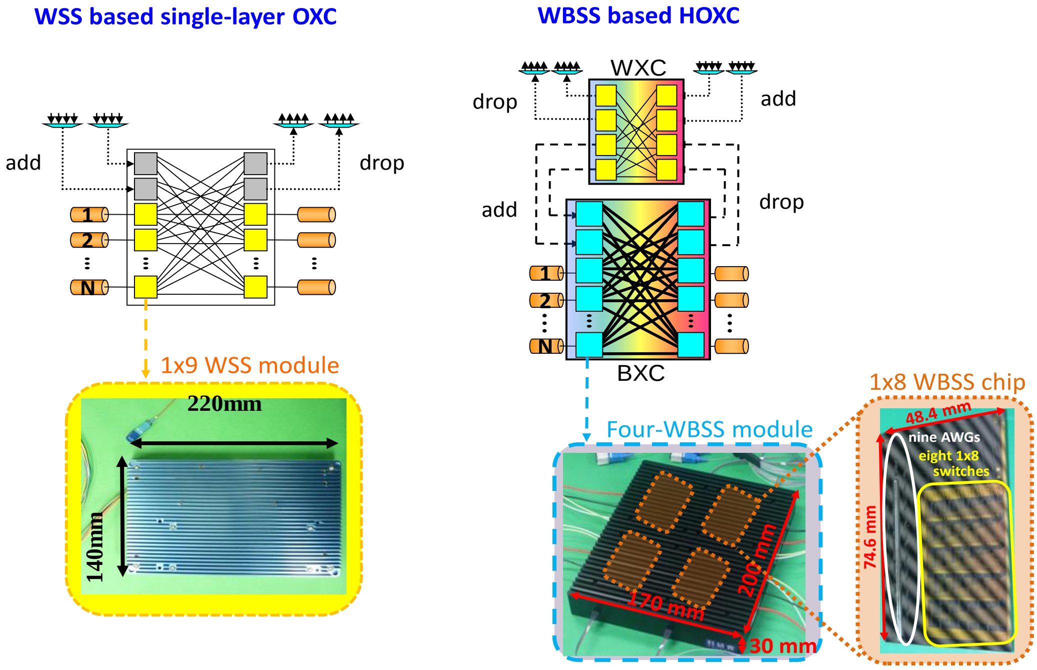


Figure 2-4. Comparison between WBSS and WSS required in different OXC architectures.

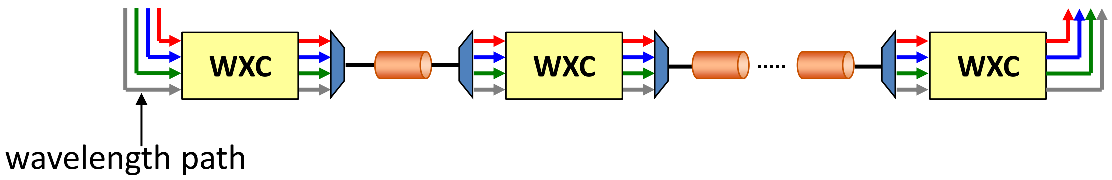
2.4 Benefits of introducing waveband path routing

The introduction of waveband paths enables the switching of several wavelength paths at one port (Please notice the differences at the intermediate node between single-layer and hierarchical optical path networks shown in Fig. 2-5), and therefore, significantly reduction in total switch port count can be expected for the hierarchical optical path networks. Meanwhile, the hierarchical optical path networks also reduce the complexity in terms of network control since multiple wavelength paths can be operated as one entity at each intermediate node for a waveband path connection. An OpenFlow-based (This protocol is expected to provide the maximum flexibility for operators to control the network) waveband selection control interlocked with dynamic resource allocation has been experimentally demonstrated [2-19].

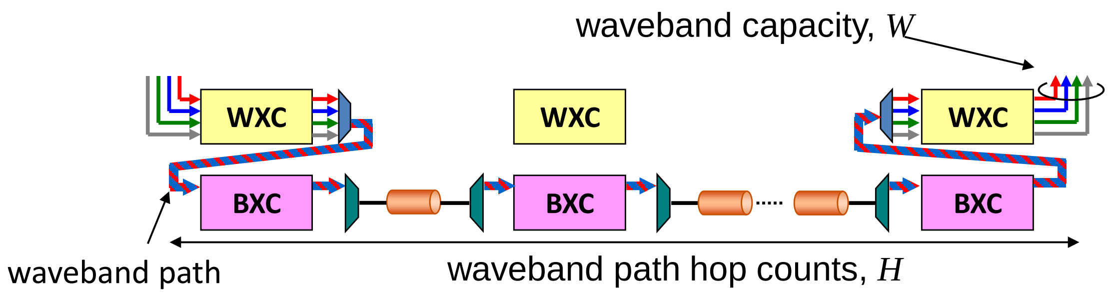
Figure 2-5 shows a simple example of port count ratio utilization for single-layer optical path network and hierarchical optical path network. For both networks, only one fiber is connected between source and destination nodes for simplicity. Suppose that the waveband capacity is fixed at *W*, while the average hop count of the waveband paths is *H*. The port count ratio *R* between the hierarchical optical path network and single-layer optical path network can be calculated as follows [2-5]:

$$R = \frac{1}{\alpha}\left(\frac{1}{W} + \frac{2}{H+1}\right) \qquad (2\text{-}1)$$

where the value α $(0 \le \alpha \le 1)$ is the waveband utilization ratio which represents the efficiency of a designed network. If $\alpha = 1$ represents the ideal situation where all the waveband paths are completely filled by the wavelength paths. Figure 2-6 plots the effectiveness of waveband switching in terms of optical switch port count ratio (*R*), the ratio of the total optical switch port count of a hierarchical optical path network to that of the equivalent single-layer optical path network. The evaluation considered several key parameters including waveband capacity (*W*), waveband utilization ratio (α), and average hop count of established waveband paths (*H*). The blue region in Fig. 2-6 represents the area where the port count ratio is less than 1. It can be concluded that the hierarchical optical path network is very effective over a wide parameter range; the cost-effectiveness of hierarchical optical path networks is enhanced as the average hop count of waveband paths increases or the waveband utilization ratio improves. However, it should be noticed that, when designing hierarchical optical path networks, the selection of the route and waveband for each waveband path can strongly affect the waveband utilization ratios. Therefore, the impact of introducing waveband paths strongly depends on the network design algorithm adopted.



(a) Single-layer optical path network



(b) Hierarchical optical path network

Figure 2-5. An example of port count ratio utilization for different networks.

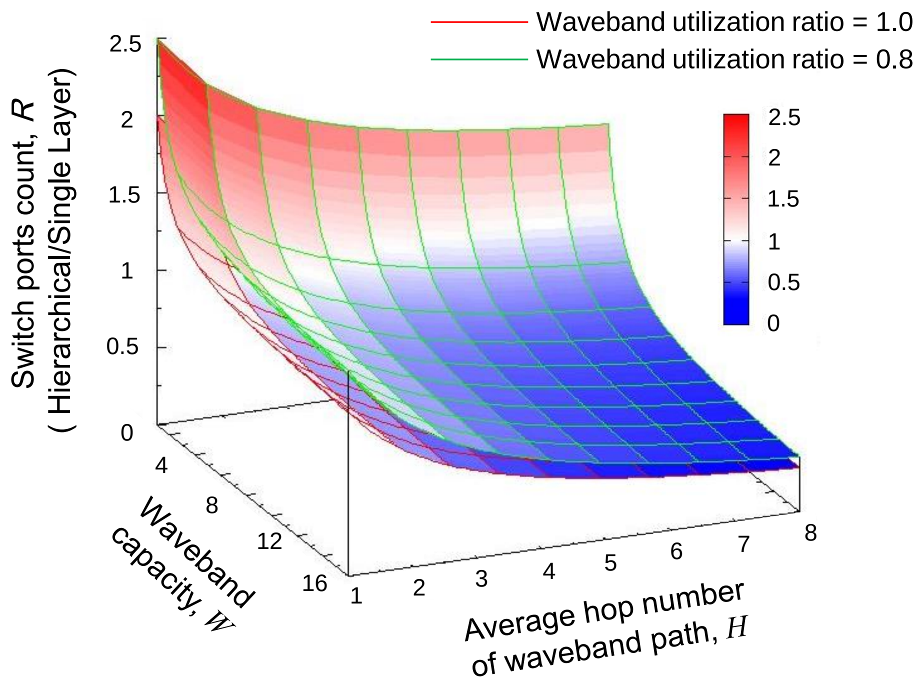


Figure 2-6. Ratio of the number of switch port counts:
hierarchical to single-layer optical path networks [2-5].

2.5 Hierarchical optical path network design problem

2.5.1 Problem statement

In the conventional single-layer optical path networks, for every arriving connection request, the network must assign an available physical route and wavelength index to establish this optical path. This process is called as routing and wavelength assignment, the well-known RWA problem in the WDM network. For the single-layer optical path network, if wavelength convertor is not used, each optical path must occupy a same wavelength index (lambda, please notice different "colors" are assigned to different optical paths in Fig. 2-7) on all the traversed fiber. This characteristic is known as the wavelength continuity constraint [2-20]. For identifying each optical path signal, the optical paths accommodated in a same fiber cannot share a same wavelength index. Moreover, the limitation of number of wavelength paths that can be accommodated in a fiber should also be considered for RWA problem, therefore, the RWA problem is known to be NP-complete if a multi-fibers network is assumed [2-8].

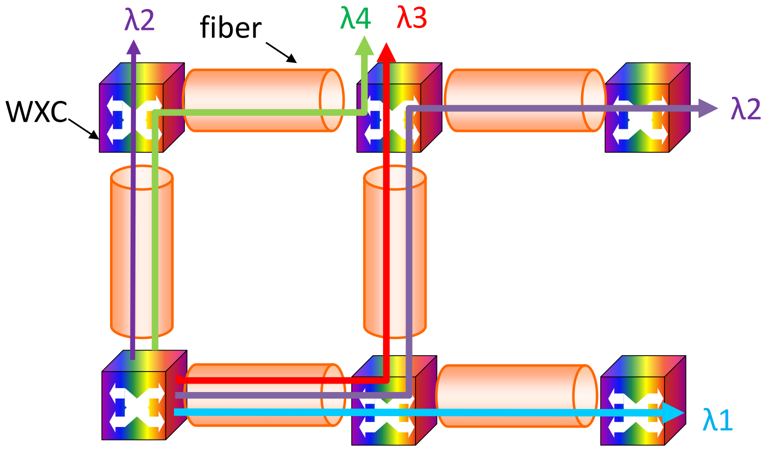


Figure 2-7. Wavelength continuity constraint.

When designing the hierarchical optical path networks, the problem will be much more difficult, since not only the same constrains in the conventional single-layer optical path networks, but also a new waveband continuity constraint (similar with the wavelength path case) should be considered. Moreover, due to the introduction of new path hierarchy - wavebands, the routing and waveband assignment for waveband paths and accommodation of wavelength/waveband paths within waveband/fiber should be optimized simultaneously. As a result, it is computationally impossible to get the optimal solutions for the hierarchal optical path networks. In the next section, various significant recent literatures on the hierarchical optical path network design algorithm are summarized.

2.5.2 Preceding studies on hierarchal optical path network design algorithm

The approach to solving the hierarchal optical path networks design problem is mainly classified into two categories: the ILP (Integer Linear Programming)-based approach and the heuristic approach. The ILP is expected as a feasible approach to solve an exact optimization if a full knowledge of all the traffic demands is known in advance. For this approach, according to the given condition, the network design problem can be formulated as an ILP model, where specific constraints required in the network design should also be considered. The ILP formulation is widely used in conventional single-layer optical path networks as shown in [2-20]-[2-22], and also in several works, ILP-based approach is introduced to the hierarchical optical path networks [2-3], [2-13], [2-23]. However, due to the high complexity of the hierarchical optical path network design problem, the optimal solution can be applicable only to the very limited conditions, e.g., very small scale network topologies and to accommodate very small traffic volume in the network.

On the other hand, a heuristic-based approach is adopted to obtain more practical solutions which are sub-optimal. For the hierarchical optical path networks, minimization of the total network cost necessary to accommodate given traffic demand is considered as one of the general objectives. With this objective, various hierarchical optical path network design algorithms have been developed under different conditions, and the results proved that the introduction of path hierarchy can reduce total facility cost substantially [2-5] [2-10] [2-13] [2-23][2-24], even for hybrid- hierarchical optical path networks consisting of electrical cross-connects standardized in optical transport network [2-23], MLR (Mixed Line Rate) networks [2-24] or elastic optical path networks [2-10]. A comprehensive review of the advancements in hierarchical optical path networks can be found in [2-13]. For the hierarchical optical path networks, the estimated facility cost can also be reduced by up to 45% in a 9x9 regular mesh network, when the average number of wavelength paths between each node pair is 8 (Fig. 2-8, [2-5]). On the contrary, in the small traffic demand area, the wavelength/waveband continuity constraints make it difficult for wavelength/waveband paths to fully utilize the fiber capacity; as a result, the total network cost cannot be reduced. Therefore, attaining cost-effectiveness in this area will expand the effectiveness of hierarchical optical path networks and promote their introduction.

In this thesis, to analyze the cost reduction effectiveness possible with the introduction of different types of convertors (i.e., both or either of wavelength/waveband convertor) to hierarchical optical path networks, novel hierarchical optical path network design algorithms based on multi-stage ILP or heuristics that can obtain a sub-optimal results in a realistic calculation time are proposed. The details will be presented in the Chapter 4.

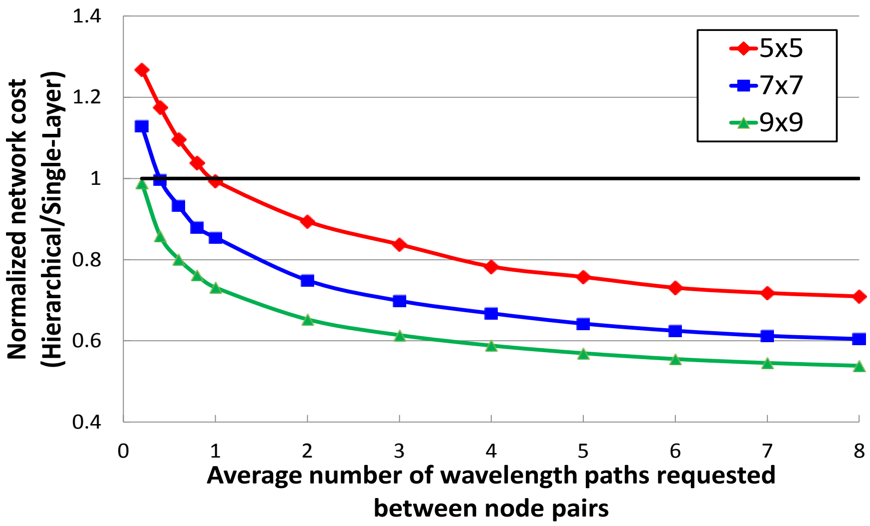


Figure 2-8. Cost comparison between hierarchical and single-layer optical path networks for wide range of traffic demand [2-5].

2.6 Summary

In this chapter, a comprehensive review of waveband switching, including node architecture, related device technologies, and recent studies on the hierarchical optical path networks, are described. The key concept of waveband routing is to group several wavelength paths and processed them as one entity; therefore, cost-effective networks can be achieved. Moreover, with the development of PLC technologies, a further cost reduction will be expected by using silicon photonics technologies in the future. However, due to the difficulty in the hierarchical optical path network design problem, further issues including attaining the cost reduction effectiveness in small traffic demand area is still to be solved. To exploit the advantage of waveband switching to create future bandwidth-abundant photonic networks, the network design algorithms for hierarchical optical path networks introducing wavelength/waveband conversion are developed, and its cost reduction effectiveness is verified. This new content will be presented in Chapter 4.

References

[2-1] K. Harada, K. Shimizu, T. Kudou, and T. Ozeki, "Hierarchical optical path cross-connect systems for large scale WDM networks," *OSA Optical Fiber Communication Conference, (OFC)*, vol. 2, pp. 356-358, San Diego, USA, February 1999.

[2-2] L. Noirie, C. Blaizot, and E. Dotaro, "Multi-granularity optical cross-connect," *IEEE European Conference on Optical Communication (ECOC)*, vol. 3, pp.269-270, Munich, Germany, September 2000.

[2-3] X. Cao, V. Anand, and C. Qiao, "Waveband switching in optical networks," *IEEE Communications Magazine*, vol. 31, no. 4, pp. 105-112, April 2003.

[2-4] K. Sato and H. Hasegawa, "Optical networking technologies that will create future bandwidth-abundant networks," *IEEE-OSA Journal of Optical Communications and Networking (JOCN)*, vol. 1, no. 2, pp. A81- A93, July 2009.

[2-5] I. Yagyu, H. Hasegawa, and K. Sato, "An efficient hierarchical optical path network design algorithm based on a traffic demand expression in a Cartesian product Space," *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 26, no. 6, pp. 22-31, August 2008.

[2-6] K. Ishii, H. Hasegawa, K. Sato, M. Okuno, and H. Takahashi, "Ultracompact waveband cross-connect module using waveband selective switches: development and performance verification," *IEEE Photonics Technology Letters (PTL)*, vol. 22, no. 23, pp. 1741-1743, December 2010.

[2-7] K. Takaha, T. Ban, H. Hasegawa, K. Sato, H. Takahashi, and M. Okuno, "Development of ultra-compact 8x8 waveband cross-connect," *OSA OptoElectronics and*

Communications Conference (OECC), paper WT2-3, Kyoto, Japan, July 2013.

[2-8] I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath communications: an approach to high-bandwidth optical WAN's," *IEEE Transactions on Communications*, no. 40, vol. 7, pp. 1171–1182, July 1992.

[2-9] R. Izmailov, S. Ganguly, V. Kleptsyn, A. C. Varsou, "Non-uniform waveband hierarchy hybrid optical networks," *Proceeding of IEEE Computer and Communications (INFOCOM)*, vol. 2, pp. 1344-1354, San Francisco, USA, March 2003.

[2-10] S. Varma and J. P. Jue, "Regenerator Placement and Waveband Routing in Optical Networks with Impairment Constraints," *IEEE International Conference on Communications (ICC)*, Kyoto, Japan, June 2011.

[2-11] A. Jirattigalachote, Y. Yamada, C. Cavdar, P. Monti, L. Wosinska, H. Hasegawa, and K. Sato, "Impairment-Aware Routing and Waveband Assignment for Efficient Optical Transport Networks," *OSA Optical Fiber Communication Conference (OFC)*, paper OW3A2, Los Angles, USA, March 2012.

[2-12] Y. Wang, and X. Cao, "Multi-Granular Waveband Assignment and Protection in WDM Networks," *IEEE/OSA Journal of Lightwave Technology (JLT)*, vol. 28, no. 13, pp. 2004-2013, May 2010.

[2-13] Y. Wang, and X. Cao, "Multi-granular optical switching: A classified overview for the past and future," *IEEE Communications Surveys & Tutorials*, vol. 14, no. 3, pp. 698-713, third quarter, 2012.

[2-14] S. Kakehashi, H. Hasegawa, K. Sato, O. Moriwaki, and S. Kamei, "Analysis and development of fixed and variable waveband MUX/DEMUX utilizing AWG routing functions," *IEEE/OSA Journal of Lightwave Technology (JLT)*, vol. 27, no. 1, pp. 30-40, January 2009.

[2-15] K. Sato, and H. Hasegawa, "Prospects and challenges of multi-layer optical networks," *IEICE Transactions on Communications*, vol. 90, no. 8, pp. 1890-1902, August 2007.

[2-16] "Interfaces for the Optical Transport Network (OTN)," ITU-T Recommendation, G.709/Y.1331, December 2009.

[2-17] K. Sato, "OOO Switching – The role and technological advances," *OSA Optical Fiber Communication Conference (OFC)*, paper NThB1, Los Angles, USA, March 2011.

[2-18] H. Song, O. Tadanaga, T. Umeki, I. Tomita, M. Asobe, S. Yamamoto, K. Mori, and K. Yonenaga, "Phase-transparent flexible waveband conversion of 43Gb/s RZ-DQPSK signals using multiple-OPM-LN waveguides," *OSA Journal Optics Express*, vol. 18, no.15, pp. 15332-15337, July 2010.

[2-19] T. Miyazawa, and H. Harai, "OpenFlow-based waveband selection control interlocked with dynamic resource allocation in an optical packet and circuit integrated network,"

Proceedings of International Conference on SDN/MPLS, Washington DC, USA, November 2014.

[2-20] H. Zang, J. P. Jue, and B. Mukherjee, “A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks,” *Springer Optical Networks Magazine*, vol. 1, no. 1, pp. 47-60, January 2000.

[2-21] J. Zheng, and H. T. Mouftah, *Optical WDM Networks: Concepts and Design Principles*, Hoboken, USA: Wiley-IEEE Press, July 2004.

[2-22] M. Tornatore, G. Maier, and A. Pattavina, “WDM network design by ILP models based on flow aggregation,” *IEEE/ACM Transactions on Networking*, vol. 15, no. 3, pp. 709-720, June 2007.

[2-23] H. Le, H. Hasegawa, and K. Sato, “Hybrid-hierarchical optical path network design algorithms utilizing ILP optimization,” *Elsevier Journal of Optical Switching and Networking (OSN)*, vol. 8, no. 4, pp. 226–234, August 2011.

[2-24] S. Ferdousi, A. Nag, A. Reaz, M. Tornatore, and B. Mukherjee, “Mixed-line-rate optical network design with wavebanding,” *Elsevier Journal of Optical Switching and Networking (OSN)*, vol. 9, no .4, pp. 286-296, November 2012.

Chapter 3
ELASTIC OPTICAL PATH NETWORKS

This chapter presents a comprehensive overview of elastic optical path networks that can achieve flexible spectrum allocation, where the minimum spectral resources can be adaptively allocated based on the network condition. The elastic optical path networks can maximize the fiber resource utilization efficiency, and significantly effectiveness on reducing link cost can be expected compared with the conventional fixed grid networks with fixed bandwidth and fixed channel spacing. In this chapter, the overview of elastic optical path network, including its enabling technologies, and the introduction benefits are described. The network design problem for elastic optical path networks and related design algorithms are also summarized.

3.1 Introduction

Transmission systems that accommodate 100 Gbps signals have been widely introduced in the backbone network to cope with the relentless traffic increase. For the currently WDM networks, the available optical spectrum range (C-band, with a frequency range from 191. 6 to 195.9 THz) is divided into several fixed spectrum grids (e.g., 50 GHz/100 GHz) which are named as ITU-T grid, and each arriving bitrate signal is assigned to one ITU-T grid. The photonic networks introducing the fixed ITU-T grid is called as fixed grid optical path network. Unfortunately, the existing fixed grid systems are inefficient in supporting future higher bitrate signals, such as 400 Gbps and 1 Tbps which are now considered as a standard transmission bitrate by both telecom and datacom industries (The transmission technologies that support the future higher bitrate rates are summarized in [3-1]); therefore, maximizing fiber spectral utilization is a critical issue to attain cost-effectiveness. The elastic optical path networks ([3-2]-[3-5], also named as "flexible grid optical path networks" in this thesis) have been proposed and standardized in ITU-T [3-6]. They offer the minimum slot width granularity (e.g. 12.5 GHz) and enable the allocation of frequency slots with different widths as needed. By allocating several contiguous 12.5 GHz width frequency slots adaptively to the different channel bandwidth demands, flexible grid networks can minimize the required total number of allocated frequency slots, which results in higher frequency utilization than conventional fixed grid systems [3-7]-[3-10]. Recent advances in related technologies including coherent optical orthogonal frequency-division multiplexing (CO-OFDM)[3-11], Nyquist-WDM [3-12] offer the possibility for envisioning fully flexible optical networks. Thherefore, the flexible grid networks are expected to be adopted as the next generation optical networks to cope with the future increasing dynamic traffic demands.

In this chapter, the fundemental concept of flexible grid optical path networks, including its introduction benefits and enabling technologies, also the future challenge is described. Then, the network model of flexible grid networks is also illustrated, and finally, the flexible grid network design problem and its related literatures on the network design algorithms are summarized.

3.2 Concept of elastic optical path

Figure 3-1 shows the spectrum assignment for different types of networks. Current WDM networks use fixed grid networks that include single line rate (SLR) networks with uniform bitrate channels, and mixed line rate (MLR) networks that accommodate several different bitrate signals simultaneously. The fixed grid networks (SLR and MLR in Fig. 3-1) are developed from middle of 1990s, and all the channels are equally spaced as a fixed ITU-T grid (e.g., 50 GHz) to meet the requirement of conventional WDM systems. Since the frequency grid spacing tends to be broader than the channel bandwidths utilized, the frequency utilization is limited, especially for the cases where various types of transmission systems co-exist in the networks. Instead of a rigid frequency grid, a flexible frequency grid with a fine granularity is expected to lead to a significant spectrum savings.

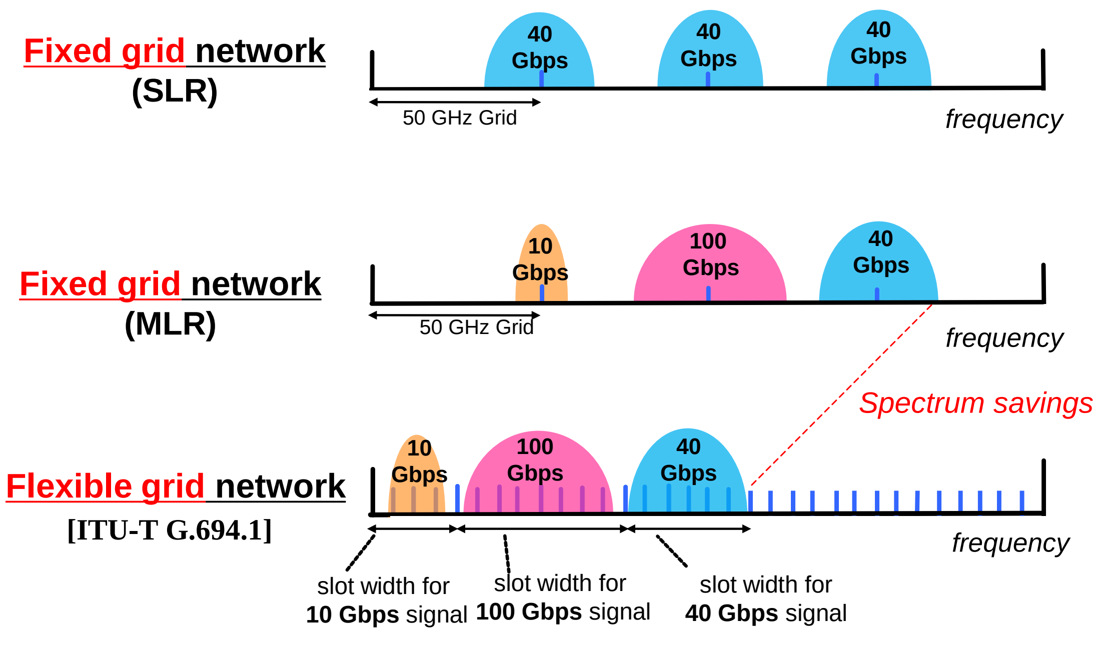
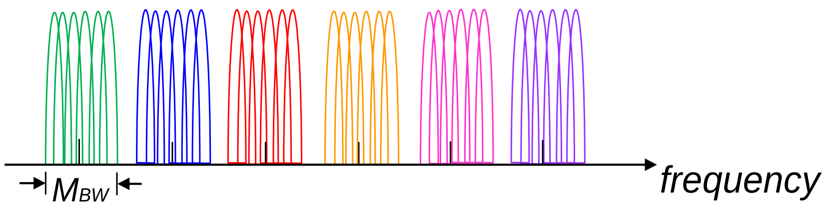


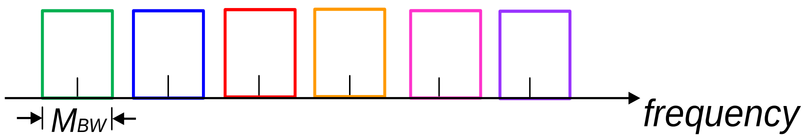
Figure 3-1. Spectrum assignment in fixed grid and flexible grid networks.

The flexible grid networks [3-2] can utilize spectrum resources more efficiently. Their channel central frequencies of different bitrate signals can be arbitrarily selected with a minimum granularity (e.g., 6.25 GHz [3-6]), and can allocate multiple frequency slots as needed. The flexible grid networks can be enhanced to maximize the spectral efficiency through the use of a set of sophisticated technologies such as CO-OFDM [3-11] or Nyquist-WDM [3-12].

Figure 3-2 compares the super-channel generation, where multiple optical carriers are combined to create a unified channel of a higher data rate, between CO-OFDM and Nyquist-WDM. The CO-OFDM uses multiple orthogonal subcarriers with a frequency spacing that is equal to bitrate. The adaptive bitrate modification of the optical path can be achieved by changing the subcarrier number. For the Nyquist-WDM, the subcarriers are shaped as almost rectangular frequency spectrum that is close to the Nyquist limit for transmission without interference-free transmission. These subcarriers are multiplexed with spacing which is close or equal to the bitrate with limited inter-subcarrier crosstalk.



(a) CO-OFDM



(b) Nyquist-WDM

Figure 3-2. Generation of super-channel by different techniques.

Moreover, the improvement of spectral efficiency can also be achieved by the adaptive modulation scheme including bitrate adaptive modulation and distance adaptive modulation. For bitrate adaptive modulation, the number of frequency slots assigned to each path is tailored to the service bitrate [3-13]. Meanwhile, for distance adaptive modulation, the maximum number of bits per symbol is selected for each path, subject to the given transmission characteristic such as OSNR (Optical Signal-to-Noise Ratio) degradation [3-14]. It should be noted that, as shown in Fig. 3-3, the high bitrate signals are difficult to transmit over long distances at high spectral efficiency since higher order modulation format is utilized. Regarding the distance adaptive modulation scheme, usually finer granularity bit rate sets are assumed since the modulation format will be changed according to the transmission distance. This raises the transponder and network operation costs significantly over those of the simple flexible grid system. The objective of this thesis is to develop cost-effective photonics networks that are applicable to not only backbone networks, but also the metro networks, and hence, bitrate adaptive modulation scheme is assumed in this thesis. The impact of introducing higher bitrate signals, i.e., 400 Gbps and 1 Tbps, which are expected to be deployed in the future, will also be verified.

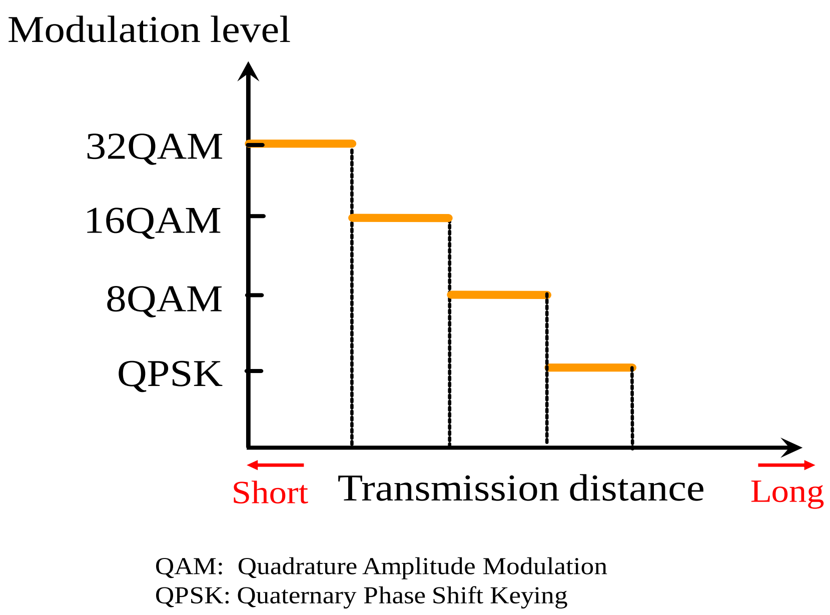


Figure 3-3. The relationship between modulation level and transmission distance.

3.3 Elastic optical path network architecture

Figure 3-4 shows an example model of flexible grid ROADMS with C/D/C (Colorless/Directionless/Contentionless) function. Here, "colorless" means that any wavelength path in a fiber can access to a transponder, "directionless" means that any transponder can be connected to any input/output fiber, and "contentionless" means that any connection can be established regardless of the other connections. This C/D/C adds/drop capability is essential to create the next generation optical path networks that can support future dynamic optical path operation.

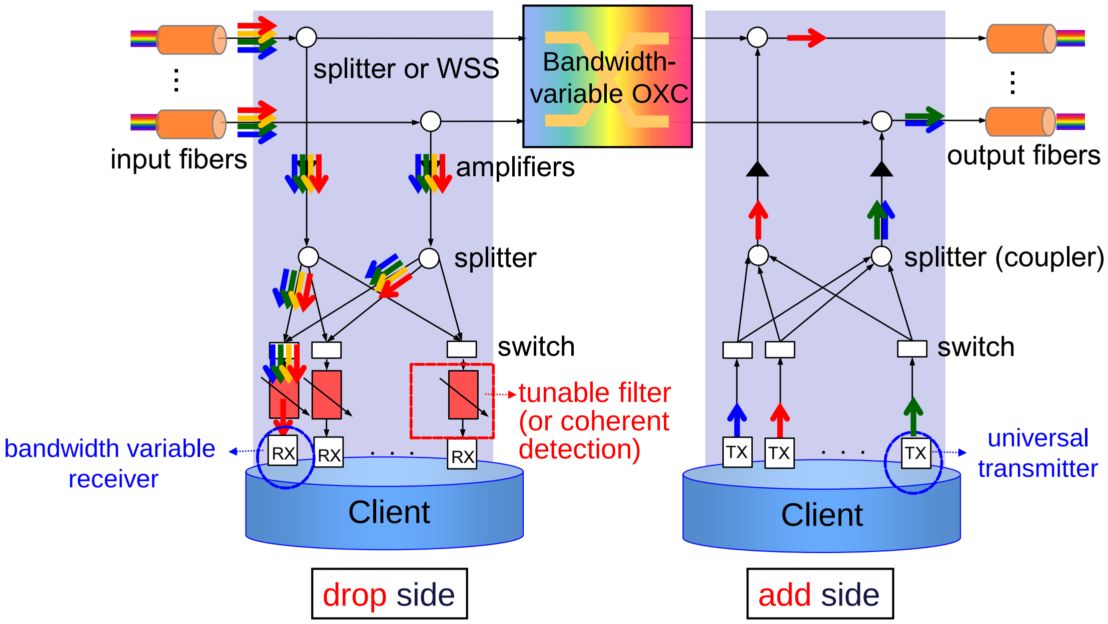
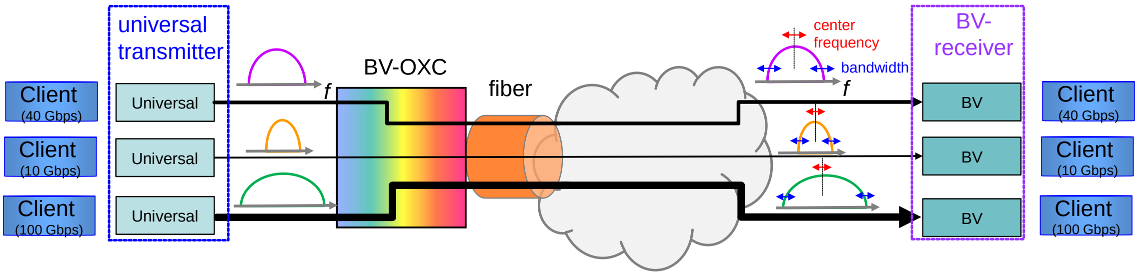
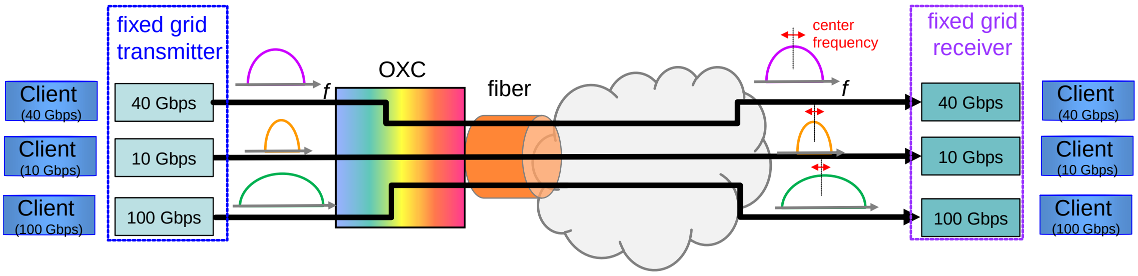


Figure 3-4. A model for a flexible grid ROADM architecture offering C/D/C function.

The key components to construct the flexible grid networks are ROADMs (The similar ones as the fixed grid based system), bandwidth-variable (BV) transponder (consisting of transmitter and receiver), bandwidth-variable OXC (BV-OXC). Figure 3-5 shows the network models for using different types of transponders. For the BV-transponder (Fig. 3-5(a)) introduced in flexible grid networks, by using the CO-OFDM or Nyquist-WDM (See Section 3.2), it can generates the optical signal using just enough spectral resource for transmitting the optical signal, that is to say, it can provide the capability to adapt various properties (modulation format/bitrate) of the transmitted optical signal, in contrast to dedicated bitrate signals (e.g. 10/40/100 Gbps in Fig. 3-5(b)) transponders implemented in the conventional fixed grid networks. Since the introduction of BV-receivers, at the drop side of the ROADM, to accommodate different bitrate signals, a tunable filter function is required [3-9]. This filter needs to tune both passband center frequency and passband bandwidth with a granularity of 6.25 GHz and 12.5 GHz, respectively (More details can be found in Chapter 5). It can be realized by introducing large port count WSS, or coherent detection technology, however, the related research is still in the initial stage, and therefore, flexible grid based transponder is still costly compared with the conventional fixed grid based transponder [3-15].



(a) Bandwidth variable transponders for flexible grid networks



(b) Fixed grid based transponders for fixed grid networks

Figure 3-5. Network models for using different types of transponders.

Meanwhile, the BV-WXC can be constructed by using BV-WSS with broadcast and select function for adding/dropping the optical signals (It is similar to the conventional fixed grid networks case where WSSs are utilized to construct the OXC). An example of a BV-WXC composed of BV-WSS is shown in Fig. 3-6. The basic function of BV-WSS is illustrated in Fig. 3-7. BV-WSSs enable the forwarding of channels having arbitrary spectral widths to arbitrary output ports. Thanks to the development of liquid crystal on silicon (LCoS)/digital light processing (DLP) technologies, advanced BV-WSSs have been commercially available (e.g., Finisar Flexgrid^{TM} WSS). More information of the cost/energy consumption parameter settings for different photonics network components can be found in Chapter 5-3

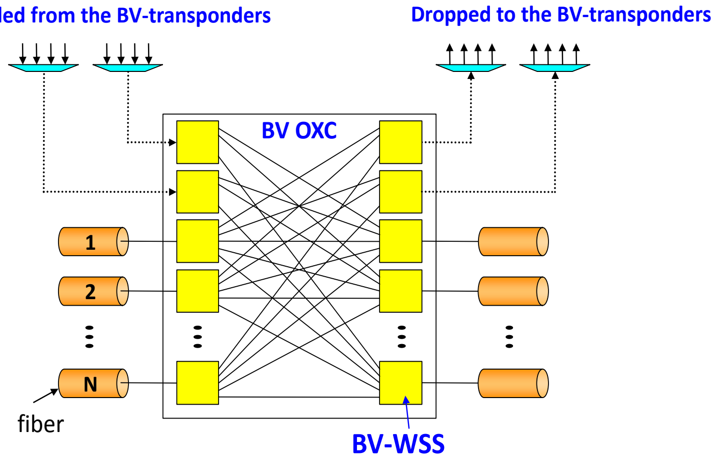


Figure 3-6. A model for a BV-OXC consisting of BV-WSS.

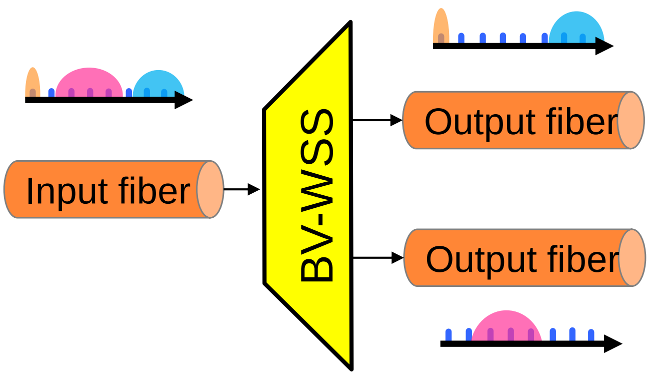


Figure 3-7. A simple model for a 1x2 BV-WSS.

3.4 Elastic optical path network design problem

3.4.1 Problem statement

As mentioned in Chapter 2.5, the design problem for the conventional fixed grid based networks is called as the routing and wavelength assignment (RWA) problem. For the flexible grid networks, the network design problem is called as routing and spectrum assignment (RSA) problem. Similar with the conventional fixed grid networks where an optical path should utilize a same wavelength index on all the fibers it traverses (wavelength continuity constraint). For the flexible grid networks case, the adaptive spectrum allocation introduces more severe constraint than the wavelength continuity constraint in terms of maintaining a same spectrum on each fiber traversed by the route (spectrum continuity constraint). This constraint makes the RSA problem much more difficult. The RSA problem is solved by searching for an available route while guaranteeing the required number of consecutive vacant slots along this route. If there is additional flexibility in the selection of modulation format, the design problem for flexible grid network is called as routing, modulation level, and spectrum allocation (RMLSA) problem

[3-14]. In this thesis, the bitrate adaptive modulation scheme is assumed where the modulation level for each bitrate signal is fixed, and therefore, the network design problem tackled in this thesis is a RSA problem.

Theoretically the RWA problem can be regarded as a special problem of RSA where each optical path occupies a same bandwidth in the fibers. However, even the RWA problem is known to be NP-complete, introducing adaptive spectrum allocation makes the problem much more difficult, and basically it is impossible to obtain the optimal solution for the flexible grid networks, especially for the dynamic network design problem where the optical path are dynamically setup/released. Most of literatures tended to adopt heuristic-based RSA algorithms to obtain sub-optimal solutions. In the next section, related proposed dynamic network design algorithms for flexible gird networks are summarized.

3.4.2 Preceding studies on elastic optical path network design algorithm

For the flexible grid networks, when a path connection is setup, continuous frequency slots to suit the signal bitrate should be allocated on each fiber along the route between the source and destination nodes. Since the required slot width for different bitrate signals can be varied, during the iterative path setup/release operation process, the free contiguous spectrum blocks become fragmented into smaller ones, and eventually, it often becomes impossible to allocate required frequency slot widths for any arriving signals. This problem is similar to the memory fragmentation problem in computer memory management. The spectrum fragmentation strongly depends on the transponders granularity diversity, that is to say, the more types of bitrates occupying different frequency slot width introducing in the network, the more severe of the spectrum fragmentation [3-16]. The spectrum fragmentation in the available spectrum resource reduces the potential capacity gains, and degrades the network performance.

Various algorithms were proposed to alleviate the spectrum fragmentation degree in the networks, and their objective is to minimize the total path setup blocking ratio in the network. In general, these studies can be classified into three aspects: 1) Using the internal fragmentation metric [3-17][3-18]; 2) Dividing the available fiber spectrum into several dedicated/shared area according to the signal bitrate [3-19]; 3) Reroute the existing connections.

For the first technique, the authors utilized different internal fragmentation metrics (such as utilization entropy [3-17] and Shannon entropy [3-18]) to quantify the spectrum fragmentation degree in the links in the network (or the links traversed by the path candidates), here, a low utilization entropy value indicates that the resource is used in an ordered form with fewer spectral gaps on the slot usage in the fiber (low level of fragmentation). During the RSA process, the entropy related metric is applied in the links while searching for the available route and frequency slot candidates with lowest resulting entropy values. However, the effectiveness of this technique is only verified in the case considering the incremental traffic scenarios; while its effectiveness on the dynamic traffic scenarios is limited.

In the conventional fixed grid networks, since each bitrate signal occupies the same bandwidth (ITU-T grid), no spectrum fragmentation occurred in the networks. The most direct way to eliminate the spectrum fragmentation is to divide the available fiber spectrum range into several non-overlapping areas where the same types of bitrates signals are assigned to each specific area exclusively, furthermore, a hybrid shared area strategy where the types of bitrate signals that can be shared is limited were also proposed [3-19]. However, for the dynamic traffic scenarios, this strategy requires high complexity in network control plane since the difficulty in obtaining optimal partitioning solutions. In Chapter 6, an improved spectrum area division strategy is proposed, and its effectiveness has also been verified.

Rerouting of existing connections (paths) can be triggered to reduce the blocking of new connection demands. This technique is also called as “spectrum defragmentation technique”. In this process, the frequency slot (sometimes the route) assigned to the original existing path will be reconfigured for accommodating a new arriving connection demand. Therefore, the disruption of existing connections may happen, and one of the main operation requirements for the defragmentation technique is to minimize the disruption time during the whole rerouting process. The authors in [3-20] proposed a novel make-before-break rerouting technique which establishes rerouting paths on alternative routes and assigns frequency slots before releasing the original optical paths. When coupled with delay management techniques defined for OTN [3-21], truly hitless rerouting can be realized. An improved algorithm utilizing the make-before-break technique will be discussed in Chapter 6.

3.5 Summary

In this chapter, a review of elastic optical path networks, including technologies for realizing the flexible frequency grid granularity and the node architecture are described. Since this flexible grid-based system can exploit the available fiber spectrum resource in maximum, if the hardware requirements in the transceiver side can be released, this novel network can be expected to achieve future bandwidth-abundant networks cost-effectively. To achieve this objective, a novel elastic optical path network (called as “semi-flexible grid networks”) where each specific bitrate signal use its own dedicated fixed grid is proposed and it will be described in Chapter 5. On the other hands, the network design problem for elastic optical path networks and related design algorithms on them are also summarized. Furthermore, a novel elastic optical path network design algorithm that minimizes disruption in spectrum defragmentation and bitrate-dependent blocking will be discussed in Chapter 6.

References

[3-1] E. Ip, P. Ji, E. Mateo, Y. Huang, L. Xu, D. Qian, N. Bai, and T, Wang, “100G and beyond transmission technologies for evolving optical networks and relevant physical-layer issues,” *Proceedings of IEEE*, vol. 100, no. 5, pp. 1065-1078, May 2012.

[3-2] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, “Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies,” *IEEE Communications Magazine*, vol. 47, no. 11, pp. 66-73, November 2009.

[3-3] O. Gerstel, M. Jinno, A. Lord, and S. J. B. Yoo, “Elastic optical networking: A new dawn for the optical layer?” *IEEE Communications Magazine*, vol. 50, no. 2, pp. 12-20, February 2012.

[3-4] S. Gringeri, B. Basch, V. Shukla, R. Egorov, and T. J. Xia, “Flexible architectures for optical transport nodes and networks,” *IEEE Communications Magazine*, vol. 48, no. 7, pp. 40-50, July 2010.

[3-5] I. Tomkos, S. Azodolmolky, J. Sole-Pareta, D. Careglio, and E. Palkopoulou, “A tutorial on the flexible optical networking paradigm: state of the art, trends, and research challenges”, *Proceedings of the IEEE*, vol. 102, no.9, pp. 1317-1337, June 2014.

[3-6] “Spectral grids for WDM applications: DWDM frequency grid,” ITU-T Recommendations G.694.1, February 2012.

[3-7] A. Klekamp and U. Gebhard, “Benefits for mixed-line-rate (MLR) and elastic networks using flexible frequency grids,” *OSA European Conference and Exhibition on Optical Communication (ECOC)*, paper Mo.1.D.1, Amsterdam, Netherlands, September 2012.

[3-8] M. Angelou, K. Christodoulopoulos, D. Klonidis, A. Klekamp, F. Buchali, E. Varvarigos, and I. Tomkos, “Spectrum, Cost and Energy Efficiency in Fixed-Grid and Flex-Grid Networks,” *OSA Optical Fiber Communication Conference (OFC)*, paper NM3F.4, Los Angeles, USA, March 2010.

[3-9] S. Woodward and M. Feuer, “Benefits and requirements of flexible-grid ROADMs and Networks,” *IEEE/OSA Journal of Optical Communications and Networking (JOCN)*, vol. 5, no. 10, pp. A19-A27, October 2013.

[3-10] N. Yoshikane, K. Igarashi, and T. Tsuritani, “Comparison of network cost and power consumption between a single-line-rate network and a flexible-bitrate network in the beyond-100-Gb/s networks era,” *OSA Optical Fiber Communication Conference (OFC)*, paper NW3E.4, Anaheim, USA, March 2013.

[3-11] W. Shieh, H. Bao, and Y. Tang, “Coherent optical OFDM: theory and design,” *Journal of Optics Express*, vol. 16, no. 2, pp. 841-859, January 2008.

[3-12] G. Bosco, V. Curri, A. Carena, P. Poggiolini, and F. Forghieri, ‘‘On the performance of Nyquist-WDM terabit superchannels based on PM-BPSK, PM-QPSK, PM-8QAM or PM-16QAM subcarriers,’’ *IEEE Journal of Lightwave Technology (JLT)*, vol. 29, no. 1, pp. 53–61, January 2011.

[3-13] K. Christodoulopoulos, I. Tomkos, and E. A. Varvarigos, "Elastic bandwidth allocation in flexible OFDM-Based optical networks," *IEEE/OSA Journal of Lightwave Technology (JLT)*, vol. 29, no. 9, pp. 1354-1366, May 2011.

[3-14] B. Kozicki, H. Takara, Y. Sone, A. Watanabe, and M. Jinno, "Distance-adaptive spectrum allocation in elastic optical path network (SLICE) with bit per symbol adjustment," *OSA Optical Fiber Communication Conference (OFC)*, paper OMU3, San Diego, USA, March 2010.

[3-15] F. Rambach, B. Konrad, L. Dembeck, U. Gebhard, M. Gunkel, M. Quagliotti, L. Serra, and V. López, "A multilayer cost model for metro/core networks," *Journal of Optical Communications and Networking (JOCN)*, vol. 5, no. 3, pp. 210–225, March 2013.

[3-16] D. Amar, E. Le Rouzic, N. Brochier, J.-L. Auge, C. Lepers, N. Perrot, and S. Fazel, "How problematic is spectrum fragmentation in operator's gridless network?" *IEEE International Conference on Optical Network Design and Modeling (ONDM)*, paper S3_4, Stockholm, Sweden, May 2014.

[3-17] X. Wang, Q. Zhang, I. Kim, P. Palacharla, and M. Sekiya, "Utilization entropy for assessing resource fragmentation in optical networks," *OSA Optical Fiber Communication Conference (OFC)*, paper OTh1A.2, Los Angeles, USA, March 2012.

[3-18] P. Wright, M. C. Parker, and A. Lord, "Simulation results of Shannon entropy based flexgrid routing and spectrum assignment on a real network topology," *OSA European Conference and Exhibition on Optical Communication (ECOC)*, paper We.2.E.4, London, UK, September 2013.

[3-19] R. Wang, and B. Mukherjee, "Spectrum management in heterogeneous bandwidth optical networks," *Elsevier Journal of Optical Switching and Networking (OSN)*, vol. 11, pp. 83-91, January 2014.

[3-20] T. Takagi, H. Hasegawa, K. Sato, Y. Sone, A. Hirano, and M. Jinno, "Disruption minimized spectrum defragmentation in elastic optical path networks that adopt distance adaptive modulation," *OSA European Conference and Exhibition on Optical Communication (ECOC)*, paper Mo.2.K.3, Geneva, Switzerland, September 2011.

[3-21] "Optical Transport Network (OTN): Linear protection," ITU-T Recommendation G.873.1, July 2011.

Chapter 4
HIERARCHICAL OPTICAL PATH NETWORKS WITH WAVELENGTH/WAVEBAND CONVERSION

This chapter presents a comprehensive investigation on the impact of wavelength/waveband convertors in reducing the hierarchical optical path network cost. Firstly, the characteristics of wavelength/waveband convertors are briefly introduced. The network design problem for hierarchal optical path networks introducing either or both wavelength/waveband conversion is also explained. And then the proposed network design algorithms that apply either or both wavelength/waveband conversions are summarized. The algorithms are based on multi-stage integer linear programming (ILP) or heuristics. Numerical evaluation testing on various simulation parameters prove that, by employing either of both wavelength/waveband convertors, hierarchical optical path networks can be cost effective over wide traffic demand ranges and a broad convertor cost range.

4.1 Introduction

Hierarchical optical cross-connects that utilize wavebands (aggregated wavelength paths) [4-1]-[4-8] have been recognized as an important technology that can reduce the scale of the optical switches and the complexity of OXCs/ROADMs currently used in single-layer optical path networks. A critical problem for the hierarchical optical path networks is the selection of the route and waveband for each waveband path can strongly affect the waveband utilization ratios. Therefore, the impact of introducing waveband paths strongly depends on the network design algorithm adopted. As mentioned in the Chapter 2.5, even for the single-layer optical path networks whose optical paths are switched only at the wavelength granularity level, the RWA problem is known to be NP-complete. For hierarchical optical path networks, wavelength paths are routed on a virtual topology whose links represent waveband paths connecting node pairs. In other words, this virtual topology must be optimized whose optimality is defined by a solution of the NP-complete problem. It is therefore basically impossible to obtain optimal solutions for hierarchical optical path network design problems due the excessive computation cost.

It has been shown that the introduction of path hierarchy reduces the total facility cost significantly if the number of wavelength paths is large, i.e. in the large traffic demand area [4-4], [4-6]. For example, the estimated total facility cost of a 9x9 regular mesh network can be reduced up to 45% [4-6]. On the contrary, in the small traffic demand area, the wavelength/waveband continuity constraints make it difficult for wavelength/waveband paths to fully utilize the fiber capacity; as a result, the total network cost cannot be reduced. Therefore, attaining cost-effectiveness in this area will expand the effectiveness of hierarchical optical path networks and promote their introduction.

Introduction of wavelength/waveband conversion is a feasible way to ease these constraints, and by this way, the fiber utilization efficiency can be significantly improved, especially for the small traffic demand area. However, since the waveband/wavelength convertors can be costly devices, to introduce them, a design algorithm that can optimize the trade-offs between fiber cost reduction attained by relaxation of the wavelength/waveband continuity constraints and the convertor cost is needed. Therefore, such algorithms should be carefully designed. To the best of the author's knowledge, no algorithms that consider the waveband convertors or the joint use of both convertors have been investigated so far, and no comparisons of the two types of convertors have been made, even though it is critical to maximizing the benefits of hierarchical optical path networks.

In this chapter, novel network design algorithms for hierarchical optical path networks that carefully select the placement and optimize the trade-off of waveband/wavelength convertors used are proposed. The goal of the proposed algorithm is to minimize the total network cost including the wavelength/waveband convertor costs. Firstly, the feature of wavelength/waveband convertors and the hierarchal optical path networks design problem introducing wavelength/waveband conversion are described. Then, the details of the proposed network design algorithm for hierarchical optical path network introducing wavelength/waveband conversion are explained. Due to the computational complexity of the hierarchal optical path network design problem, the proposed algorithms divide the original problem into some simpler sub-problems and solve them sequentially in order to attain a suboptimal solution within reasonable time. Moreover, for waveband assignment, a key substep that affects the cost reduction effectiveness achieved by the introduction of waveband/wavelength convertors, different novel strategies that consider the cost of waveband/wavelength convertors to minimize the facility cost in this stage are adopted. Numerical experiments show that compared to conventional single-layer optical path networks and hierarchical optical path networks without any conversion, hierarchical optical path networks with either of both wavelength/waveband convertors can be cost-effective over a wide traffic demand area, even when the convertor costs are set at relatively high values.

4.2 Wavelength convertor and waveband convertor

4.2.1 Wavelength convertor

Wavelength convertor [4-9]-[4-13] is an optical device that can convert arbitrary input wavelength index to any desired output wavelength index, as shown in Fig. 4-1. For the transparent WDM network, wavelength convertor is inserted at an intermediate switching node to resolve wavelength continuity constraint for a selected wavelength path, and by this way, the fiber utilization efficiency can be improved. Figure 4-2 shows a simple example of the introducing impact of wavelength conversion in the optical path networks.

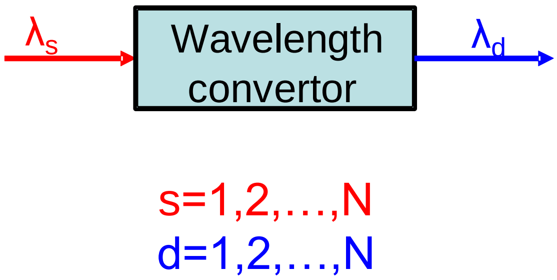
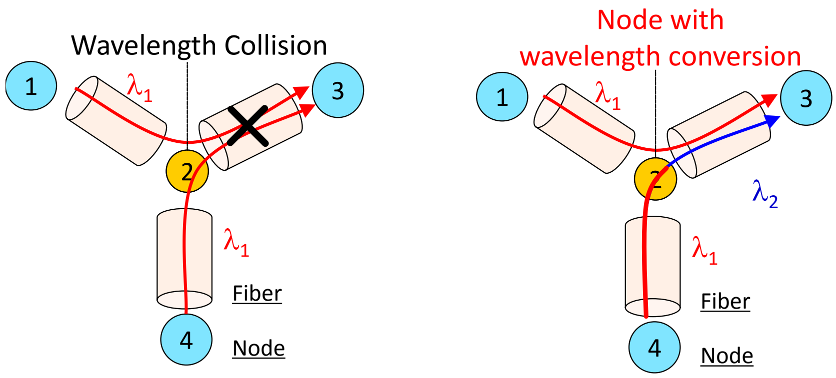


Figure 4-1. Function of a wavelength convertor with full conversion capability.



(a) Without wavelength conversion (b) With wavelength conversion

Figure 4-2. Introducing impact of wavelength conversion.

Wavelength convertors are generally classified into two types: optoelectronic-based conversion and all-optical-based conversion. Nowadays, most of the wavelength conversion function is realized by the optoelectronic-based technology, in this case, the input optical signal to be converted is firstly translated into electronic signal in the electronic domain by a photo-detector, and then, this electronic signal is converted to the optical signal with a desired wavelength by a tunable laser. However, the dispersion and nonlinearities in the optical fiber severely limits the transmission distance, and this method has been proved to be available for only the low bitrate signals (up to 10 Gbps) [4-9]. Meanwhile, the required O/E/O conversion strongly hinders the introduction of WDM technology where high fiber utilization efficiency can be achieved in the optical domain, and therefore, all-optical-based wavelength conversion is expected. The all-optical-based wavelength conversion can be achieved by utilizing linear/non-linear optics effects mechanism including gain saturation in semiconductor optical amplifiers (SOAs), interferometric effects, and nonlinear wave-mixing. The details of these mechanisms can be found in [4-11]. Nowadays, research on acheving all-optical-based wavelength conversion has been widely studied: In [4-12], an all-optical wavelength conversion of a 640 Gbps using nonlinear wave-mixing mechanism has been demonstrated. Moreover, this demonstration is realized in a compact silicon photonic chip. In the material research area, the authors identify the mechanism that offers a great potential in improving the overall performance of wavelength conversion materials [4-13].

4.2.2 Waveband convertor

For the hierarchical optical path networks that utilize wavebands (aggregated wavelength paths), the waveband continuity constraint impede the high fiber utilization efficiency. Waveband convertor can be regarded as a direct way to resolve this constraint. As shown in Fig. 4-3, an ideal waveband convertor can convert arbitrary input waveband index to any desired output waveband index [4-14]-[4-15], that is to say, waveband conversion can convert several wavelengths simultaneously. Similar with wavelength convertor, waveband convertor is inserted at an intermediate switching node to resolve waveband continuity constraint for a selected waveband path, and hence, fiber utilization efficiency can be improved. Figure 4-4 shows a simple example of the introducing impact of waveband conversion in the hierarchical optical path networks.

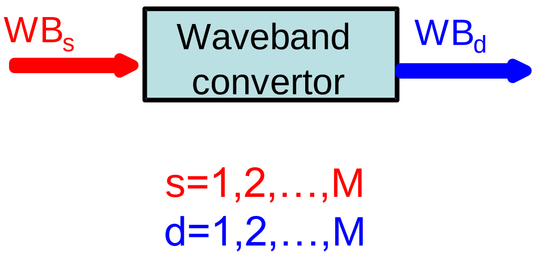
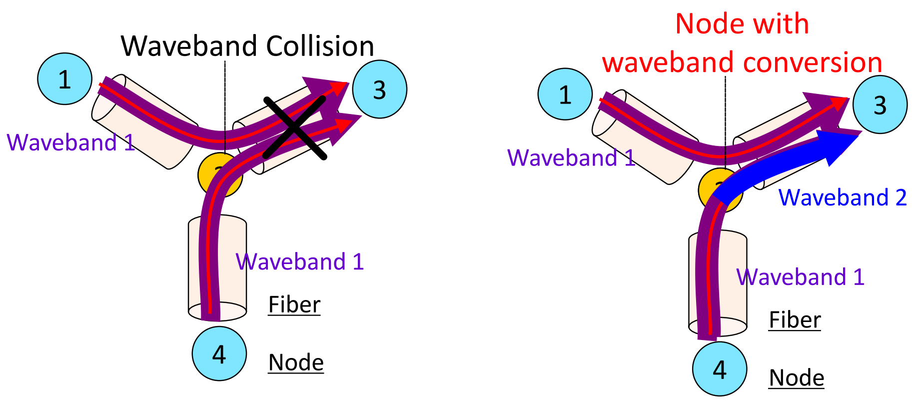


Figure 4-3. Function of a waveband convertor with full conversion capability.



(a) Without waveband conversion (b) With waveband conversion

Figure 4-4. Introducing impact of waveband conversion.

Although the research on realizing waveband conversion is still on the preliminary stage, several experimental demonstrations on the waveband conversion have been reported: The authors in [4-14] describe a multi-wavelength nonlinear wave-mixing model utilized to simulate as a waveband convertor, and its feasibility is implemented experimentally. In [4-15], the authors developed an apodized multi-period quasi-phase-matched $LiNbO_3$ device for low-crosstalk waveband conversion that also uses nonlinear wave-mixing mechanism. It should be noted that, to realize the simultaneous conversion of multiple wavelengths by the currently waveband conversion technology, an input waveband is converted to a new waveband so that each component wavelength is converted symmetrical around the center frequency as show in Figure 4-5. This characteristic is considered in the proposed algorithm for the hierarchical optical path networks considering the waveband conversion function.

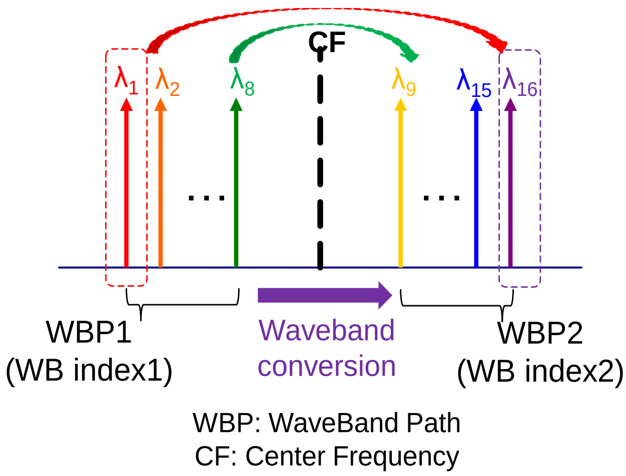


Figure 4-5. Characteristics of waveband conversion.

Both wavelength/waveband conversions require highly-functional devices, and therefore, they can be costly. The effectiveness of their introductions strongly depends on the respective convertor cost. The developed network design algorithm described in this thesis evaluates the cost bound for the wavelength/waveband convertor that can reduce network cost against that of comparable single-layer optical path networks, and the hierarchical optical path networks without any types of conversion.

4.3 Preliminaries

4.3.1 Network cost model

The generic HOXC architecture adopted in this thesis is shown in Figure 4-6. It consists of a BXC for routing higher order waveband paths and a WXC for routing lower order wavelength paths. Wavelength convertors can be applied to NNI ports of WXC, while waveband convertors can be inserted to NNI ports of BXC when necessary. This arrangement yields the node structure called the dedicated wavelength/waveband convertible switch architecture [4-17]. Compared with alternatives such as the ones consider the wavelength/waveband convertor bank, the dedicated architecture offers lower implementation complexity.

The network cost is evaluated by the sum of node cost (Figure. 4-6) and link costs (Figure. 4-7). The costs of node/link are expressed as follows by using the given parameters and variables in Table 4-1 and Table 4-2 respectively. They include a constant that represents the costs of control systems and other overheads. Specific cost values used for the calculations are updated equivalents of the values given in [4-16]. The details of the cost parameters are summarized as follows:

(i) Node cost: BXCs, WXCs and waveband/wavelength convertors

$$C_{Node} = \sum_{i=1}^{N} (C_{B\_NNI} \times B\_NNI_i + C_{B\_UNI} \times B\_UNI_i + C_{BXC} + C_{W\_NNI} \times W\_NNI_i + C_{W\_UNI} \times W\_UNI_i + C_{WXC}) + C_{WC} \times WC + C_{WBC} \times WBC \tag{4-1}$$

(ii) Link cost: optical fiber and amplifiers

$$C_{Link} = \sum_{i=1}^{N}\sum_{j=1}^{N}\left(C_{fiber}(i, j) \times F_{ij}\right) \tag{4-2}$$

where

$$C_{fiber}(i, j) = C_F \times D_{ij} + C_{AMP} \times \left\lfloor \frac{D_{ij}}{D_{AMP}} \right\rfloor \tag{4-3}$$

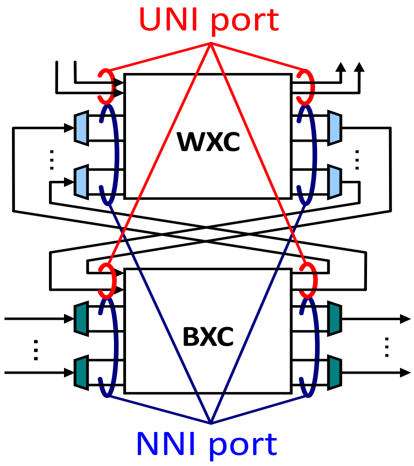


Figure 4-6. Node cost model.

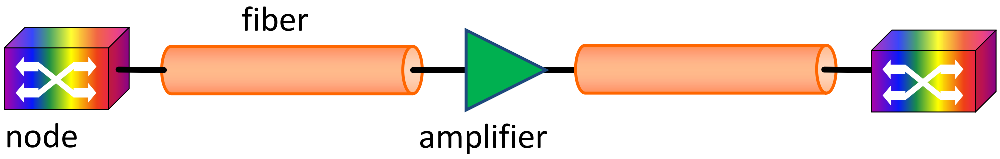


Figure 4-7. Link cost model.

Table 4-1. Parameters for cost evaluation.

Item	Description	Value
C_{B_NNI}	BXC NNI port cost per waveband	1
C_{B_UNI}	BXC UNI port cost per waveband	1.2
C_{BXC}	BXC base cost	4
C_{W_NNI}	WXC NNI port cost per wavelength	1
C_{W_UNI}	WXC UNI port cost per wavelength	1.2
C_{WXC}	WXC base cost	4
C_F	Optical fiber cost per km	0.012
C_{AMP}	Amplifier cost	2.04
C_{WC}	Wavelength convertor cost	(*)
C_{WBC}	Waveband convertor cost	(*)
D_{AMP}	Amplifier span	60
	Network parameters	
W	Maximum number of wavelength per waveband	
B	Maximum number of waveband per fiber	
K	Number of nodes in network	
D_{ij}	Distance between node *i* and node *j*; D_{ij} =0 for node pair that is not physically adjacent to each other.	

(*): Please see the convertor cost evaluation in Section 4-5.

Table 4-2. Variables for cost evaluation.

Item	Description
F_{ij}	Number of fibers between node *i* and node *j*
B_NNI_i	Number of BXC NNI ports at node *i*
B_UNI_i	Number of BXC UNI ports at node *i*
W_NNI_i	Number of WXC NNI ports at node *i*
W_UNI_i	Number of WXC UNI ports at node *i*
WC	Number of wavelength convertor
WBC	Number of waveband convertor

4.3.2 Problem statement

As aforementioned in the Chapter 2, compared with the design problem of the conventional single-layer optical path network, the design problem of hierarchical optical path network is much more difficult due to the complexity of establishing optical paths with different granularities while avoiding wavelength/waveband collisions. Although in the large traffic demand area, the introduction of path hierarchy can significantly reduce the total network facility cost, in contrast, due to the wavelength/waveband continuity constraints, no cost reduction by path hierarchy has been achieved on the small traffic demand area where the fiber utilization efficiency is relatively low [4-4][4-6]. Attaining cost-effectiveness in this small traffic area will expand the effectiveness of hierarchical optical path networks and promote their introduction.

Introduction of wavelength/waveband conversion is a feasible way to ease these constraints. Researches on the hierarchical optical path network design problem evaluating the introduction impact of wavelength conversion have been widely studied. In [4-18], a network design algorithm was proposed that considers 3R regenerator (with the capability of wavelength conversion) optimization subject to a given signal impairment condition. However, this work assumes non-hierarchical multi-granular optical paths (please see the details of this structure in Chapter 2.3.1) and the evaluation assumes a fixed regenerator cost. In [4-19], the authors proposed a hierarchical optical path network algorithm which minimizes the number of total required wavelength convertors while reducing the blocking ratio as much as possible. However, the trade-off between the convertor (cost) impact and the network performance/cost needs further investigation. On the other hand, to the best of our knowledge, no study has evaluated the cost reduction attained by waveband conversion. Indeed, the fact that waveband conversion cannot mitigate wavelength collision directly makes the network design problem evaluating the impact of waveband convertors much more difficult. The difficulty in minimizing the network cost including the convertor cost prevented a sufficient improvement for hierarchal optical path networks introducing wavelength/waveband conversion.

In this chapter, a novel network design algorithm for hierarchical optical path networks that carefully select the placement and optimize the trade-off of wavelength/waveband convertors used is proposed. The goal of this algorithm is to minimize the total network cost including wavelength/waveband convertor cost. All necessary physical resources, including the number of fibers and convertors are constructed, to satisfy a given traffic demand. The cost of resources needed is denoted by a cost function to be minimized (the Section 4.3.1 gives a detailed definition of the cost function and an example of cost parameter values). This study focuses on static network design where the traffic demand is given in advance.

Since the optical path network design problem is known to be NP-complete even if without considering path hierarchy, due to the infeasibility of solving this minimization task, the original optimization problem is divided into two stages as shown in Fig. 4-8: 1) accommodating wavelength paths within waveband paths and routing the waveband paths, and 2) wavelength/waveband index assignment. The second step is still computationally very intensive and so is further divided into two sub-stages: waveband index assignment and wavelength index assignment. For the second and third steps, sub-routines according to requirements on the types of utilized convertors and the scale of networks are proposed. Figure 4-9 shows the flowchart of the proposed algorithms and the requirement classification.

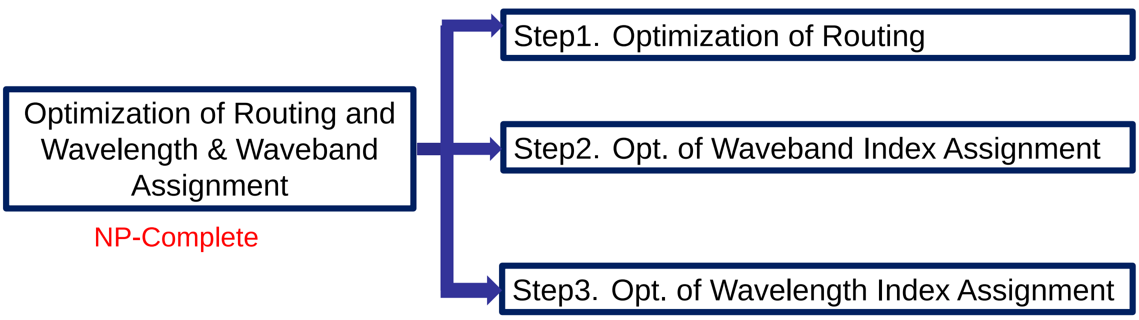


Figure 4-8. Outline of the proposed design algorithm.

	Design algorithm w/ wavelength conversion	Design algorithm w/ waveband conversion	Design algorithm w/ waveband & wavelength conversion
Step1 Accommodation of wavelength paths and routing of waveband paths Chapter 4.4.1	2-stage ILP-based algorithm *Section (A)*		
Step2 Waveband index assignment Chapter 4.4.2	ILP-based algorithm *Section (B-1)* Heuristic-based algorithm *Section (B-2)*	ILP-based algorithm *Section (B-3)* Heuristic-based algorithm *Section (B-4)*	Heuristic-based algorithm *Section (B-5)* Step i. Initial assignment Step ii. Re-assignment
Step3 Wavelength index assignment Chapter 4.4.3	Heuristic-based algorithm *Section (C-1)*	Heuristic-based algorithm *Section (C-2)*	Heuristic-based algorithm *Section (C-1)*

Figure 4-9. Flowchart of the proposed design algorithm.

For the routing sub-step in Step 1, an ILP-based method [Section (A)] can be applied to solve this problem; the number of variables grows linearly with the product of the number of links and the number of nodes [4-20]. However, for the waveband assignment sub-step, the computation load of the ILP-based algorithm (Section (B-1), and (B-3)) rises exponentially with the number of waveband paths to be assigned and therefore it is not possible to obtain useful results in relatively large traffic demand areas by using this method. Since the placement of costly wavelength/waveband convertors is decided in this sub-step and the assignment results definitely affect the total facility cost, some efficient heuristic-based algorithms (Section (B-2), (B-3) and (B-4)) are also proposed for waveband assignment that offer greatly reduced computational complexity. Here a novel heuristic algorithm [Section (B-2) and (B-4)] is adopted to minimize the total number of necessary waveband/wavelength convertors for different convertor usages: For the case considering wavelength conversion, the minimization of the number of wavelength convertors is considered. Wavelength convertors are classified into two types; for conversion between different wavebands and within same wavebands. Similarly classification is performed for the case considering only waveband conversion. These classes of convertors for different usages are minimized in different sub-stages.

On the other hand, for the case considering both wavelength and waveband conversion, a heuristic algorithm in Section (B-5) is utilized to optimize the trade-off between two different costly devices, wavelength and waveband convertors in the initial waveband assignment, and after finishing this process, a waveband re-assignment process is performed to achieve a further reduction in the total cost of necessary wavelength/waveband convertors. Since the previous substep is the major network cost factor, for the wavelength index assignment process, heuristic algorithms is applied for resolving wavelength collision [Section (C-1) and (C-2)] to minimize the necessary equipment cost. This approach substantially reduces the computation load. The procedure of the proposed algorithm is summarized in the next section.

4.4 Network design algorithm for hierarchical optical path networks considering wavelength/waveband conversion

4.4.1 Accommodation of wavelength paths and routing of waveband paths

In this step, establish a set of waveband paths accommodating the given wavelength path demand and assign waveband path routes by using a two-stage ILP based algorithm. The objective is to minimize the total cost of the BXC ports, WXC ports and fibers, including optical amplifiers (see Section 4.3.1). The waveband/wavelength continuity constraints are not considered in this step. The details are summarized as follows:

(A) A 2-stage ILP-based accommodation and routing algorithm

Stage (i) Accommodation of wavelength paths into waveband paths

Create a virtual full mesh graph whose links represent waveband paths connecting each node pairs. Here, the directional waveband link is weighted by the cost of the end-to-end shortest waveband paths connecting each node pairs.

To the established virtual full graph, apply the source flow ILP formulations [4-20], which consider all the requests originating from a single source node as a single commodity to minimize the cost of grooming wavelength paths into waveband paths (represented by total cost of WXC switch ports and wavebands required to accommodate the given traffic demands). In this stage, the source/destination node of each waveband path and the accommodation of each wavelength path into waveband paths can be determined. Here, the wavelength continuity constraint is not considered.

Stage (ii) Routing of waveband paths and fiber setup

By using the waveband traffic demands obtained from the previous stage, establish a virtual full mesh graph whose links represent fibers connecting each node pair. The objective is to minimize the total cost of BXC ports and fibers needed to accommodate all the waveband paths by applying the source flow formulation [4-20]; waveband path continuity constraints are not considered.

4.4.2 Waveband index assignment

In this step, different waveband assignment algorithms are adopted for the hierarchical optical path networks that introduce either wavelength/waveband convertors or both of the convertors. For the case of only wavelength or waveband conversion, an ILP-based algorithm [Section (B-1) and (B-3)] is proposed to obtain sub-optimal solutions for traffic with moderate volumes, and a heuristic-based algorithm [Section (B-2) and Section (B-4)] that covers a wider traffic demand area. The performances of these two algorithms will be compared in the next section. For the case of utilizing both or either wavelength/waveband conversion, a heuristic-based algorithm [Section (B-5)] is developed with consideration of the cost of wavelength convertor

(C_{WC}) and waveband convertor (C_{WBC}); please see Table 4-1 and Table 4-2. The details are as follows:

(B-1) An ILP-based waveband index assignment algorithm for hierarchical optical path networks that employ only wavelength convertors

Formulate the waveband assignment problem through ILP optimization using the following notation:

(a) Input

- L : The set of all unidirectional physical links

- P : The set of all waveband paths that are calculated in Step1.

- B : The set of all waveband indices.

- $T \subset P \times P$: The set of concatenated waveband path pairs traversed by same wavelength paths.

- $wc_{(p_1, p_2)}$: For each $(p_1, p_2) \in T$, this function returns the number of wavelength path traversing p_1 and p_2 .

- $C_{fiber(l)}$: The cost to establish a fiber on a physical link $l \in L$

- c_{WC} : The cost of a wavelength convertor.

NOTE: The cost of a wavelength convertor will be iteratively updated to evaluate cost bound. The details will be explained in the numerical experiment part.

(b) Integer variables

(b-1) Binary variables

- $b_{(p,b)}$: If a waveband index $b \in B$ is assigned to a waveband path p , $b_{p,b} = 1$. Otherwise $b_{p,b} = 0$.

- $y_{(p,l)}$ **:** If a waveband path p traverses a link $l \in L$, $y_{p,l} = 1$. Otherwise $y_{p,l} = 0$.

(b-2) Non-binary variables

- $f_{(l,b)}$ **:** The number of waveband paths with waveband index $b \in B$ traverse a link $l \in L$.

- f_l **:** The number of fibers on a link $l \in L$. That is, $f_l \geq \max_b m_{(l,b)}$

- $e_{(p_1, p_2; b)}$ **:** For the concatenated waveband path pair $(p_1, p_2) \in T$, if the same waveband index $b \in B$ assigned to both waveband paths, $e_{(p_1, p_2; b)} = 1$. Otherwise $e_{(p_1, p_2; b)} = 0$.

- $n_{(p_1,p_2)}$: If wavelength convertors must be inserted at the boundary of concatenated waveband path pair $(p_1,p_2)\in T$, $n_{(p_1,p_2)}=1$. Otherwise $n_{(p_1,p_2)}=0$ $e_{(p_1,p_2)}=0$.

(c) Constraints

(c-1) Waveband assignment constraints:

$$\sum_{b\in B} b_{(p,b)} = 1, \quad \forall p\in P \tag{4-4}$$

Equation (4-4) means that each waveband path p occupies only one waveband index.

(c-2) Fiber constraints:

$$f_{(l,b)} \ge 0, \quad \forall (b,l)\in B\times L \tag{4-5}$$

$$f_l \ge 0, \quad \forall l\in L \tag{4-6}$$

$$\sum_{\forall y_{(p,l)}=1} b_{(p,b)} = f_{(l,b)}, \quad \forall (p,b,l)\in P\times B\times L \tag{4-7}$$

$$f_l \ge f_{(l,b)}, \quad \forall (b,l)\in B\times L \tag{4-8}$$

Constraints (4-5) and (4-6) ensure that the number of fiber laying on a link l is a positive number or zero. Equation (4-7) and constraint (4-8) show that the number of fibers laying on a link l is defined by the maximum number of waveband paths with same waveband index going through that link.

(c-3) Wavelength convertor constraints:

$$e_{(p_1,p_2;b)} \ge -1, \quad \forall (p_1,p_2;b)\in T\times B \tag{4-9}$$

$$n_{(p_1,p_2)} \ge 0, \quad \forall (p_1,p_2)\in T \tag{4-10}$$

$$b_{(p_1,b)} - b_{(p_2,b)} - e_{(p_1,p_2;b)} = 0, \quad \forall (p_1,p_2;b)\in T\times B \tag{4-11}$$

$$n_{(p_1,p_2)} \ge e_{(p_1,p_2;b)}, \quad \forall (p_1,p_2;b)\in T\times B \tag{4-12}$$

If two waveband paths p_1 and p_2 occupy different waveband indices, by equation (4-11), one of $e_{(p_1,p_2;b)}$ will be 1 for some of $b\in B$. Then equation (4-12) restricts $n_{(p_1,p_2)}$ to be equal or larger than 1. The minimization of objective function in (4-13) makes $n_{(p_1,p_2)}$ to be the minimum value in the range [1,∞), and then $n_{(p_1,p_2)}=1$. On the other hand, if p_1 and p_2 occupy the same index, $e_{(p_1,p_2;b)}$ be always 0 for all $b \in B$. Then $n_{(p_1,p_2)}$ will be 0.

(d) Objective

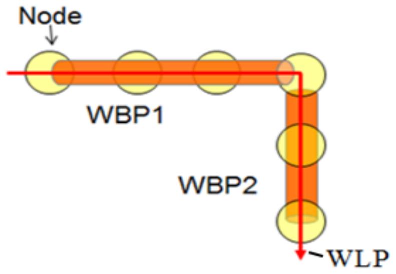
$$\sum_{l \in L} C_{fiber(l)} \times f_l + c_{WC} \times \sum_{(p_1,p_2)\in T} (n_{(p_1,p_2)} \times wc_{(p_1,p_2)}) \qquad (4\text{-}13)$$

The original objective is to minimize the total cost of wavelength convertors and fibers. The cost function includes exact fiber cost and cost for wavelength convertors necessary for wavelength paths that traverse multiple concatenated waveband paths with different waveband indices. In the next stage for wavelength assignment, fibers/wavelength convertors may needed to resolve wavelength collision.

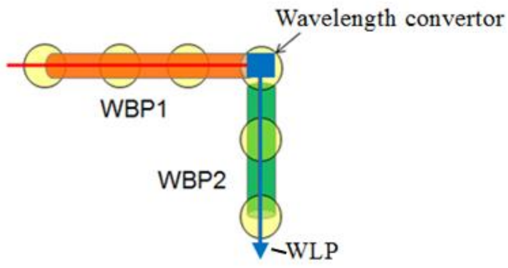
(B-2) A heuristic-based waveband index assignment algorithm for hierarchical optical path networks that employ only wavelength convertors

This section describes the proposed heuristic algorithm for waveband assignment substep when introducing waveband conversion to the hierarchical optical path networks. In assigning wavebands, fibers may be needed to eliminate waveband collision at links. The probability of adding a fiber to one link is independent from that of another link. Here, assume the probability of adding fiber at each link is *p*, so for a *k*-hop count waveband path, the expected number of additional fibers is $k \cdot p$ during the process of assigning a waveband index to the path. Although the independence of fiber addition probability does not hold exactly, the number of waveband/wavelength paths is relatively large and the approximation can be adopted to simplify the situation.

Suppose there is a pair of concatenated waveband paths, each of which carries a group of wavelength paths (See Figure. 4-10). If the same waveband index is assigned to both waveband paths, no wavelength convertor is needed in this process (please note that the later wavelength path index assignment process may introduce a wavelength convertor). However, if different waveband indices are assigned, assign a wavelength convertor to each wavelength path at the boundary node. Therefore, in order to suppress the introduction of wavelength convertors, try to assign the same waveband index to concatenated waveband paths if they carry many wavelength paths.



(a) Without wavelength convertor (*)



(b) With wavelength convertor

WLP=Wavelength path, WBP=Waveband path.

Figure 4-10. Wavelength convertor set in waveband assignment substep.

In summary, it is possible to estimate the potential cost increment to accommodate a pair of concatenated waveband paths from the sum of the hop count of waveband paths and the number of wavelength paths traversing the waveband paths. The algorithm is summarized as follows:

Step1. Let $N(p_1, p_2)$ be the number of wavelength paths that traverse the concatenated waveband path pair (p_1, p_2). Eq. (4-14) is the cost function for (p_1, p_2).

$$C_{(p_1,p_2)} = \max hop(p_1, p_2) + N(p_1, p_2) \tag{4-14}$$

where $\max hop(p_1, p_2)$ represents the maximum of hop counts of waveband paths p_1 and p_2.

Step2. For all concatenated waveband path pairs where each waveband path pair (p_1, p_2) is traversed by at least one wavelength path and at least p_1 or p_2 is not accommodated yet, calculate $C_{(p_1,p_2)}$ in Eq. (1). Find the path pair (p_i, p_j) with largest $C_{(p_i,p_j)}$. If both p_i and p_j are not accommodated yet, find a waveband index for the longest one so that the cost for additional fibers is minimized. For the rest, if the same waveband index can be assigned without adding any fibers, assign that index. Otherwise, assign a waveband index such that the cost of additional fibers is minimized. If p_i or p_j is already accommodated, then follow the latter half of the above procedure. Repeat until all waveband pairs are accommodated.

NOTE: After finishing this step, all waveband paths that are not accommodated yet are end-to-end waveband paths; i.e. each waveband path carries only wavelength paths whose source and destination nodes coincide with those of the waveband path.

(B-3) An ILP-based waveband index assignment algorithm for hierarchical optical path networks that employ only waveband convertors

Use ILP optimization to search for an assignment of waveband indices to all waveband paths established in Section 4.4.1 such that the number of waveband convertors is minimized. Here, the waveband convertors are classified into two classes; one handles express waveband paths, named "waveband convertor for express paths", and the other handles groomed waveband paths to resolve waveband collision at intermediate grooming nodes, named "waveband convertor for grooming operations". Here, express waveband paths at a node are those that pass through the node without grooming operation at the WXC.

Following notation is used to formulate the waveband assignment sub-step through ILP optimization:

(a) Input

- L The set of all unidirectional physical links
- P The set of all waveband paths that are calculated in Section 4.4.1.
- B The set of all waveband indices.
  (The value ranges from 1 to the maximum number of wavelength paths that a waveband path can accommodate)
- $T \subset P \times P$ The set of pairs of concatenated waveband paths where each waveband path pair is traversed by at least one wavelength path.
- $n_{(l)}^{Fiber}$ The number of fibers (obtained from Step1) in a link $l \in L$.

(b) Integer variables

(b-i)Binary variables

- $u_{(p,b)}^{WB}$ If waveband index $b \in B$ is assigned to waveband path *p*, $u_{(p,b)}^{WB} = 1$.Otherwise $u_{(p,b)}^{WB} = 0$.
- $u_{(p,l)}^{WB}$ If waveband path *p* traverses link $l \in L$, $u_{(p,l)}^{WB} = 1$. Otherwise $u_{(p,l)}^{WB} = 0$.
- $cont_{(p_1,p_2;b)}^{WB}$ For concatenated waveband path pair $(p_1, p_2) \in T$, if the same waveband index $b \in B$ is assigned to both waveband paths, $cont_{(p_1,p_2;b)}^{WB} = 1$. Otherwise, $cont_{(p_1,p_2;b)}^{WB} = 0$.

- $n^{WBC.GRM}_{(p_1,p_2)}$ If a waveband convertor is needed to convert groomed waveband paths at the boundary of concatenated waveband path pair $(p_1,p_2)\in T$, $n^{WBC.GRM}_{(p_1,p_2)}=1$. Otherwise $n^{WBC.GRM}_{(p_1,p_2)}=0$.

(b-ii) Non-binary variables

- $n^{WB}_{(l,b)}$ The number of waveband paths with waveband index $b\in B$ traversing link $l\in L$.
- $n^{WBC.EXP}_{(l)}$ The number of waveband convertors to convert waveband paths used to resolve waveband collisions on a link $l\in L$

(c) Constraints

(c-i) Waveband assignment constraints:

$$\sum_{b\in B} u^{WB}_{(p,b)}=1,\quad \forall p\in P \tag{4-15}$$

Equation (4-15) means that each waveband path p occupies only one waveband index.

(c-ii) Constraints for waveband convertors for express paths:

$$n^{WB}_{(l,b)}\geq 0,\quad \forall (l,b)\in L\times B \tag{4-16}$$

$$n^{WBC.EXP}_{(l)}\geq 0,\quad \forall l\in L \tag{4-17}$$

$$n^{WBC.EXP}_{(l)}=\sum_{\forall u^{WB}_{(p,l)}=1}\left(n^{WB}_{(l,b)}-n^{Fiber}_{(l)}\right),\ \forall (p,l,b)\in P\times L\times B \tag{4-18}$$

The first two equations, (4-16) and (4-17), guarantee the non-negativity of the number of waveband convertors put on the source node of link l. Equations (4-18) show the number of waveband convertors for express paths inserted at the source node of link l. Indeed, the value $n^{WB}_{(l,b)}-n^{Fiber}_{(l)}$ stands for the number of waveband paths with waveband index b at link l that cannot be accommodated by $n^{Fiber}_{(l)}$ fibers.

(c-iii) Constraints for waveband convertors for grooming operations:

$$cont^{WB}_{(p_1,p_2;b)} \geq -1, \quad \forall (p_1, p_2; b) \in T \times B \tag{4-19}$$

$$n^{WBC.GRM}_{(p_1,p_2)} \geq 0, \quad \forall (p_1, p_2) \in T \tag{4-20}$$

$$u^{WB}_{(p_1,b)} - u^{WB}_{(p_2,b)} - cont^{WB}_{(p_1,p_2;b)} = 0, \quad \forall (p_1, p_2; b) \in T \times B \tag{4-21}$$

$$n^{WBC.GRM}_{(p_1,p_2)} \geq cont^{WB}_{(p_1,p_2;b)}, \quad \forall (p_1, p_2; b) \in T \times B \tag{4-22}$$

The supporting variable $cont^{WB}_{(p_1,p_2;b)}$ is introduced to express the necessity of a waveband convertor at the boundary of a pair of waveband paths p_1 and p_2. Equation (4-19) and (4-20) guarantee the non-negativity of the number of this type of waveband convertor. If two waveband paths p_1 and p_2 occupy different waveband indices, that is to say, for some of $b \in B$, the value of $u^{WB}_{(p_1,b)}$, $u^{WB}_{(p_2,b)}$ will be one and the other zero, and by Eq. (4-21), one of $cont^{WB}_{(p_1,p_2;b)}$ will be 1, then Eq. (4-22) makes $n^{WBC.GRM}_{(p_1,p_2)}$ 1 since the minimization of the objective function restricts the variable to be the lowest value. On the other hand, if p_1 and p_2 occupy the same index, $cont^{WB}_{(p_1,p_2;b)}$ is always 0 for all $b \in B$. Then $n^{WBC.GRM}_{(p_1,p_2)}$ will be 0.

(d) Objective function:

$$\sum_{l \in L} n^{WBC.EXP}_{(l)} + \sum_{(p_1,p_2) \in T} n^{WBC.GRM}_{(p_1,p_2)} \tag{4-23}$$

The objective of ILP is to minimize the total number of waveband convertors for different usages. Here, waveband convertors include those that handle express waveband operations at any point of a waveband path at links, and those to convert groomed waveband paths to resolve waveband collision.

(B-4) A heuristic-based waveband index assignment algorithm for hierarchical optical path networks that employ only waveband convertors

The objective here is to minimize the total number of necessary waveband convertors. Herein, the introduction of waveband convertors for different usage is determined with the following process: To resolve waveband collisions at links in the express paths, the introduction of waveband convertors at an outgoing fiber is determined by the total hop count of the wavebands. On the other hand, for grooming at the node, waveband convertors may be needed to change the waveband indices, and the introduction of those convertors is determined by the waveband occupancy rate, i.e., the number of wavelengths accommodated in the waveband path. By following this measure, estimate the potential waveband convertor increment for all the pairs of concatenated waveband paths, then in the descending order of the increment value for each waveband path pair, assign waveband indices to them to avoid waveband collisions as much as possible. The procedure of the algorithm is similar to that described in Section B-3.

(B-5) A heuristic-based waveband index assignment algorithm employing both waveband convertors and wavelength convertors

In this case, utilize waveband convertors to convert waveband paths at links to eliminate waveband collision, and employ wavelength convertors so that wavelength paths can be accommodated within multiple concatenated waveband paths with different waveband indices. (Fig. 4-11)

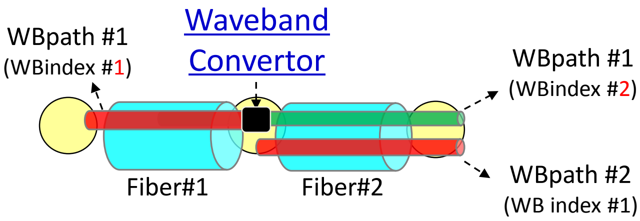


Figure 4-11. Mitigation of waveband collision by waveband convertors.

Since wavelength and waveband convertors are two different devices and their cost strongly depends on the technology adopted, define the relative cost value (C_{WC} and C_{WBC}) to evaluate their cost-effectiveness in this process. Herein, assign waveband indices to the waveband paths in the following manner to reduce the potential cost increment of both waveband convertors and wavelength convertors. To resolve waveband collisions at links in the express paths, the introduction of waveband convertors at an outgoing fiber is determined by the total hop count of the wavebands. On the other hand, for a grooming operation at the node, wavelength convertors may be needed to change the wavelength indices, and their introduction is determined by the waveband occupancy rate, i.e., the number of wavelengths accommodated in the waveband path.

In this sub-step, firstly, select wavelength paths traversing multiple concatenated waveband paths by a novel measure that represents the potential need for waveband/wavelength convertors in terms of each concatenated waveband path pair, then assigne waveband paths traversed by the selected wavelength path sequentially, so that the total cost of both waveband/wavelength convertors for each assignment can be minimized. After initial waveband index assignment, for each waveband path, waveband re-assignment is done to achieve a further reduction in the total cost of wavelength/waveband convertors needed. The algorithm is summarized as follows:

(Step i) *Initial waveband assignment*

Let (P_1, P_2) be all concatenated waveband path pairs traversed by wavelength path *lp*, and $N(p_1, p_2)$ be the number of wavelength paths that traverse the concatenated waveband path pair (p_1, p_2). Eq. (4-24) is the cost function for each *lp*.

$$C_{lp} = C_{WC} \cdot \sum_{(p_1, p_2) \in (P_1, P_2)} N(p_1, p_2) + C_{WBC} \cdot \sum_{p_3 \in P} hop(p_3) \tag{4-24}$$

where $hop(p_3)$ represents the hop count of a waveband path p_3 that belongs to all waveband paths traversed by wavelength path *l*. The right side of Eq. (4-24) represents the potential cost increment of the wavelength convertor and the waveband convertor. Here, If p_3 has to be accommodated in the previous waveband assignment process, $hop(p_3) = 0$.

For all wavelength paths, *lp*, calculate the corresponding C_{lp}. In descending order of C_{lp} value, assign waveband indices to all waveband paths traversed by the corresponding wavelength path *lp* so that the potentially necessary waveband/wavelength convertors cost can be minimized. It should be noted that C_{lp} will be updated after each waveband assignment process. This process is repeated until all waveband paths are processed.

(Step ii) *Waveband re-assignment*

In this step, simple re-assignment is achieved by searching for a waveband assignment better than the current one for each waveband path, i.e., to achieve a further reduction in the total cost of wavelength/waveband convertors needed. The applied algorithm is summarized below:

Step (ii-0) Obtain waveband index for each waveband path from waveband assignment algorithm in Step i.

Step (ii-1) Set *REPEAT = FALSE*.

Step (ii-2) For each waveband path p_i:

(a) Set b_0 = current waveband index.

(The value of "b_0" ranges from 1 to the maximum number of wavelength paths that a waveband path can accommodate; it is a constant value determined in the "Initial waveband assignment" operation)

(b) Remove b_0 for p_i

(c) Compute $C_{(p_i, b)}$ for all possible waveband indices *b* by Eq. (4-25).

$$C_{(p_i, b)} = C_{WBC} \cdot \sum_{\forall l} link_{(l,b)} + C_{WC} \cdot [\sum_{\forall (p_i, p_j)} N(p_i, p_j) + \sum_{\forall (p_k, p_j)} N(p_k, p_i)] \tag{4-25}$$

Here, $link_{(l,b)}$ represents the number of waveband paths with waveband index *b* while these waveband paths are accommodated in the same fiber at link *l* as p_i.

If p_j or p_k is assigned to different waveband indices ($\neq b$) as p_i, $N(p_i, p_j)$ or $N(p_k, p_i)$ be the number of wavelength paths that traverse the concatenated waveband path pair (p_i, p_j) or (p_k, p_i), else $N(p_i, p_j)$ or $N(p_k, p_i)$ to be 0.

(d) For each p_i, calculate Z_{p_i} by Eq. (4-26).

$$Z_{p_i} = \max[C_{(p_i,b_0)} - C_{(p_i,b)}], \qquad \forall b \tag{4-26}$$

(e) Find waveband path p_0 with largest Z_{p_i} value; assign waveband index *b* to waveband path p_i, set REPEAT=TRUE.

Step (ii-3) If REPEAT = TRUE, repeat from Step (ii-1). Otherwise, terminate.

4.4.3 Wavelength index assignment

Assign Wavelength indices to all wavelength paths in descending order of the number of waveband paths that each wavelength path traverses. If wavelength collision occurs, a different solution will be adopted according to the case:

(C-1) Considering wavelength conversion or both waveband/wavelength conversion

In this case, if a wavelength path traverses a pair of concatenated waveband paths with different waveband indices, split the path virtually at the boundary into two wavelength paths. For all new wavelength paths that result, assign wavelength indices in descending order of the number of waveband paths that each wavelength path traverses. For each assignment, minimize the number of wavelength convertors as much as possible while resolving wavelength collision.

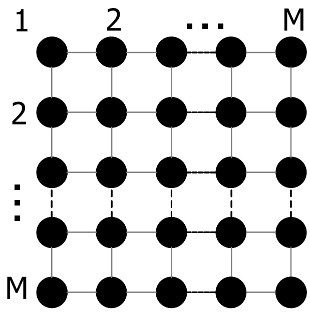
(C-2) Considering waveband conversion

In this case, since waveband convertor cannot resolve wavelength collisions directly, a new waveband path or a new fiber is added if necessary.

4.5 Performance evaluation

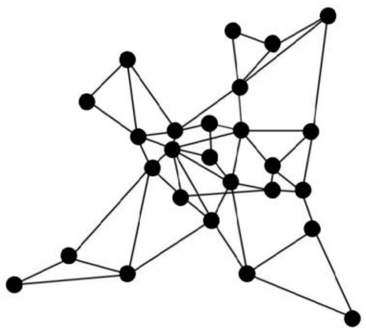
4.5.1 Simulation parameters

This evaluation adopts $M \times M$ (M = 4, 5, 6) regular mesh networks (Fig. 4-12(a)), a COST266 pan-European network (COST266, Fig. 4-12 (b), [4-21]), a US nationwide network (USnet, Fig. 4-12 (c), [4-22]), and a Telecom Italia backbone network (Italia, Fig. 4-12 (d), [4-23]). Traffic demands, represented by the average number of wavelength paths requested between node pairs, were randomly distributed. In this paper, set the link length to be uniform (500 km) to clarify the topology dependence of routing performance. The generalization to the variable link length case is straightforward. Each fiber accommodates 8 wavebands and each waveband supports 8 wavelengths; i.e. 64 wavelengths per fiber (Fig. 4-13). The network cost is approximated by the weighted sum of the numbers of switch ports, wavelength or waveband convertors, fibers, and optical amplifiers in addition to a constant term that represents control systems and other overheads as shown in Section 4.3.1. The cost ratio between waveband convertor, wavelength convertor and NNI of WXC port is set at 2:1:1 initially.



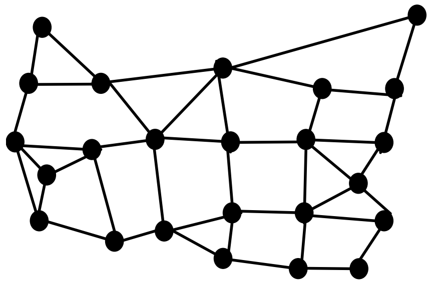
Number of nodes		*MxM*
Node degree	Min	2
	Max	4
	Ave	-
Number of links		$2M^2 - 2M$
Number of hops	Min	1
	Max	$2M$-2
	Ave	-

(a) $M \times M$ regular mesh network



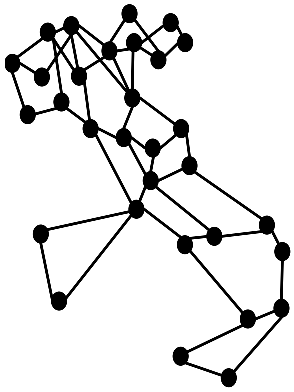
Number of nodes		26
Node degree	Min	2
	Max	8
	Ave	3.92
Number of Links		51
Number of hops	Min	1
	Max	6
	Ave	2.76

(b) COST266 pan-European network



Parameters		Values
Number of nodes		24
Node degree	Min	2
	Max	5
	Ave	3.5
Number of Links		42
Number of hops	Min	1
	Max	6
	Ave	3.04

(c) US nationwide network



Parameters		Values
Number of nodes		31
Node degree	Min	2
	Max	5
	Ave	3.12
Number of Links		49
Number of hops	Min	1
	Max	9
	Ave	3.72

(d)Telecom Italia backbone network

Figure 4-12. Network topologies.

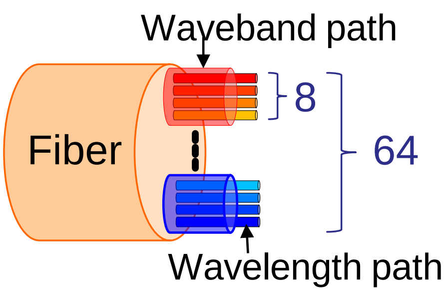


Figure 4-13. Capacity of fiber/waveband path.

4.5.2 Comparison between ILP-based and heuristic-based waveband index assignment algorithm

A) Hierarchical optical path networks introducing wavelength conversion

Currently utilized single-layer optical path networks [4-8] are adopted as the benchmark to verify the effectiveness of hierarchical optical path networks introducing wavelength/waveband conversions. It should be noted that the impact of introducing wavelength convertors to single-layer optical path networks has been shown to be very limited [4-20], so any conversion is not assumed in single-layer optical path networks. Figure 4-14 shows the cost ratio of proposed hierarchical optical path networks by using ILP-based (WC-ILP, Section 4.4.2-B-1)/heuristic-based (WC-ILP, Section 4.4.2-B-2) methods. As shown in Fig. 4-14, for a 5x5 regular mesh network, the result of ILP-based method is available only in the small traffic demand area due to its intensive computation load. On the other hand, the proposed heuristic-based method can obtain the results in a wide traffic demand area including a large traffic demand area (Please see the results shown in Section 4.5.3), while almost a same results can be achieved compared with the ILP method. Furthermore, the computation time of the proposed algorithm is much shorter than that of the ILP-based method. Although the computation time for the ILP-based method strongly depends on the acceptable gap, when the average number of wavelength paths requested between node pairs is 1, the ILP-based method takes 7 days while the proposed one takes only about 1 minute. For the next section, to analyze a larger network topology and a wide traffic demand area, the heuristic-based waveband assignment algorithm is adopted hereafter.

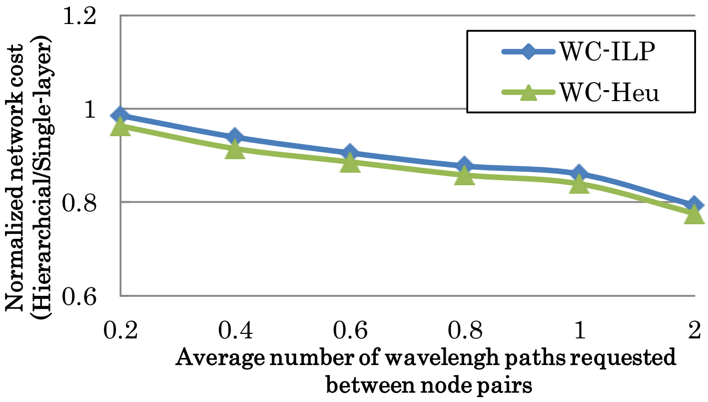


Figure 4-14. Cost comparison between hierarchical and single-layer optical path networks.

B) Hierarchical optical path networks introducing waveband conversion

Figure 4-15 depicts the obtained normalized network costs for hierarchical optical path networks considering waveband conversion, in comparison to single-layer optical path network cost. Here, compare the results from different algorithms used in the waveband assignment sub-steps: an ILP-based algorithm (WBC-ILP, Section 4.4.2-B-3) and a heuristic-based one (WBC-Heu, Section 4.4.2-B-4). Similar with the case for hierarchical optical path networks introducing wavelength conversion, the results in Fig. 4-15 prove that the heuristic-based waveband assignment algorithm can achieve almost the same performance as the ILP-based algorithm. The simulation time for different strategy is similar with the case shown in the previous section. Therefore, the heuristic-based waveband assignment algorithm is adopted hereafter.

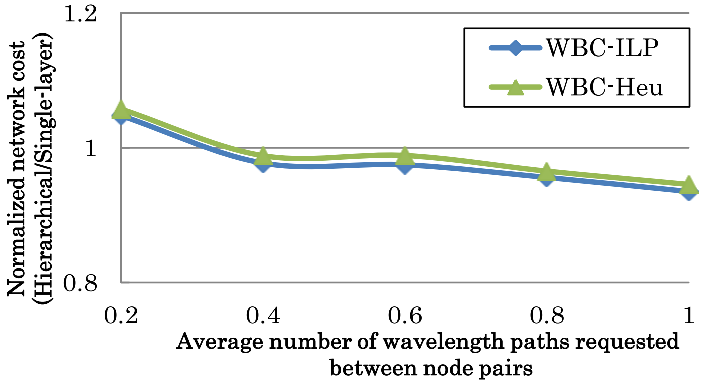
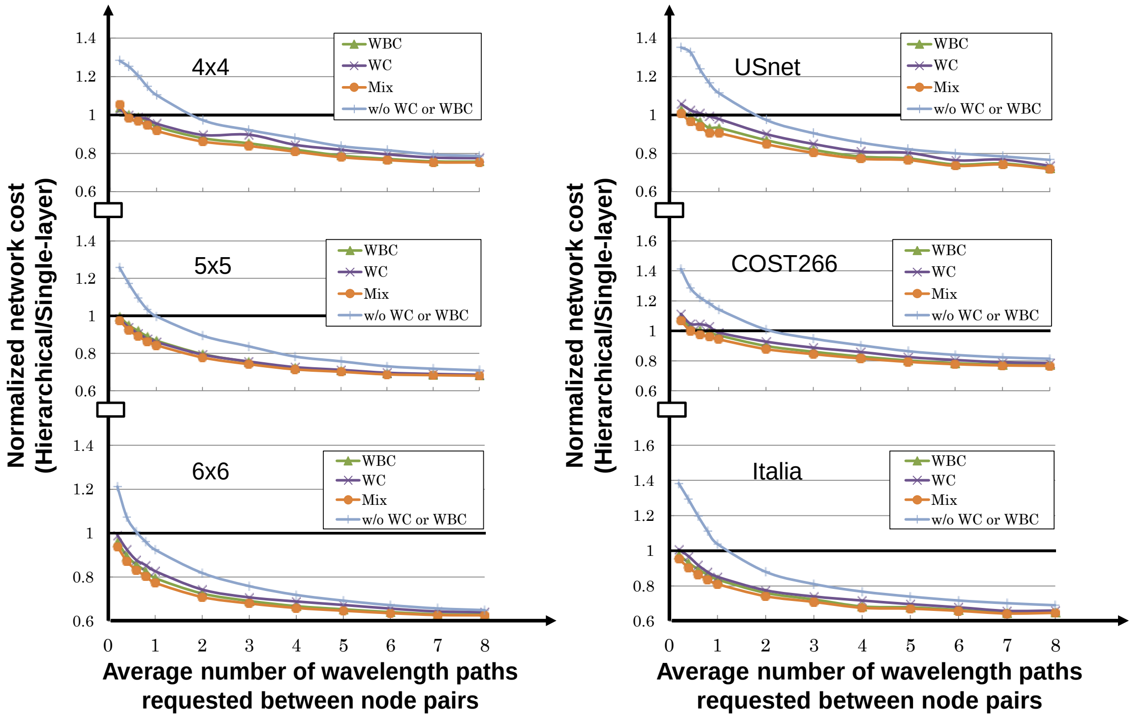


Figure 4-15. Cost comparison between hierarchical and single-layer optical path networks.

4.5.3 Introduction impact of wavelength/waveband conversion

A) Cost reduction achieved by introducing wavelength/waveband conversion for hierarchical optical path networks against comparable single-layer optical path networks

Figure 4-16 shows the obtained normalized network costs for hierarchical optical path networks that utilize only waveband conversion (WBC), only wavelength conversion (WC), and both of them (Mix), in comparison to single-layer optical path network cost with different network topologies. It demonstrates that by introducing either or both of waveband/wavelength conversion, hierarchical optical path networks can be more cost-effective than the conventional single-layer optical path networks over a wide range of traffic demand including the small traffic demand area where the algorithm [4-6], which does not consider wavelength nor waveband conversion (w/o WC or WBC), cannot offer any reduction. The degree of cost reduction is enhanced as the traffic demand volume increases due to the improvement in the utilization efficiency of each waveband. The degree of cost reduction is also enhanced as network size increases. This mostly stems from the increase in average hop count of each waveband, which is determined by network size.



(a) Regular network topologies (b) Irregular network topologies

Figure 4-16. Cost comparison between hierarchical and single-layer optical path networks by different network topology.

Next, evaluate the upper bound of wavelength/waveband convertor cost that permits the hierarchical optical path networks to be cost-effective compared with the single-layer optical path networks. It shows the allowable bound of the convertor cost for the hierarchical optical path networks, and hence it can be regarded as a cost target for wavelength/waveband convertors for hierarchical optical path networks. Suppose that the number of utilized wavelength/waveband convertors is #WC/#WBC, and that hierarchical optical path network cost (c_H) should be less than that of an equivalent single-layer optical path network (c_{SL}). The upper bound cost is determined by c_{WC} (or c_{WBC}) = (c_{SL} – c_H) / (#WC or #WBC). Figure 4-17 shows that as traffic demand increases, the bound increases. It also demonstrates that hierarchical optical path networks that introduce waveband convertors can be cost-effective even when the waveband convertor cost is relatively high. Please note that in some small traffic demand areas, for 4x4, US nationwide and COST266 pan-European networks, cost reduction cannot be achieved even if the cost of wavelength/waveband convertor is 0.

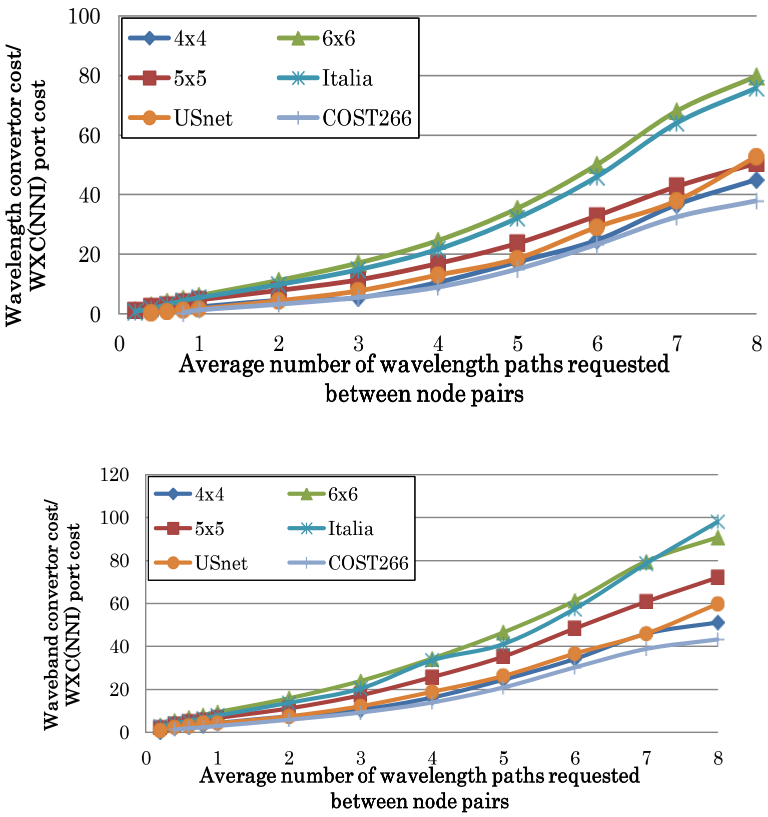
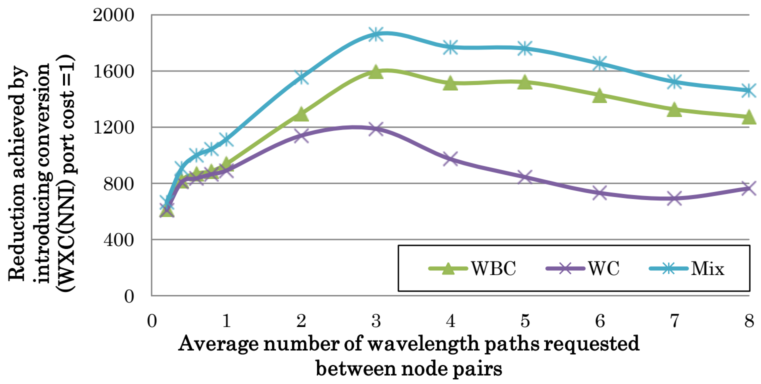


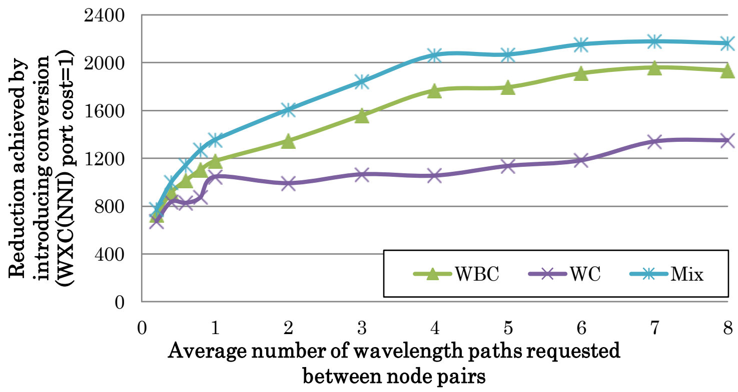
Figure 4-17. Bounds of (a) waveband or (b) wavelength convertor cost that attain cost reduction from the comparable single-layer optical path networks.

B) Cost reduction achieved by introducing wavelength/waveband conversion for hierarchical optical path networks

Figure 4-18 compares the costs achieved by introducing either or both wavelength/waveband convertors to hierarchical optical path networks, relative to those of the corresponding hierarchical optical path networks that do not apply any conversion [4-6] for the 5x5 regular mesh network and COST266 pan-European network. It shows that by introducing wavelength/waveband conversion, a significant cost reduction can be achieved in a wide area of traffic demand, and that the largest cost reduction can be attained by utilizing both types of convertors. This effectiveness, however, declines as traffic volume increases. This is because as the traffic demand between node pairs approaches the waveband capacity, direct waveband paths between source and destination nodes effectively accommodate the traffic, so wavelength/waveband convertors are seldom needed. This phenomenon can be seen in Fig. 4-19, which plots the number of necessary wavelength/waveband convertors for different schemes. It also demonstrates that with applying both types of conversion, even just a few waveband convertors (Mix(#WBC)) can significantly reduce the necessary number of wavelength convertors (Mix(#WC)), compared to that when only wavelength convertors are used (WC). This indicates that even when waveband convertor cost is relatively high; employing both types of convertors can well reduce the cost of hierarchical networks. Of course, the increases in complexity possible with using both convertor types should be considered from the operational viewpoint.

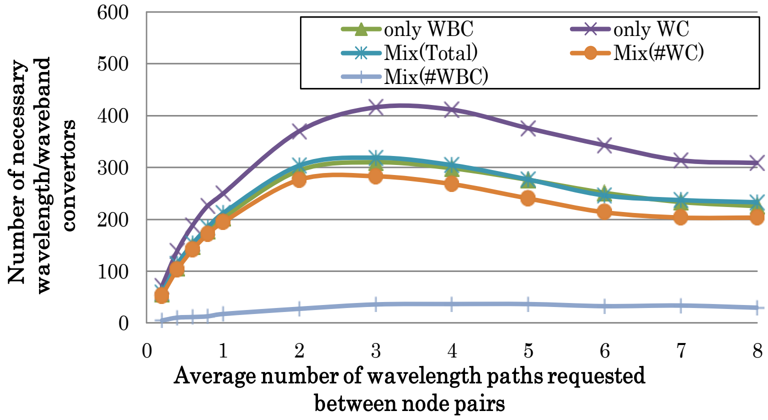


(a) 5x5 regular mesh network

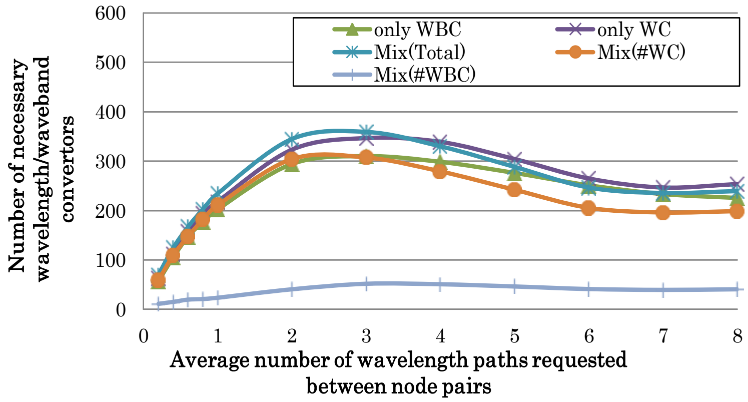


(b) COST266 pan-European network

Figure 4-18. Cost reduction achieved by introducing conversion.



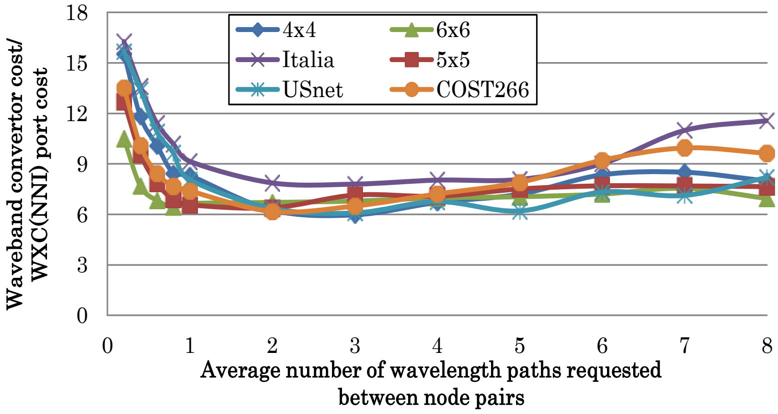
(a) 5x5 regular mesh network



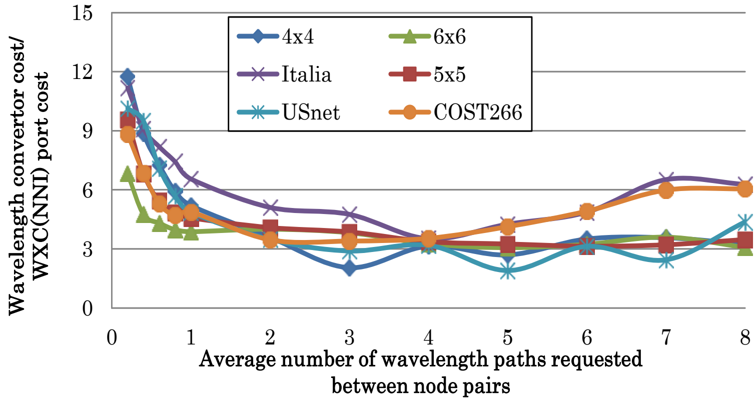
(b) COST266 pan-European network

Figure 4-19. Number of necessary wavelength/waveband convertors.

Next the upper bound of wavelength/waveband convertor cost is estimated compared with the comparable hierarchical optical path networks that do not utilize waveband/wavelength conversion. Figure 4-20 verifies that the cost bound for the waveband convertor is still higher than that of the wavelength convertor in a wide traffic demand area, especially in the small traffic demand area. It also shows that wavelength/waveband convertors can reduce the cost of hierarchal optical path networks. Especially in the low traffic demand area, even relatively high wavelength/waveband convertor cost allows the cost of hierarchical optical path networks to be reduced. Its effectiveness is verified on different network topologies, regardless of network size examined. The results show little dependency on topology or parameter setting.



(a) Waveband convertor cost bound



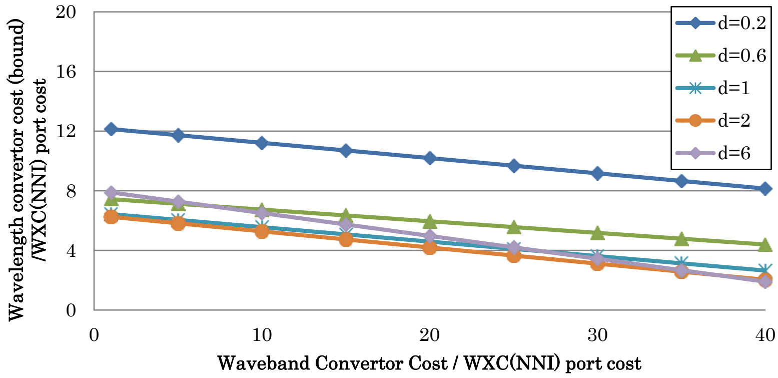
(b)Wavelength convertor cost bound

Figure 4-20. Convertor cost bound that can reduce cost of hierarchical optical path network.

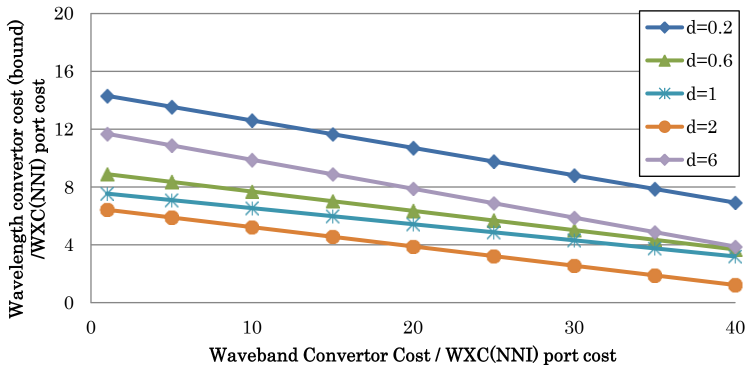
The effects of the relative cost of wavelength and waveband convertors are also analyzed for networks that utilize wavelength and waveband convertors. Suppose that the total number of utilized wavelength/waveband convertors is (*#WC + #WBC)*, and that hierarchical optical path network cost (c_H) should be less than that of an equivalent single-layer optical path network (c_{HW}). The upper bound of wavelength convertor cost is determined by

$$c_{WC} = (c_{HW} - c_H - \#WBC \cdot C_{WBC}) / \#WC \qquad (4\text{-}27)$$

Figure 4-21 shows the obtained wavelength convertor cost bound for different traffic demands ("*d*" means the average number of a wavelength paths requested between node pairs) against the given relative cost of waveband convertors. The results also verify that, by appropriately introducing both wavelength/waveband convertors, hierarchical optical path networks can still achieve cost reduction effectiveness over a wide traffic demand area with a wide relative cost range of waveband convertors.



(a) 5x5 regular mesh network



(b) COST266 pan-European network

Figure 4-21. Wavelength convertor cost bound against different waveband convertor costs that can reduce cost of hierarchical optical path network for different traffic demand values.

4.5.4 Sensitivity analysis

A) Dependence of costs on network size

Figure 4-22 shows the normalized network costs for hierarchical optical path networks introducing both wavelength/waveband conversions with different network topology sizes (*N*: the number of nodes in the topology). The result demonstrates that the hierarchical optical path network can be more cost effective than the conventional single layer optical path network over a wide range of traffic demands. Moreover, the cost reduction effectiveness is enhanced as the network topology size increases. This is because the average length (hop count) of waveband paths establishing in the network increases as the network topology size increases which exploits the advantages of waveband paths in minimizing the required port count necessary in the intermediate nodes.

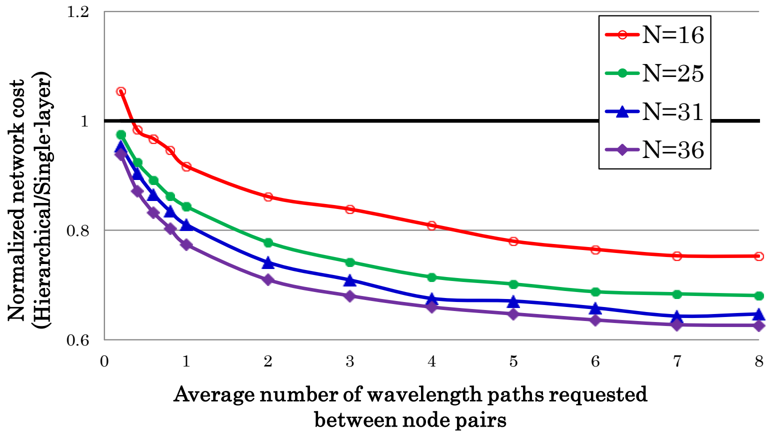


Figure 4-22. Cost comparison between hierarchal and single-layer optical path networks for different network size.

B) Dependence of costs on waveband capacity

Waveband capacity, *W*, is one of the critical parameters determining the effectiveness of hierarchical optical path networks. Generally, a small *W* value offers a smaller link cost but higher node cost; waveband utilization is increased while the number of wavebands and hence that of optical ports are increased. In this section, the impact of different *W* is evaluated for hierarchical optical path networks examining on a 5x5 regular mesh network.

Herein, estimate normalized network costs for hierarchical optical path networks (Figure 4-23: with waveband and wavelength conversion, Figure 4-24: without waveband/wavelength conversion) against the comparable single-layer optical path networks with different *W*. To obtain the result over a wider traffic demand area, for the case of introducing both types of convertor, set the waveband/wavelength convertor cost to be 0 for simplicity (this assumption yields the upper bound of available cost reduction).

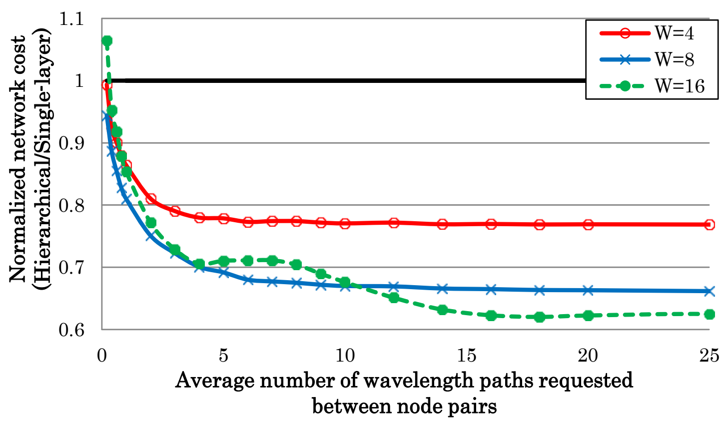


Figure 4-23. Cost comparison between hierarchical (with both waveband/wavelength conversions) and single-layer optical path networks with different waveband capacity.

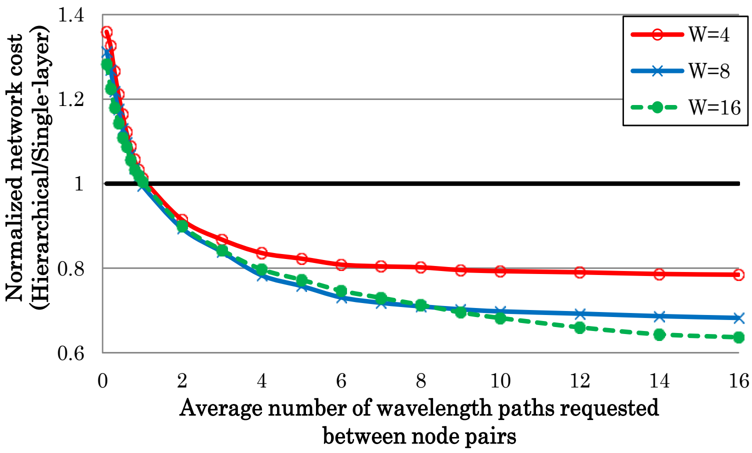


Figure 4-24. Cost comparison between hierarchical (without considering any type of conversion) and single-layer optical path networks with different waveband capacity [4-6].

Figure 4-23 shows that, regardless of waveband capacity, by introducing wavelength/waveband conversion, hierarchical optical path networks can be cost-effective over a wide traffic demand area. The capacity of W=4 results in the least cost reduction because of a fall in port reduction when traffic demands are large. On the other hand, though in the small traffic demand area, W=16 offers almost no cost reduction because of the low utilization ratio of waveband paths, the cost reduction increases with increasing traffic demand as the waveband is filled. It should be noted that, compared with the results in Fig. 4-24, in Fig. 4-23, for the area where the average number of wavelength paths between each node pair is between 5 and 10, the cost reduction for W=16 is relatively small. This is because in this traffic demand area, the utilization ratio of waveband paths is relatively low. Moreover, since each fiber can only accommodate 4 waveband paths, the possible frequent waveband contention tends to add costly fibers to resolve waveband collision. Therefore, in general, W should be large enough to offer some port reduction effect, and cost reduction is maximized when W is equal to or slightly larger than the given average traffic demand.

4.6 Summary

Routing and waveband/wavelength assignment algorithms are proposed for hierarchical optical path networks that utilize either of both wavelength/waveband convertors to investigate their impact. The results demonstrate that, by utilizing both wavelength and waveband convertors, hierarchical optical path networks can be cost-effective over a wide traffic demand area, and the wavelength/waveband convertor cost bound that makes the introduction of conversions effective was elucidated. The technologies of wavelength/waveband conversion, in particular in the optical domain, are not mature yet, but the investigations done in this thesis will provide a useful guideline for the target cost that makes the conversion effective in creating cost-effective photonic networks.

References

[4-1] K. Sato, "Next generation transport network architecture," *OSA Optical Fiber Communication Conference (OFC)*, paper OWR1, San Diego, USA, March 2010.

[4-2] X. Cao, V. Anand, and C. Qiao, "Framework for waveband switching in multigranular optical networks: part I- Multigranular cross-connect architectures," *OSA Journal of Optical Networking (JON)*, vol. 5, pp. 1043–1055, December 2006.

[4-3] P. Torab, V. Hutcheon, D. Walters, and A. Battou, "Waveband switching efficiency in WDM networks: Analysis and case study," *OSA Optical Fiber Communication Conference (OFC)*, paper OTuG3, Anaheim, USA, March 2006.

[4-4] Y. Yamada, H. Hasegawa, and K. Sato, "Survivable hierarchical optical path network design with dedicated wavelength path protection," *IEEE/OSA Journal of Lightwave Technology (JLT)*, vol.29, no. 21, pp.3196-3209, November 2011.

[4-5] Y. Wang, and X. Cao, "A new hierarchical waveband assignment algorithm for multi-granular optical networks," *IEEE International Conference on Computer Communications and Networks (ICCCN)*, paper ON_1_1, San Francisco, USA, August 2009.

[4-6] I. Yagyu, H. Hasegawa, and K. Sato, "An efficient hierarchical optical path network design algorithm based on a traffic demand expression in a Cartesian product space," *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 26, no. 6, pp. 22-31, August 2008.

[4-7] M. Li and B. Ramamurthy, "Heterogeneous waveband switching in wavelength division multiplexed networks based on autonomous clustering architecture," *OSA Journal of Optical Networking (JON)*, vol. 5, no. 9, pp. 667–680, 2006.

[4-8] J. Yamawaku, A. Takada, W. Imajuku, and T. Morioka, "Evaluation of amount of equipment on single-layer optical path networks managing multigranularity optical paths," *IEEE/OSA Journal of Lightwave Technology (JLT)*, vol.23, no. 6, pp.1971-1978, June 2005.

[4-9] S. J. B. Yoo, "Wavelength conversion technologies for WDM network applications," *IEEE/OSA Journal of Lightwave Technology (JLT)*,vol.14, no. 6, pp. 956-966, June 1996.

[4-10] B. Ramamurthy and B. Mukherjee, "Wavelength conversion in WDM networking," *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 16, no. 7, pp.

1061-1073, September 1998.

[4-11] T. S. El-Bawab, *Optical Switching*, New York, USA: Springer, August 2006.

[4-12] H. Hu, H. Ji, M. Galili, M. Pu, C. Peucheret, H. C. H. Mulvad, K. Yvind, J. M. Hvam, P. Jeppesen, and L. K. Oxenløwe, "“Ultra-high-speed wavelength conversion in a silicon photonic chip," *OSA Journal Optics Express*, vol. 19, no. 21, pp. 19886-19894, October 2011.

[4-13] H. Nakamura, Y. Shirakawa, H. Kitamura, N. Sato, O. Shinji, K. Saito, and S. Takahashi, "Mechanism of wavelength conversion in polystyrene doped with benzoxanthene: emergence of a complex", *Scientific Report* 3, no. 2502, August 2013.

[4-14] C. Politi, D. Klonidis, and M. J. O'Mahony, "Waveband converters based on four-wave mixing in SOAs," *IEEE/OSA Journal of Lightwave Technology (JLT)*, vol. 24, no. 3, pp. 1203–1217, March 2006.

[4-15] I. Tomita, T. Umeki, O. Tadanaga, H. Song, M. Asobe, and H. Takenouchi, "Properties of power dependence on low-crosstalk waveband conversion with an apodized multiperiod-QPMLiNbO3 device," *OSA Journal Optics Express*, vol. 22, no. 12, pp. 15232-15244, June 2014.

[4-16] S. Kaneda, T. Uyematsu, N. Nagatsu, and K. Sato, "Network design and cost optimization for label switched multilayer photonic IP networks," *IEEE Journal on Selected Areas in Communications*, vol. 23, pp. 1612–1619, August 2005

[4-17] J. Zheng, and H. T. Mouftah, *Optical WDM Networks: Concepts and Design Principles*, Hoboken, USA: Wiley-IEEE Press, July 2004.

[4-18] S. Varma, and J.P. Jue, "Regenerator placement and waveband routing in optical networks with impairment constraints," *IEEE International Conference on Communcations (ICC)*, Kyoto, Japan, June 2011.

[4-19] X. Cao, V. Anand, J. Li, and C. Xin, "Waveband Switching Networks with Limited Wavelength Conversion," *IEEE Communications Letters*, vol. 9, pp. 646-648, Jan. 2005.

[4-20] M. Tornatore, G. Maier, and A. Pattavina, "WDM network optimization by ILP based on source formulation," *IEEE Computer and Communications Societies (INFOCOM)*, vol. 3, pp. 1813-1821, New York, USA, June 2002.

[4-21] R. Inkret, A. Kuchar, and B. Mikac, *Advanced Infrastructure for Photonic Networks – Extended Final Report of COST266 Action*. Zagerab, Crotia: Faculty of Electrical Engineering and Computing, University of Zagreb, 2003.

[4-22] S. F. Gieselman, N. K. Singhal, and B. Mukherjee, "Minimum-cost virtual-topology adaptation for optical WDM mesh networks", *IEEE International Conference on Communications (ICC)*, vol. 3, pp. 1787-1791, Seoul, Korea, May 2005.

[4-23] A. Allasia, V. Brizi, and M. Potenza, "Characteristics and trends of Telecom Italia transport networks", *Journal of Fiber and Integrated Optics,* vol. 27, no. 4 , pp. 183-193, July 2008.

Chapter 5
SEMI-FLEXIBLE GRID OPTICAL PATH NETWORKS

This chapter presents a novel semi-flexible grid optical path network where each specific bitrate signal uses its own dedicated fixed grid and one edge of its frequency grid is anchored at a specific frequency. The proposal is expected to retaining the high spectral utilization efficiency that can be achieved with the flexible grid networks while it can utilize almost the same hardware as the currently cost-effective fixed grid systems. In this chapter, the challenges of actively studied flexible grid networks are explained, and then, the concept of proposed semi-flexible grid networks, including the signal frequency allocation strategy, is described. At last, the architecture of the proposed semi-flexible grid network is illustrated, and the future tasks of the proposal are also discussed.

5.1 Introduction

Wavelength routing networks that utilize ROADMs [5-1] have been extensively introduced to cope with the rapid penetration of broadband/high-speed mobile access. These ROADMs are equipped mostly with fixed add/drop capabilities. To support the future broadband advanced wavelength services [5-2], the dynamic operation of wavelength paths is necessary. Enhanced optical layer flexibility is also critical to attain optical layer protection/restoration and to enable future advanced SDN (Software Defined Networking, which allows switches to be virtualized along with storage and compute/transport resources) [5-3]. As a result, ROADMs with so-called C/D or C/D/C (Colorless/Directionless/Contentionless) add/drop capabilities are required; to this end, various add/drop architectures have been discussed [5-4]-[5-6].

To achieve a high fiber transmission capacity, maximizing the spectral utilization with minimum cost increment (minimizing link cost) is an important issue. Flexible grid optical path network uses a minimum frequency slot granularity (e.g., 12.5 GHz, the standardizations can be found in [5-7]) and can allocate multiple frequency slots as needed [5-8]-[5-11]. Therefore, it can possibly maximize the fiber utilization efficiency. More details about flexible grid networks can be found in Chapter 3. However, this benefit is obtained at the cost of using a set of sophisticated technologies (such as CO-OFDM [5-12] and Nyquist-WDM [5-13], See Chapter 3.2), and as a result, high system cost (especially the node cost) and operation cost are required. In particular for metro networks, node cost dominates and the relative link (fiber) cost can be much smaller than that of core network segment.

Another practical issue comes from the network evolution scenario. With most large carriers, few kinds of transmission systems generally co-exist so optimization of overall network design and operation is possible [5-14]. In other words, old generation systems will be generally replaced fiber by fiber. Therefore, this chapter discusses flexible grid systems that can be most effectively applied widely, including the metro segment. More specifically, the bitrates considered here are a small set of those that have been standardized in ITU-T so far and future plausible higher bitrates; full coverage of highly granular bitrate signals is not considered.

In this chapter, a novel semi-flexible grid optical path network, where each specific bitrate signal uses its own dedicated fixed grid and one edges of its frequency slot width is anchored at a specific frequency, is proposed. Herein, according to the flexible grid definition [5-7], frequency slots are defined with 12.5 GHz slot width granularity and 6.25 GHz central frequency granularity, instead of a grid. Since in the semi-flexible grid network, each bitrate signal is aligned with a fixed grid that is specific to each bitrate, current cost-effective fixed grid based hardware can be utilized. The details of the aforementioned contents will be explained in this chapter.

5.2 Concept of semi-flexible grid strategy

Figure 5-1 shows channel frequency allocation examples for: (a) ITU-T fixed grid, (b) flexible grid, and (c) proposed semi-flexible grid. With the flexible grid [Fig. 5-1(b)], the channel central frequencies of different bitrate signals can be arbitrarily selected with a minimum granularity of 6.25 GHz provided no channels overlap.

The proposed semi-flexible grid network can attain the same frequency slot granularity as the flexible grid network, but each set of same bitrate channels is located in a fixed frequency slot width that is determined specifically to suit the channel bitrate and modulation format. Fig. 5-1(c) illustrates a simple channel frequency allocation example for the proposed semi-flexible grid. In this example, three types of bitrate signals are processed sequentially, and each types of bitrate signal can only assigned to the fixed grid that is equal to the required slot width occupied by the respective bitrate. Moreover, the edges of different frequency slot arrangements are anchored at specific frequencies. This anchored frequency slot assignment scheme can be expected to reduce the spectrum fragmentation (The details will be presented in Chapter 6.2) triggered by iterative path setup/release operations. It should be noted that, this scheme is different from present MLR (Mixed Line Rate、Figure 5-1(a)) systems where different line rate channels are accommodated on a single fixed grid (e.g., 50/100 GHz spacing). Since each bitrate signal is aligned using a fixed grid that is specific to each bitrate, the interfaces of a semi-flexible grid network can be developed as for a fixed grid, whose bitrate depends on the client side interface.

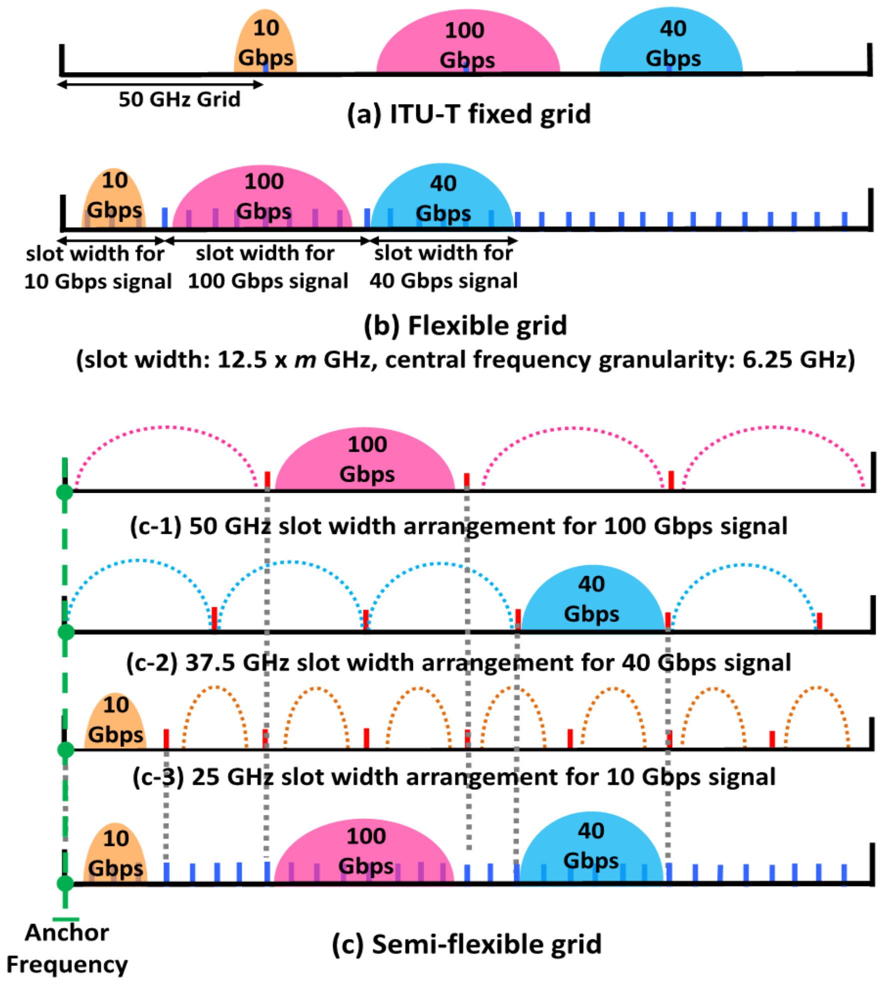


Figure 5-1. Comparison of (a) ITU-T fixed grid, (b) flexible grid, and (c) semi-flexible grid.

5.3 Semi-flexible grid network architecture

Figure 5-2 shows a model for proposed semi-flexible grid ROADM architectures that offer C/D/C function (Please compare the ones for the flexible grid networks shown in Fig. 3-4). The ROADM architecture includes a wavelength drop part, a wavelength add part and a wavelength express part. Since the proposed semi-flexible grid networks use a same frequency granularity as the conventional flexible grid networks, bandwidth-variable OXCs are required at the wavelength express part. For the semi-flexible grid networks, the bitrate specific frequency slot width (frequency grid) enable each client system (router) interface-card uses a fixed bitrate receiver, which is the same as that for fixed grid systems. In the wavelength add side, when tunable lasers are used for the transponder, the tunability follows that of the fixed grid system. On the other hand, in the wavelength drop side, cost-effective tunable filters can be utilized at wavelength drop part, which are the same as those used for fixed grid systems. Tunable filter is one of the key devices for creating cost-effective C/D/C ROADM architecture, and its manufacturing technique is rapidly developed. For example, for a novel fixed grid based tunable filter architecture shown in Fig. 5-3, all the functions are integrated on a small PLC chip (it combines arrayed waveguide grating and optical switches with the use of asymmetric Mach-Zehnder interferometer), and its feasibility is confirmed through transmission experiments [5-15]. Further size reduction and cost-effective implementation will be possible in the future by the use of silicon photonics technology.

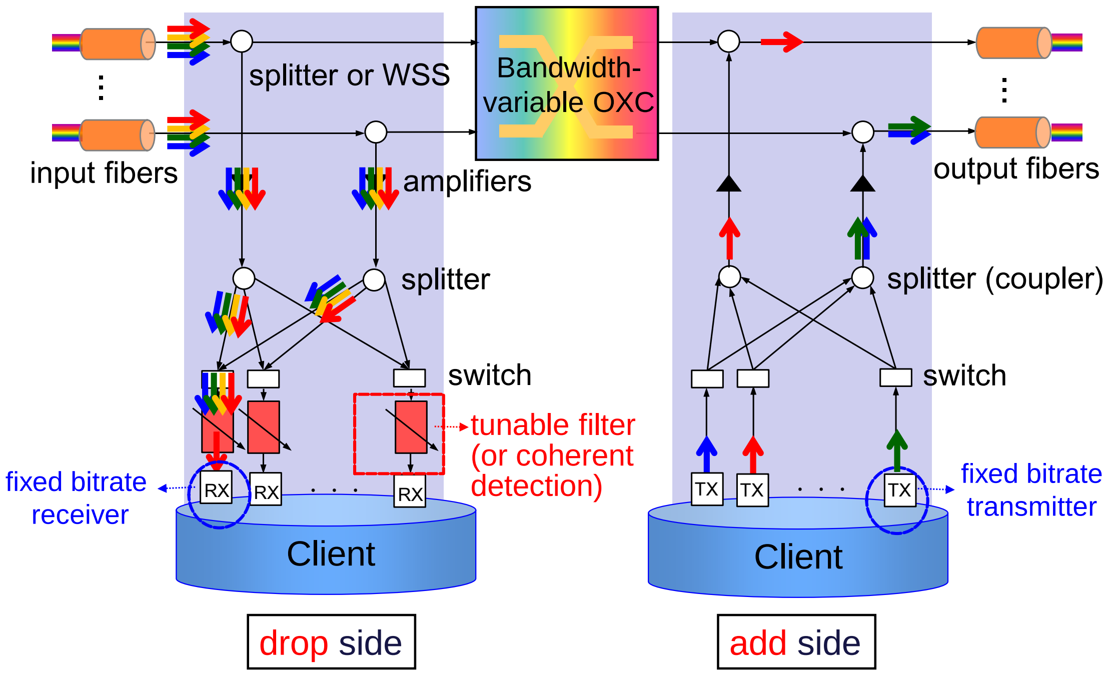


Figure 5-2. A model for a semi-flexible grid ROADM architecture offering C/D/C function.

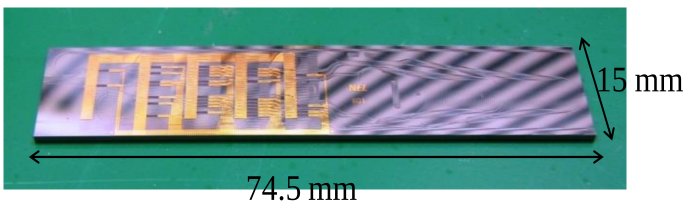


Figure 5-3. Prototype of a cost-effective tunable filter for fixed grid network [5-15].

Figure 5-4 compares a simplified model for the flexible and semi-flexible grid ROADM architectures that offer C/D/C function. For the flexible grid networks, the tunable filter at the drop side of the ROADM needs to tune both passband center frequency and passband bandwidth with a granularity of 6.25 GHz and 12.5 GHz, respectively. This tunable filter function is possible with coherent detection or with WSSs. Coherent detection [5-16] is rather expensive and may take substantial time to be extensively deployed including metro area where non-coherent transmission can be substantially utilized for a certain period of time in the future; WSSs are also expensive devices and the port counts of commercially available WSSs are still limited to 20+ and expansion will not be easy [5-17].

Fortunately, the fixed grid based ROADMs that can be utilized in semi-flexible grid networks have much relaxed filter requirement compared with the flexible grid ones, and hence are more cost-effective. The filter only needs to tune its passband center frequency (6.25 GHz) on the fixed grid and the passband bandwidth matches the bitrate of the client system (router) interface card.

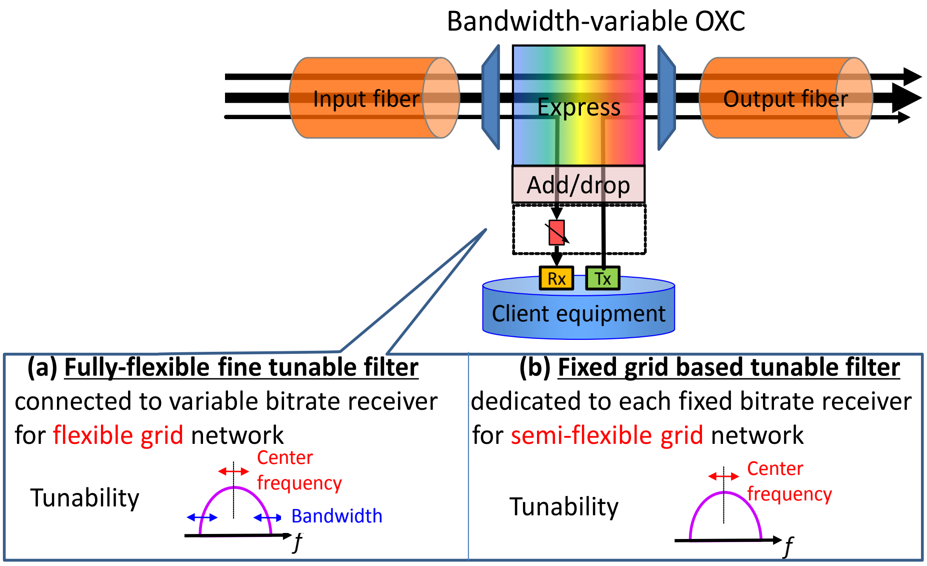


Figure 5-4. Example model for (a) proposed semi-flexible grid and (b) conventional flexible grid ROADMs with C/D/C function.

Figure 5-5 compares different channel frequency allocation strategies described so far. For flexible grid networks, high spectral efficiency is realized at the cost of hardware implementation complexity (cost). On the other hand, the existing fixed grid networks have much relaxed hardware requirements, and so are cost-effective in terms of hardware. The best approach is to combines both superiorities; the high spectral utilization offered by the flexible grid networks without additional hardware complexity (i.e., utilize existing fixed grid based hardware as much as possible). The proposed semi-flexible networks can be regarded as a subset of the flexible grid networks, but new advantages are created by the proposed scheme: transponder simplification which includes filter simplification. It should be noted that, the universal transponder is still very costly although the cost (also energy consumption) of different types of transponders strongly depends on the adopted technology and required frequency grid. Related literature released by the telecommunications equipment vendor proved that the total network cost (also energy consumption) is dominated by the transponder cost /energy consumption [5-18], and the cost/energy consumption of flexible grid based transponder (CO-OFDM) is much higher than that of the fixed grid based transponder utilized by our proposed semi-flexible grid networks. Table 5-1 summarizes the cost (normalized) and energy consumption of different WDM network components obtained from different literatures.

Table 5-1. Cost (normalized)/energy consumption of different WDM network components

Item			Ref. [5-19]	Ref. [5-20]		Ref. [5-21]
			Cost	Cost	Power (W)	Power (W)
Transponder	Fixed grid	10G	1	1	47	34
		40G	3	2.5	125	98
		100G	6	3.75	215	188
		400G	n/a	5.5	330	n/a
	Flexible grid	10G	6	3.75	215	108.16
		40G	6	3.75	215	158.653
		100G	6	3.75	215	259.63
		400G	n/a	5.5	400	n/a
OXC	Fixed grid		n/a	3.75†	430	$85 \cdot N + 150$††
	Bandwidth-variable		n/a	4.68	430	$85 \cdot N + 150$††
Amplifier (1 per degree)			n/a	n/a	145	170

† The cost of a fixed grid based WSS is 12, 000 €.

†† *N*: Number of fibers that the node connects to other node

In the future, as technology advances, the universal transponder can be expected to be a cost-effective way of implementing dynamic bitrate-adaptive optical path services. However, in this thesis, a dynamic fixed bandwidth optical path service where the client interface speed does not change dynamically is assumed. In this case, making the best use of the current fixed-grid based transponders will be a feasible solution without waiting for implementation of the future dynamic optical level traffic management scenario. Therefore, a novel semi-flexible grid network that can enhance frequency utilization while utilizing current fixed-grid based transponders is proposed.

Another important issue is the management of bitrate signals variation: the conventional flexible grid network can smoothly manage different bitrate signals since universal transponders are utilized. However, as mentioned before, in the aspect of network evolution scenario, with most large carriers, few kinds of transmission systems generally co-exist so optimization of overall network design and operation is possible. Therefore, the bitrates considered here are a small set of those that have been standardized in ITU-T so far and future plausible higher bitrates. Therefore, with the introduction of future SDN technologies [5-3], the proposed semi-flexible grid networks can also manage the bitrate signals variation. As a result, cost effective semi-flexible networks can be created by adopting the semi-flexible grid strategy.

The proposed semi-flexible network can be regarded as a subset of the flexible grid network, but new advantages are created with our proposed scheme: transponder simplification which includes filter simplification. The next important task here is to evaluate the performance of the proposed network in terms of the amount of traffic that can be carried on the same fiber networks. The network performance evaluation for the proposed semi-flexible grid networks will be discussed in Chapter 6 in details.

	Fixed Grid	**Semi-flexible** Grid	**Flexible** Grid
Spectral Efficiency	*Poor*	*Good* (*detailed in Chapter 6*)	*Good*
Transmitter	*Fixed*	*Fixed*	*Universal* - Fully-flexible fine tunable laser - Programmable modulator - Symbol rate adaptive - Adjust subcarrier number
Receiver (Filtering)	- Fixed grid based tunable filter OR -Coherent detection	-Fixed grid based tunable filter -Coherent detection	- Fully-flexible fine tunable filter OR - Coherent detection
Signal Frequency Allocation Strategy	Aligned with fixed grid	Aligned with fixed grid (fixed slot width) which is specific to each bitrate signal	Center frequency and slot width flexible for each channel

Figure 5-5. Comparisons of different channel frequency allocation strategies.

5.4 Summary

A novel elastic optical path network, called as semi-flexible grid network which utilizes an anchored frequency slot assignment that is defined selectively for each bitrate signal, is proposed. Compared with the conventional flexible grid networks, the proposed ones can significantly mitigating hardware requirements by utilizing the currently cost-effective fixed grid based hardware. The proposed approach yields flexible grid systems with much reduced hardware requirements and will be a viable approach to realizing flexible bandwidth networks cost-effectively.

References

[5-1] K. Sato, "How to create large scale OXCs/ROADMs for future networks," IEEE *International Conference on Transparent Optical Networks (ICTON),* paper We.B1.4, Graz, Austria, July 2014.

[5-2] A. L. Chiu, G. Choudhury, G. Clapp, R. Doverspike, M. Feuer, J. W. Gannett, G. Kim, J. Klincewicz, T. Kwon, G. Li, P. Magill, J. M. Simmons, R. A. Skoog, J. Strand, A. Lehmen, B. J. Wilson, S. L. Woodward, and D. Xu, "Architectures and protocols for capacity efficient, highly dynamic and highly resilient core networks," *IEEE/OSA Journal of Optical Communications and Networking (JOCN),* vol. 4, no.1, pp. 1–14, January 2012.

[5-3] L. Tancevski, "SDN concept: from theory to network implementation," *OSA Optical Fiber Communication Conference (OFC)*, paper W1E.3, San Francisco, USA, March 2014.

[5-4] M. D. Feuer and S. L. Woodward, "Advanced ROADM networks," *OSA National Fiber Optic Engineers Conference (NFOEC)*, paper NW3F.3, Los Angeles, USA, March 2012.

[5-5] R. Jensen, A. Lord, and N. Parsons, "Colourless, directionless, contentionless ROADM architecture using low-loss optical matrix switches," *OSA European Conference and Exhibition on Optical Communic*ation (ECOC), paper Mo.2.D.2, Turin, Italy, September 2010.

[5-6] H. Ishida, H. Hasegawa, and K. Sato, "Highly scalable subsystem modular OXC nodes that host tailored add/drop mechanism," *OSA Optical Fiber Communication Conference (OFC)*, paper Th2A.47, Los Angeles, USA, March 2015.

[5-7] "Spectral grids for WDM applications: DWDM frequency grid," ITU-T Recommendations G.694.1, February 2012.

[5-8] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, "Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and

enabling technologies," *IEEE Communications Magazine*, vol. 47, no. 11, pp. 66-73, November 2009.

[5-9] S.L. Woodward, and M. Feuer, "Benefits and requirements of flexible-grid ROADMs and networks," *IEEE/OSA Journal of Optical Communications and Networking (JOCN)*, vol. 5, no. 10, pp. A19-A27, October 2013.

[5-10] K. Sato, "Recent developments in and challenges of elastic optical path networking," *OSA European Conference and Exhibition on Optical Communication (ECOC)*, paper Mo.2.K.1, Geneva, Switzerland, September 2011.

[5-11] T. Zami, "What is the benefit of elastic superchannel for WDM network?" *OSA European Conference and Exhibition on Optical Communication (ECOC)*, paper We.2.E.1, London, UK, September 2013.

[5-12] G. Zhang, M. De Leenheer, A. Morea, and B. Mukherjee, ''A survey on OFDM-based elastic core optical networking,'' *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 65–87, First Quarter, 2013.

[5-13] G. Bosco, V. Curri, A. Carena, P. Poggiolini, and F. Forghieri, ''On the performance of Nyquist-WDM terabit superchannels based on PM-BPSK, PM-QPSK, PM-8QAM or PM-16QAM subcarriers,'' *IEEE Journal of Lightwave Technology (JLT)*, vol. 29, no. 1, pp. 53–61, January, 2011.

[5-14] P. Magill, presented at the workshop on spectrally/bit-rate flexible optical network design and operation, *OSA Optical Fiber Communication Conference (OFC)*, Los Angeles, USA, March 2011.

[5-15] S. Takashina, Y. Mori, H. Hasegawa, K. Sato and T. Watanabe, "Low crosstalk wavelength tunable filter that utilizes symmetric and asymmetric Mach-Zehnder interferometers," *OSA Optical Fiber Communication Conference (OFC)*, paper Th3F.6, San Francisco, USA, March 2014.

[5-16] D. Geisler, N. Fontaine, R. Scott, T. He, L. Paraschis, O. Gerstel, J. Heritage, and S. Yoo, "Bandwidth scalable, coherent transmitter based on the parallel synthesis of multiple spectral slices using optical arbitrary waveform generation," *OSA Journal of Optics Express*, vol. 19, no.9, pp. 8242-8253, April 2011.

[5-17] B. Collings, "The next generation of ROADM devices for evolving network applications," presented at the market focus on *OSA European Conference and Exhibition on Optical Communication (ECOC)*, Geneva, Switzerland, September 2011.

[5-18] A. Klekamp, U. Gebhard, and F. Ilchmann, "Energy and cost efficiency of adaptive and mixed-line-rate IP over DWDM networks," *IEEE Journal of Lightwave Technology (JLT)*, vol. 30, no. 2, pp. 215–221, January 2012.

[5-19] O. Rival, and A. Morea, "Cost-efficiency of mixed 10-40-100Gb/s networks and elastic optical networks," *OSA Optical Fiber Communication Conference (OFC)*, paper OTuI4, Los Angeles, USA, March 2011.

[5-20] M. Angelou, K. Christodoulopoulos, D. Klonidis, A. Klekamp, F. Buchali, E. Varvarigos, and I. Tomkos, "Spectrum, cost and energy efficiency in fixed-grid and flex-grid networks," *OSA Optical Fiber Communication Conference (OFC)*, paper NM3F.4, Los Angeles, USA, March 2012.

[5-21] J. Vizcaíno, Y. Ye, and I. Monroy, "Energy efficiency analysis for dynamic routing in optical transport networks," *IEEE International Conference on Communications (ICC)*, paper ONS01-4, Ottawa, Canada, June 2012.

Chapter 6

DEVELOPMENT OF FLEXIBLE/SEMI-FLEXIBLE GRID NETWORKS DESIGN ALGORITHM

This chapter presents a novel disruption-minimized dynamic rerouting and spectrum defragmentation algorithm that addresses blocking ratio equalization on different bandwidth signals in flexible grid networks and the proposed semi-flexible grid networks (the details can be found in Chapter 5). The blocking ratio inequality among channels stems from non-uniform frequency bandwidth allocation to different channels, which is unique to flexible/semi-flexible grid networks. The non-uniform assignment also causes more frequent channel set-up blocking due to the severe fragmentation that is possible in the frequency domain. To resolve these issues, a dedicated bandwidth reservation technique for the broadest bandwidth paths is introduced to cope with the inequality issue, and the path blocking ratio is reduced by applying rerouting and spectrum defragmentation technique. Numerical evaluations verify that combining these techniques can maximize network performance including blocking ratio and equality. The results also confirm that semi-flexible grid networks can achieve almost the same performance as the currently proposed flexible grid solution. Since the former have much relaxed hardware requirements, this novel approach is expected be a viable solution to realizing future flexible bandwidth networks cost-effectively.

6.1 Introduction

Transmission systems that accommodate 100 Gbps signals have been widely introduced in the backbone network to cope with the relentless traffic increase. Unfortunately, the existing fixed grid system cannot efficiently support higher bitrate signals, such as 400 Gbps and 1 Tbps. Maximizing fiber spectral utilization is a critical issue to attain cost-effectiveness, and hence flexible grid optical path networks [6-1]-[6-3] have been proposed and standardized in ITU-T [6-4]. The flexible fine frequency tunability offered enables the efficient use of fiber spectrum resources but this benefit is offset by the higher hardware costs than present fixed grid based networks. A novel semi-flexible grid network architecture was proposed (See Chapter 3) where each specific bitrate signal is aligned to a fixed grid that is specific to each bitrate, and hence current cost-effective fixed grid based hardware can be utilized. However, the network performance that can be achieved by the semi-flexible grid networks is still unknown.

Spectrum fragmentation is a critical issue impacting network performance for not only conventional flexible grid networks, but also the proposed semi-flexible grid networks. During the dynamic operation, since spectrum slots are allocated dynamically and non-uniformly (diverse slot widths required for different bitrate signals), unusable spectral gaps (too narrow to accommodate new paths) will multiply. This fragmentation degrades the spectral utilization efficiency. To solve this problem, several spectrum defragmentation techniques have been proposed for flexible grid networks, such as re-optimization [6-5], push-and-pull defragmentation [6-6], and make-before-break (MBBR) defragmentation [6-7]. Indeed, by introducing defragmentation techniques, the network performance can be certainly improved for flexible grid networks but their effectiveness in semi-flexible gird networks is still unknown. Moreover, most spectrum defragmentation techniques tend to focus on reducing the blocking of relatively small bitrate channels while ignoring or increasing the blocking of high bitrate channels that occupy broader frequency bandwidth. This fundamental blocking ratio inequality can degrade service quality.

In this chapter, a novel disruption minimized dynamic rerouting and spectrum defragmentation (using make-before-break technique) and blocking ratio equalization techniques (introducing exclusive area size for highest bitrate signal) are presented for both flexible grid and semi-flexible grid networks. The MBBR technique establishes rerouting paths on alternative routes and assigns frequency slots before releasing the original paths, which can minimize the disruption time. Moreover, when coupled with delay management techniques defined for optical transport network [6-8] that include electrical buffer memory management, truly hitless rerouting can be realized. The MBBR-based rerouting technique is proved to be effective in enhancing the network integrity of flexible grid networks [6-7]. Meanwhile, to alleviate the blocking ratio inequality among different bandwidth channels, reserve an exclusive contiguous frequency slot area in a fiber for the highest bitrate channels. Analyses demonstrate that by combining these two techniques, the proposed algorithm can improve the network performance for both flexible and semi-flexible grid networks significantly over wide parameter ranges. The results also verify that semi-flexible grid networks that utilize aligned frequency slot assignment can achieve almost the same performance as flexible grid networks, which conclusively confirms the effectiveness of semi-flexible grid network proposal.

6.2 Spectrum fragmentation for flexible/semi-flexible grid networks

For conventional fixed grid networks, the establishment of a path with a large hop count tends to be blocked more often due to the wavelength continuity constraint, i.e., the same wavelength must be assigned to a path in all fibers traversed. This issue becomes more obvious in both flexible grid and semi-flexible grid networks. In this case, a set of contiguous frequency slots must be commonly available in all traversed fibers and reservation is often prevented by the occupation of some of these slots by other paths. During the dynamic path setup/release operation process, the path routing and frequency slot assignment for an arriving connection tend to diverge from the optimal path accommodation condition, and eventually, the spectrum area is fragmented and may not accommodate a new connection even though each fiber has many unoccupied slots. This fragmentation degrades the spectrum utilization efficiency (i.e., causes high path set-up blocking ratios), and this is most evident with higher bitrate signals which occupy broader bandwidths.

Figure 6-1 shows an example of a blocking ratio distribution among different bitrate signals on flex/semi-flex networks; the evaluation considered a 6x6 regular mesh network. In this evaluation, 4 different types of bitrate signals (Table 6-1, "SP", abbreviation of Slot width Pattern, represents the pattern of required slot widths for each assumed bitrate signals.) were generated with the same ratio among bitrates. The results demonstrated that for both the semi-flexible and flexible grid networks, more than 90% of path setup blocking is caused by the 1 Tbps signals, which occupy the broadest bandwidth in the assumed bitrate signals.

The objective of this study is to improve the network blocking performance while resolving the blocking ratio inequality caused by the non-uniform bandwidth assignment for both flexible grid and proposed semi-flexible grid networks.

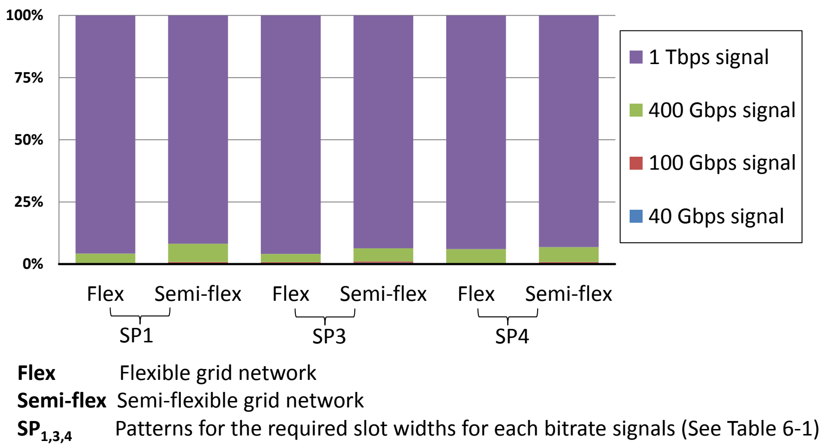


Figure 6-1. Comparisons of blocking distribution per bitrate signal.

Table 6-1. Four different slot widths allocated in terms of *m*: multiple of 12.5 GHz for different bitrate signals

	40 Gbps	100 Gbps	400 Gbps	1 Tbps
SP1 (Ref.[6-2])	3	4	7	16
SP2 (Ref.[6-2])	3	3	7	16
SP3 (Ref.[6-3])	4	4	6	12
SP4	4	4	8	16

6.3 Disruption minimized in spectrum defragmentation

For conventional fixed grid networks, rerouting is a viable and cost-effective approach to decreasing the path set-up blocking. An extension of this technique, the so-called rerouting and spectrum defragmentation has also widely been studied for flexible grid networks. The authors of [6-5] formulated the defragmentation problem as an ILP and proposed two heuristic algorithms to obtain sub-optimal solutions. However, the re-optimization process involves cutting off existing paths for reconfiguration, which causes service interruption. In [6-6], the authors proposed a push-and-pull technique which performs defragmentation by crawling over the contiguous unoccupied frequency range along the same route of the original path. This technique can prevent service interruption, but the relocation to the other route or to another unused frequency range separated by the existing other paths is limited. In [6-6], the authors proposed a MBBR technique in which paths are established on alternative routes and assigned frequency slots before releasing the original paths, which can minimize the disruption time. Furthermore, if a delay adjustment mechanism that can absorb the delay differences between original and rerouting routes is introduced at the signal receiving side, hitless rerouting will become possible. This can be achieved by using the phase information of digital paths as standardized in the optical transport network process [6-8]. It should be noted that for high bitrate signals, hitless rerouting becomes difficult since large-capacity memories are required. In this situation, the distance difference between original and rerouting routes may need to be limited. The differences among these 3 rerouting techniques are summarized in Fig. 6-2.

In this study, for dynamic optical path control in both flexible and semi-flexible grid networks, an MBBR rerouting technique [6-6] is introduced since this technique can achieve not only a good network performance, but also a smooth network operation compared with the other rerouting candidates. Figure 6-3 illustrates the process of MBBR technique: When a new path is blocked, an alternative path for the existing path that blocks the new path is established. After the existing path is switched to its alternative route, the existing path is released and the new path is accommodated. This defragmentation technique can cover all spectral areas/existing paths, and a significant improvement in network blocking performance can be expected for proposed semi-flexible grid networks.

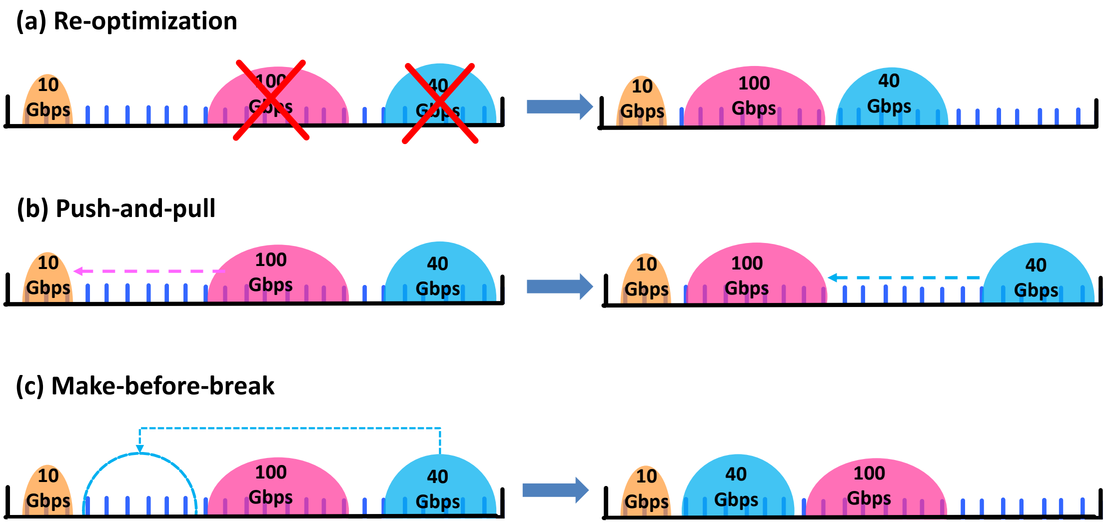


Figure 6-2. Mechanism for different defragmentation technologies.

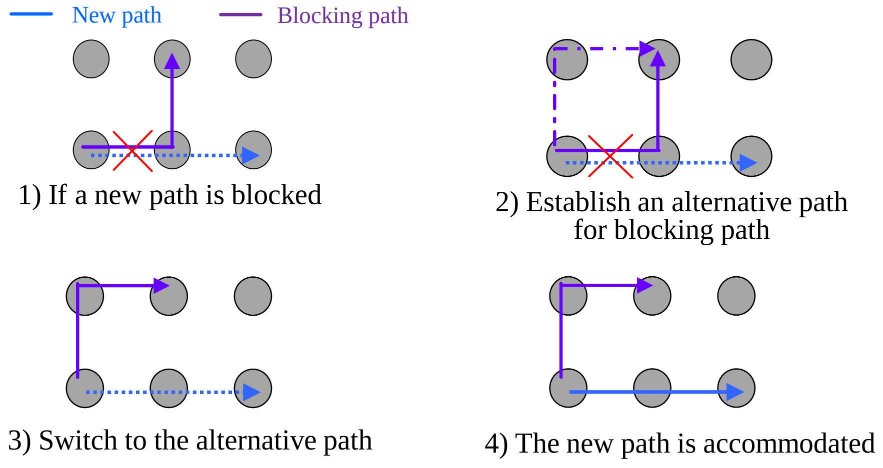


Figure 6-3. Outline of make-before-break rerouting mechanism.

6.4 Reservation of exclusive spectrum area for high bitrate channel

For both flexible and semi-flexible grid networks, reducing the imbalance in blocking ratios caused by the non-uniform frequency bandwidth assignment (as presented in the example in Fig. 6-1) is also a critical issue. For the case without rerouting, several techniques [6-9]-[6-10] have been proposed to solve this problem in flexible grid networks. The authors in [6-9] proposed an approach to divide the available fiber spectrum range into several non-overlapping areas where the same bitrate signals are assigned to each specific area exclusively (Fig. 6-4 (a)). Although uniform bandwidth allocation can be achieved in each area, ideal gapless packing will not be possible because routes of paths are different. Moreover, the bandwidth ratios of those areas will not match the bitrates due to the ever-changing traffic distribution. Therefore, common utilization of the available frequency range by all bitrate paths can reduce the unused gaps substantially. The authors in [6-10] introduced area-based frequency slot assignment, i.e., for each bitrate signal, first try to allocate it within a preferential zone, if no available space exists in the zone, try the other area (Fig. 6-4 (b)). An improved strategy was proposed in [6-9], where a hybrid shared area is created and in each area, the type of bitrate signals that can be shared is limited (Fig. 6-4 (c)). In both strategies, however, it is still difficult to obtain optimal partitioning solutions given the ever-changing traffic distribution, particularly in the case of multiple fibers on each link.

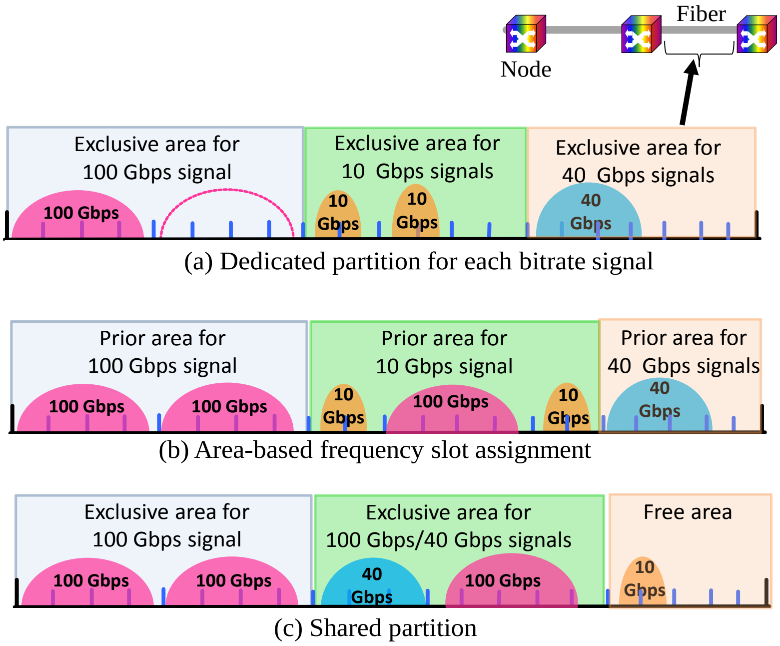


Figure 6-4. Example of spectrum assignment strategy for different conventional methods.

In this study, a novel spectrum assignment strategy that reserves an exclusive spectrum area for high bitrate signals is proposed. Figure 6-5 illustrates an example of our proposed reservation strategy. In this example, signal bit rates are 10 Gbps, 40 Gbps and 100 Gbps. The exclusive area is located at the edge of spectrum resource of each fiber while the remaining resources are called the free area. The exclusive area is reserved for 100 Gbps signals since they have the broadest bandwidth in this example. Here, the exclusive area size (*W*) is defined as the maximum number of respective bitrate signals that can be reserved in the exclusive area. The size of the exclusive area is set to be twice (*W*=2) the bandwidth necessary for the 100 Gbps signal in this example. During spectrum assignment, if the exclusive area has no space left to accommodate a new 100 Gbps signal connection, the free area (the green area in Fig. 6-5) can also be utilized for the new 100 Gbps signal, while the other bitrate signals (10/40 Gbps) cannot utilize the exclusive area even if it has unused resources. This method can reduce high blocking ratio for the highest bitrate channels, without imposing a strict separation on the available frequency range for each bitrate signal (the other bitrate paths that need narrower bandwidth can share the remaining spectrum area). Moreover, since the proposed assignment method is only concerned with the critical signals most likely to be degraded, the complexity of area size optimization is substantially reduced. The proposal can also be realized without introducing any special hardware.

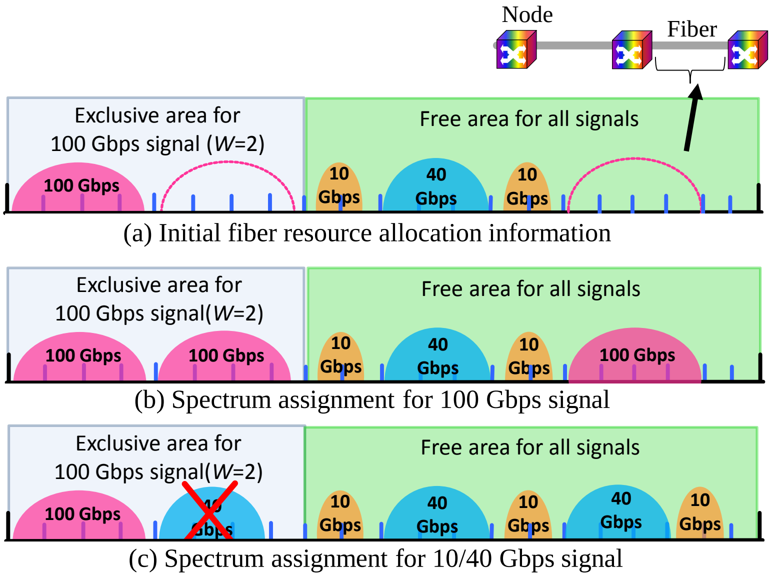


Figure 6-5. Example of proposed spectrum assignment strategy introducing exclusive area for 100 Gbps signals.

Expanding the exclusive area size will increase the blocking ratio of the lower bitrate signals, especially those with the second broadest bandwidth (e.g., 40 Gbps signal in Fig. 6-5). Therefore, to reduce the total blocking ratio in the network, it is important to appropriately set the size of the exclusive area considering the blocking ratio distribution among different bitrate signals. The impact of exclusive area size is discussed in the numerical experiments section.

6.5 Proposed rerouting and spectrum defragmentation algorithm

This chapter tackles a dynamic network design problem that assumes dynamic optical path setup/release requests; the objective here is to minimize the blocking ratio in the network, along with attaining blocking ratio equality for different bitrate signals. In the preparation stage, for the given topology and fibers, the algorithm accommodates a new path demand request by first calculating a set of route candidates for the source and destination node pair using the *k*-shortest path algorithm. It then assigns a route and slot pair set to the new path demand in lexicographical order of (“route priority”, “frequency slot index”); according to the route priority, search for vacant and consecutive 12.5 GHz slots and assign them to the selected path. If an available route and slot index pair is not found, existing paths are rerouted in MBBR manner to generate vacant frequency slots on the related links that can accommodate the arriving path demand. When the path setup/release request arrives, execute the process shows in Fig. 6-6. The outline of the developed algorithm is described as follows:

Step1. For all connection demands whose holding times have expired, release the paths and free all occupied frequency slots on their routes.

Step2. Select one of the path set-up requests in order of arrival. For the new request, assign the first found pair of route and slot to the request, establish the path, and update the slot usage database on all fibers traversed by the new path. Otherwise go to Step3. Repeat this procedure until all set-up requests are processed. Go back to Step 1.

Step3. For each blocked path connection, find a pair of route and slot index set candidates for which the number of links the blocked path demand cannot go through is smallest.

Step4. Find all existing paths that conflict with the pair of route and slot set candidates selected in Step 3. For each conflicting path, try to find an available alternative pair of route and slot set. Note that the original route with different slot sets can be a candidate.

Step5. For each blocked demand, if alternative pairs of route and slot sets are found for all existing conflicting paths, perform path relocation in the make-before-break manner. Otherwise, block the connection demand.

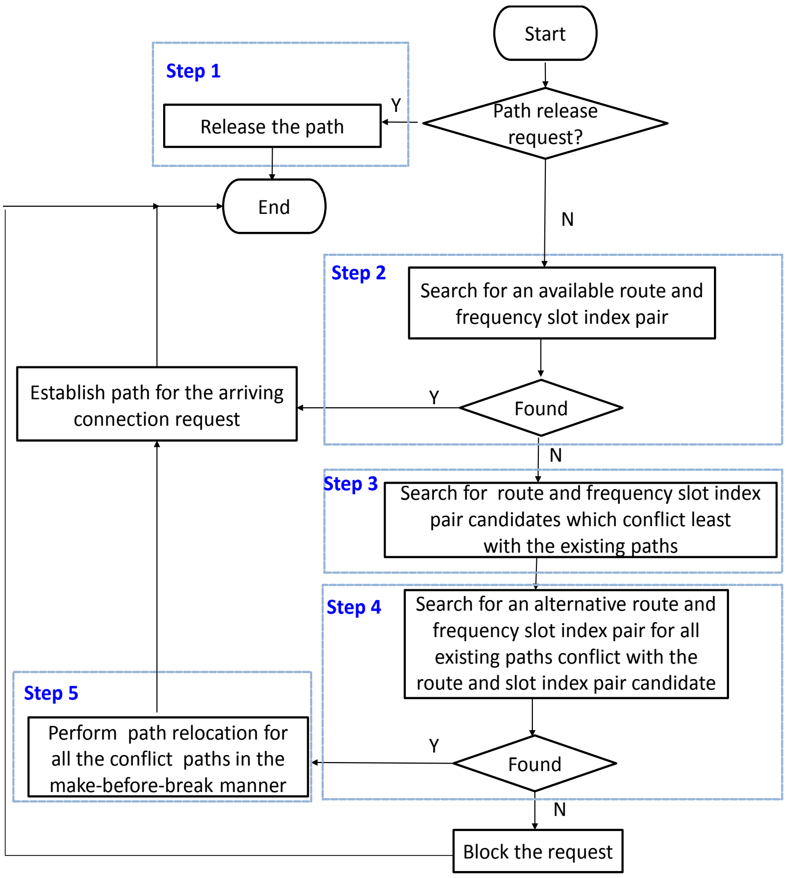


Figure 6-6. Flowchart of the proposed rerouting and spectrum defragmentation algorithm.

To reduce the spectrum fragmentation for flexible/semi-flexible grid networks, the following two different frequency slot assignment scenarios is adopted in the proposed spectrum defragmentation technique:

1) Scenario 1 (**MBBR1**)

Select the first found available contiguous slot blocks in fibers that can accommodate the arriving connection demand. This classical algorithm has been proven to be effective in maximizing the spectrum utilization efficiency of conventional flexible grid networks and is widely adopted as a major verification benchmark [6-7], [6-9]-[6-12].

2) Scenario 2 (**MBBR2**)

For all available contiguous slot blocks in the fibers, for all possible bitrate types assumed in the evaluation, calculate the differences between the before and after of the number of possible accommodation patterns. Select the contiguous slot blocks with the minimum difference value. Moreover, in this scenario, reserve exclusive spectrum area for 1 Tbps signals to reduce the blocking ratio inequality. That is to say, to accommodate the highest bitrate signal assumed in the evaluations, it first tries to find a vacant area in the exclusive area, if the exclusive area has no space left to accommodate this new connection request, try to utilize the free area (Fig. 6-5b). On the other hand, the other bitrate signals cannot utilize the exclusive area even if unused resources exist (Fig. 6-5(c)).

Meanwhile, to reduce the computation burden of the spectrum assignment process, the following fast available frequency slot search method is utilized in the proposed algorithm:

Step (a). Establishment of fiber map

For each frequency slot index in a fiber, calculate the number of consecutive vacant frequency slots that begins from this index for each fiber in the network. Create an information map for each fiber.

Step (b). Establishment of link map

Establish the link information maps based on the information on each fiber obtained from Step1. Here, the value on each frequency slot index is calculated by choosing the maximum value for the same frequency slot index for all fibers on the same link. For example, in Fig. 6-7, the map information of link #2 is calculated by performing the “MAX” operation on fibers #2 and #3.

Step (c). Establishment of path map

Establish the route information maps based on the link information obtained from Step3. Here, the value on each frequency slot index is calculated by choosing the minimum value on the same frequency slot index for all links traversed by the route. For example, in Fig. 6-7, the information map of route #1 is calculated by performing the "MIN" operation on links #1 and #2.

Step (d). Search of available frequency slot index

Assign the first consecutive 12.5 GHz slots in the frequency slot area (exclusive area or free area) sufficient to support the arriving bitrate signal. Here, it is only needed to locate the frequency slot index whose value in the route map is larger than the required slot width of the arriving path request. For example, in Fig. 6-7, if the required slot width of an arriving signal is 3, find a slot index whose value in the route map is equal to or larger than 3; and then assign the first slot index to route #1.

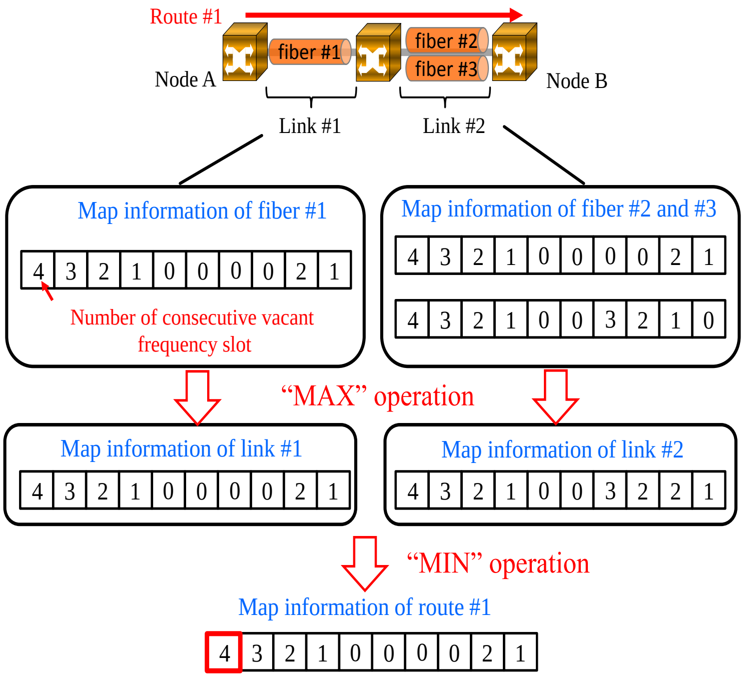


Figure 6-7. Example of fast frequency slot search method.

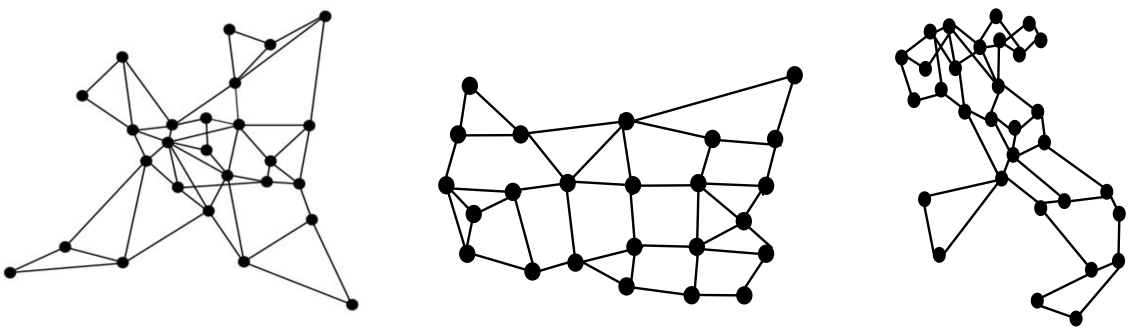
The next section verifies the effectiveness of introducing either or both of MBBR-based rerouting technique or/and reserving exclusive spectrum area for high bitrate signal technique. Unlike the currently discussed defragmentation technique, which tends to reduce the blocking of relatively small bitrate channels while keeping or even increasing the blocking of high bitrate channels, the evaluation proved that by reserving a contiguous frequency slot area for the high bitrate signals, not only the path set-up blocking ratio, but also the resource over-provision for the high bitrate signals to guarantee their certain blocking ratio can be significantly reduced.

6.6 Performance evaluation

6.6.1 Simulation parameters

The minimum frequency slot width, the unit of frequency slot assignment, is assumed as 12.5 GHz in the C-band (4,400 GHz wide) following ITU-T standards. All the connection demands are full-duplex, i.e., each demand requires a pair of bidirectional paths. The bitrates requested are set at 40 Gbps, 100 Gbps, 400 Gbps and 1 Tbps which represents the current trend in channel bitrates towards the next generation core networks; the ratio of expected numbers of different bitrate connections is set at 1:1:1:1 (named “GR1”) so that generated connection request number of each bitrate signal is the same in the network, or the ratio corresponding to the inverse of capacity so that the total demand bandwidth for each bitrate signal is equal (named “GR2”). 4 different slot width requirements (SP1-SP4, Table 6-1) for each bitrate are tested. In this evaluation, finer bandwidth granularity or particular modulation formats like Nyquist WDM or CO-OFDM is not considered. Wavelength conversion is not assumed either due to its high cost (Please notice that the wavelength convertor required for flexible grid/semi-flexible grid networks is different from that for fixed grid networks). According to [6-2], 1 Tbps transmission is expected to be realized by DP-QPSK/DP-16QAM in the future, so regenerators seem redundant since a relatively long transmission distance can be achieved by using these modulation formats.

Physical network topologies tested are $M \times M$ (M = 4, 5, 6) regular mesh networks, COST266 pan European network, US nationwide network, and Telecom Italia backbone network as shown in Fig. 6-8. More details of these network topologies can be found in Fig. 4-12.



(a) COST266 pan-European (b) US nationwide (c) Telecom Italia backbone

Figure 6-8. Network topologies.

The dynamic connection demands are generated following a Poisson process and the source/destination nodes are assigned randomly to each dynamic connection demand and the demanded bitrate is distributed as mentioned before. The holding time of each connection follows a negative exponential distribution. The data obtained in the initial period, 10 times the average holding time, is not utilized in the blocking ratio calculation to ensure that the system has reached its steady state. The running time for each evaluation is 100 times the average holding time (when the tested traffic distribution patterns are more than 25, virtually the same results can be achieved as those with a large number of patterns, i.e., 200 patterns). Therefore to reduce the excessive computation burden, 25 different traffic distribution patterns are used in all evaluation; the results are the ensemble average of the obtained results.

In order to construct a network that suits the traffic distribution considered, the initial stage applies a static flexible grid network design algorithm to determine the number of fibers needed in each link. Full mesh and random traffic demands are assumed where each demanded bitrate is also randomly selected according the ratio shown in Table 6-1. The demands between node pairs are then accommodated one by one in descending order of the shortest hop count among node pairs so as to minimize the number of fibers needed. For dynamic path setup/release, path requests are processed using the algorithm described in Section 5 for flexible grid/semi-flexible grid networks.

To verify the effectiveness of the rerouting and defragmentation technique, two algorithms are also adopted for comparison. The First-Fit (FF) algorithm is the same method as Scenario 1 (MBBR1, Section 5) if spectrum defragmentation is not considered, while the Shannon-Entropy (SE) algorithm [6-11] selects the available contiguous slot blocks by using a quantitative fragmentation index according to the so called Shannon entropy method in flexible grid networks.

From the next section, firstly the effectiveness of our proposed rerouting and spectrum defragmentation algorithm is demonstrated in terms of the blocking performance and blocking distributions among different bitrate signals. Then network performance of semi-flexible grid networks and of conventional flexible grid and fixed grid networks is compared.

6.6.2 Simulation criteria

In this simulation, 3 simulation criteria are adopted to evaluate the performance of the proposed semi-flexible grid optical path network. Here, example shown in Table 2 is utilized to explain these criteria:

<u>Criterion 1</u> - Blocking ratio

This criterion shows the ratio of total number of blocked connection requests to total number of connection requests. For example in Table 6-2, the blocking ratio is (1 + 10) / (400 + 400 + 200 + 100) = 1 %.

<u>Criterion 2</u> - Blocking distribution per bitrate signal

This criterion shows the ratio of the total number of blocked connection requests of a certain bitrate signal to the total number of blocked connections requested. For the example in Table

6-2, the value for a 1 Tbps signal is 10 / (10 + 1) = 90.9%.

Criterion 3 - Blocking bandwidth ratio

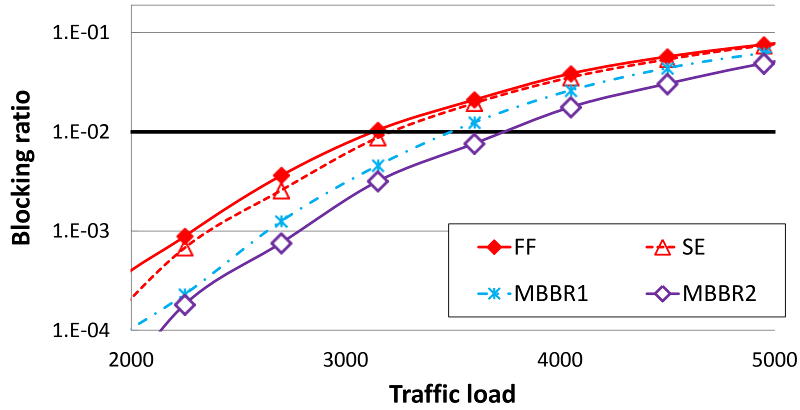
This criterion shows the ratio of total blocked connection request bandwidth over total connection request bandwidth. For the example in Table 6-2, the blocking bandwidth ratio is (1 × 8 + 10 × 16) / (400 × 4 + 400 × 4 + 200 × 8 + 100 × 16) = 2.63 %.

Table 6-2. Simulation results.

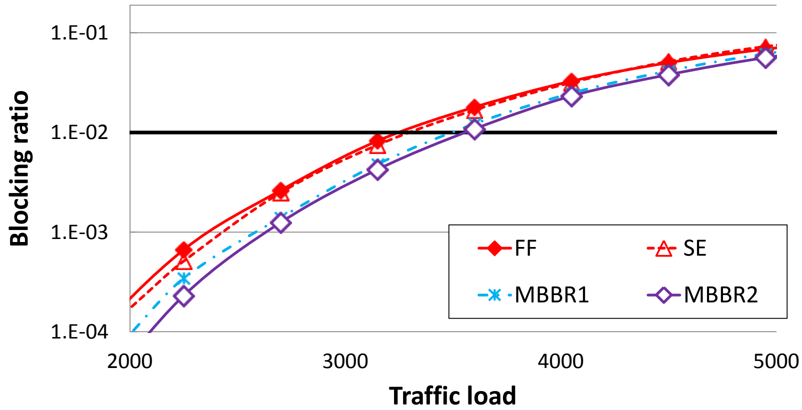
	40 Gbps	100 Gbps	400 Gbps	1 Tbps
Slot width in terms of m; multiple of *m* x 12.5 GHz	4	4	8	16
Connection demand ratio	4	4	2	1
The total number of arrived connection request	400	400	200	100
The total number of blocked connection requests	0	0	1	10

6.6.3 Network blocking performance

Figure 6-9 and 6-10 plots the path blocking ratios versus traffic volume for the 5x5 regular mesh network and COST266 pan-European network, respectively, with slot assignment pattern SP1 (Table 6-1) and the connection demand ratios of GR1. The horizontal axis is determined by the averaged summation of *SWsignal* in the network, where *SWsignal* represents the slot width an arriving connection requires. Here, the target blocking ratios are set to around 10^{-2}-10^{-3}. The results show that for both flexible and semi-flexible grid networks, the introduction of MBBR rerouting for spectrum defragmentation (MBBR1/MBBR2) can improve the network performance, and a larger improvement is attained with exclusive area reservation (MBBR2, we show only the results obtained by setting optimal exclusive area sizes). Since the algorithm that introduces both techniques (MBBR2) offers better performance than the other algorithms for various parameter values, the results of MBBR2 is used as the benchmark in the following evaluations.

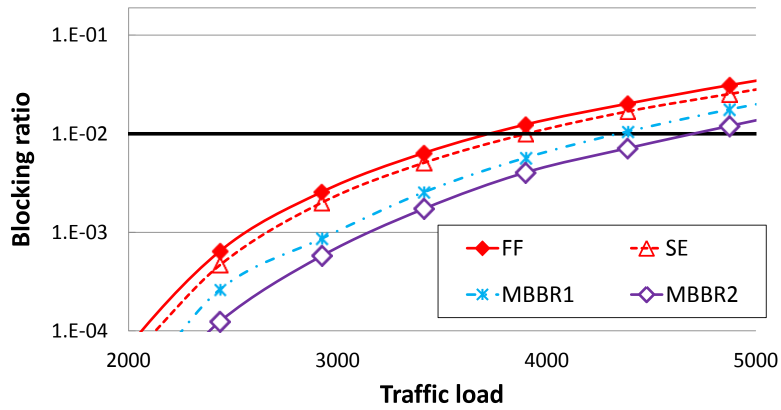


(a) Flexible grid networks

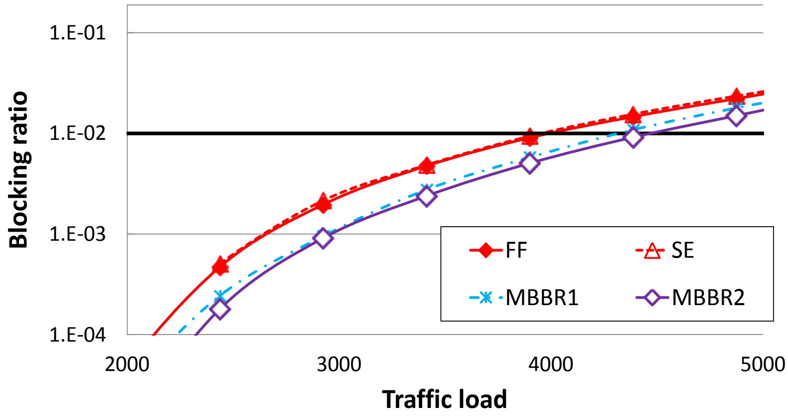


(b) Semi-flexible grid networks

Figure 6-9. Comparison of blocking ratio for SP1 with 5x5 regular mesh network tested on different networks.



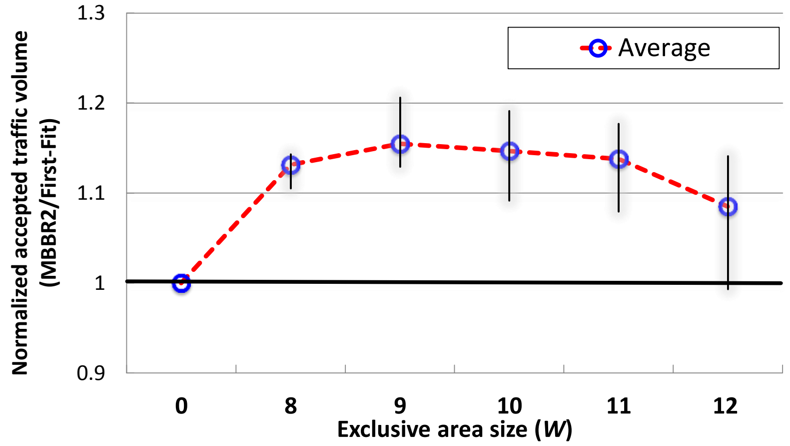
(a) Flexible grid networks



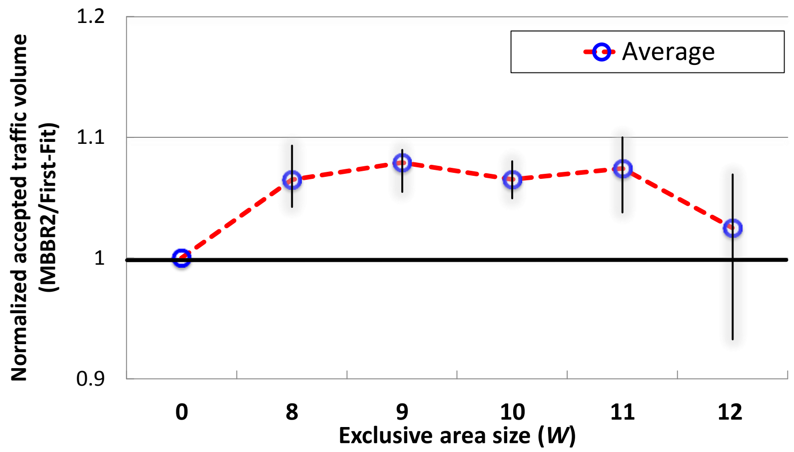
(b) Semi-flexible grid networks

Figure 6-10. Comparison of blocking ratio for SP1 with COST266 pan-European network tested on different networks.

Next, evaluate the effectiveness of our proposed strategy while changing exclusive area size. Figure 6-11 compares the traffic volume that can be accommodated when the total blocking ratio is set at 1% (For dynamic services, the target blocking ratio that is commonly assumed [6-13]-[6-14] is around 10^{-2}.) for the 5x5 regular mesh network with different slot requirement patterns (SP1-SP4, Table 6-1, the graph plots the maximum/minimum/average results tested on these four patterns.) and the connection demand ratio of GR1. The horizontal axis represents the exclusive area size *W* while vertical axis plots the relative accepted traffic volume attained under MBBR2 scenario (please see Section 5), normalized by those yielded by the First-Fit scheme. The results demonstrate that by introducing the rerouting technique and reserving an exclusive spectrum area for 1 Tbps signals, the accepted traffic volume can be increased over a wide range of exclusive area size (*W* represents the maximum number of respective bitrate signals that can be reserved in the exclusive area). The improved ratio can be up to 20% for flexible grid networks and 10% to semi-flexible grid networks. With setting different exclusive area sizes (W=8-12), compared with the case without introducing this exclusive area (W=0), the average accepted traffic volume can be improved up to 20% for flexible grid networks, and 10% to semi-flexible grid networks. (Please see the blue circle in Fig. 6-11).



(a) Flexible grid networks



(b) Semi-flexible grid networks

Figure 6-11. Comparison of normalized accepted traffic volume for different exclusive area sizes for 5x5 regular mesh network.

Next discuss the optimum exclusive area size. First, assume that the exclusive area is always fully occupied by bitrate signals occupying the broadest bandwidth (e.g., 100 Gbps in Fig. 6-12) and the free area is also fully occupied by the other bitrate signals as shown in Fig. 6-12 (a). This would be the ideal condition for the given fibers. Let w_E be the largest integer that does not exceed the ideal exclusive area size w_T:

$$w_E = \lfloor w_T \rfloor; \quad w_T = (BW_f / SW_{1T}) \cdot r_{1T} \tag{6-1}$$

where BW_f represents the available frequency bandwidth in each fiber, SW_{1T} is 1 Tbps signal slot width and r_{1T} is the occupancy ratio of 1 Tbps signals in the fiber's total bandwidth. In Fig. 6-12 (a), the value of w_E can be calculated as $\lfloor(20/4) \text{ x } (8/20)\rfloor = 2$.

Since the highest bitrate signal (e.g., 100 Gbps in Fig. 6-12) can also use the free area (the fiber is not always fully utilized), the proposed assignment will valid even if W is smaller than w_E as shown in Fig. 6-12 (b).

For the numerical experiments assuming complex multi-fiber networks where setup/release paths are dynamic operated, when the connection demand ratio is GR1 and slot assignment pattern is SP1, w_T is 11. As shown in Fig. 6-11, the network supports a high traffic volume at around W=w_E = 9 - 11 which is close to w_T (=11).

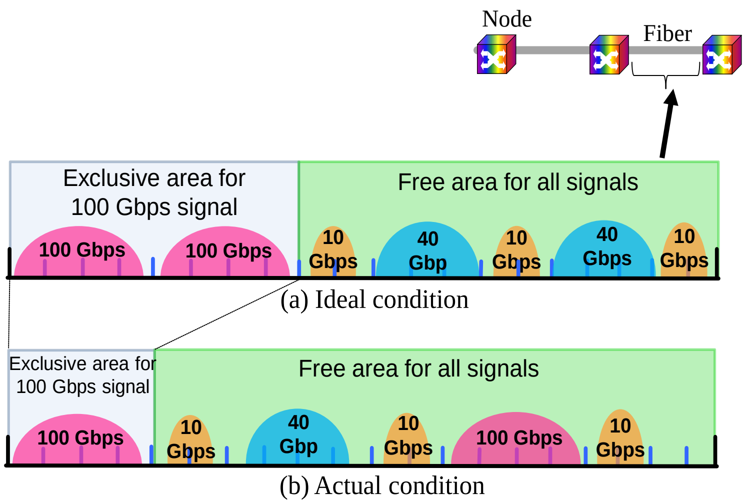
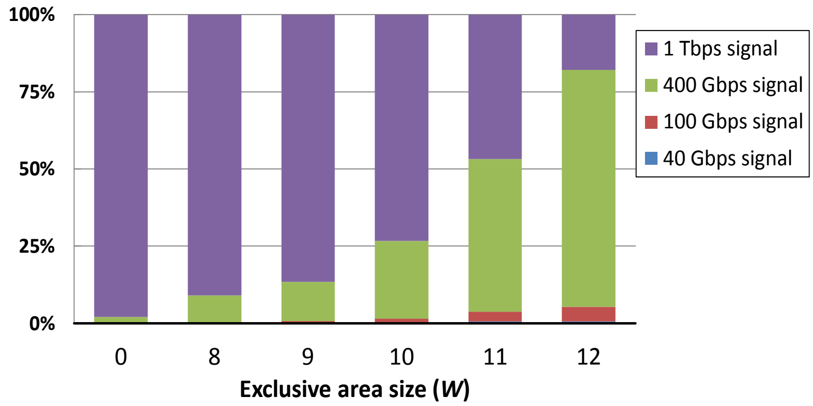


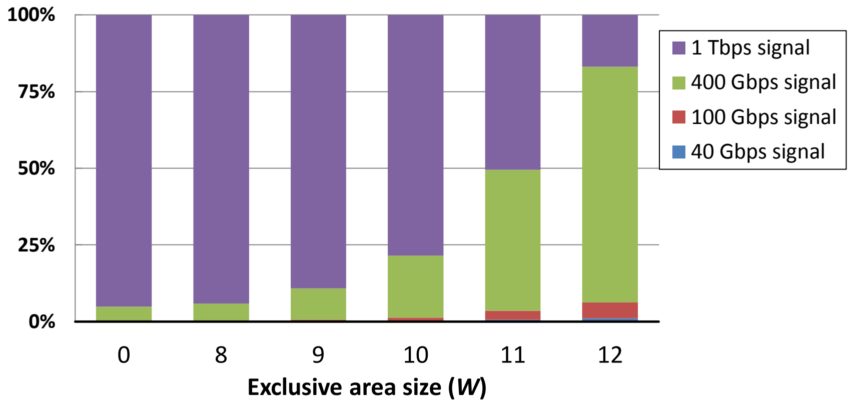
Figure 6-12. Example for deciding the optimum exclusive area size.

6.6.4 Blocking ratio distribution for each bitrate signal

Reducing the blocking ratio inequality for different bitrate signals is another important goal of our proposed strategy. Figure 6-13 compares the blocking distribution for different bitrate signals by using the same parameter values as Fig. 6-11. Without reserving the exclusive spectral area (“W=0”), more than 90% of path blocking is triggered by the 1 Tbps signals (Fig. 6-1). Setting the exclusive area (i.e. the cases of “W>0”) can significantly alleviate the blocking ratio inequality caused by the non-uniform bandwidth demand, and moreover, by introducing the MBBR-based rerouting technique, the traffic volumes that can be accommodated (See the results shown in Fig. 6-9 and Fig. 6-10) can also be increased. This confirms that better network performance can be attained by introducing both rerouting and spectrum defragmentation technique and reserving the exclusive area for high bitrate signals.



(a) Flexible grid networks

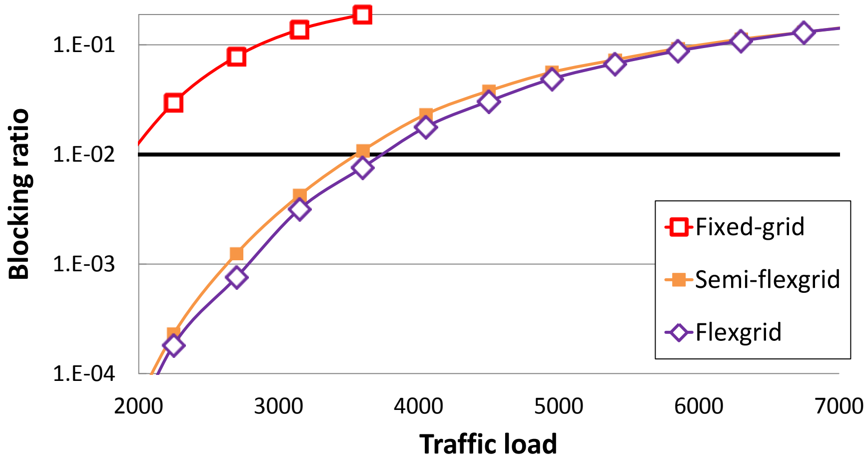


(b) Semi-flexible grid networks

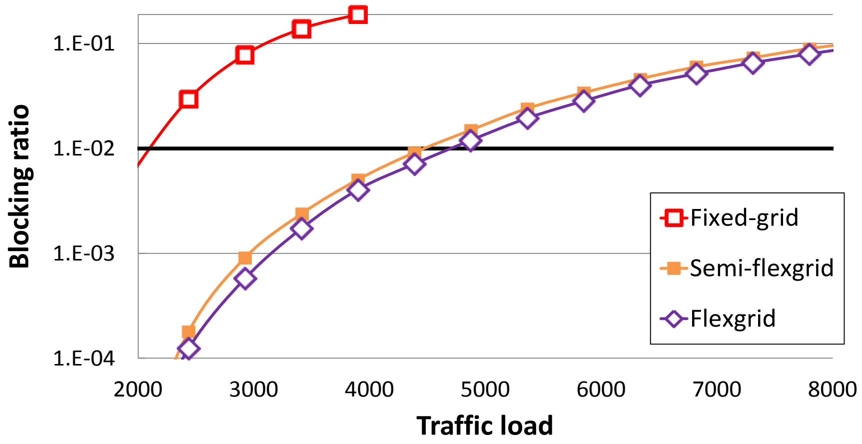
Figure 6-13. Comparison of blocking distributions among different bitrate signals for different networks. The connection demand ratio is GR1 with 5x5 regular mesh network.

6.6.5 Network performance comparison: semi-flexible grid vs. flexible grid

This section compares the performance of conventional flexible grid/fixed grid network to that of the proposed semi-flexible grid network. Figure 6-14 plots blocking ratios versus traffic volume for different networks tested with slot assignment pattern SP1. For each network, only the results calculated by MBBR2 (Section 5) are adopted since this method can achieve the best performance. The results verify that semi-flexible grid networks can attain almost the same blocking performance as flexible grid networks over a broad blocking ratio range, including the low blocking ratios. For comparison, the equivalent fixed grid network is also tested. For the fixed grid network, the grid spacing is set at 200 GHz to accommodate the 1 Tbps signal. The results show that both flexible and semi-flexible grid networks can accommodate much larger traffic volume at the same blocking ratio, which results in significantly improved spectral utilization efficiency.



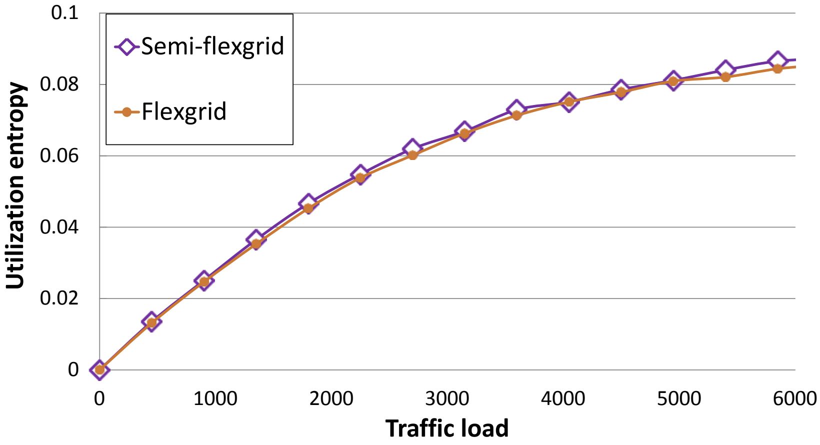
(a) 5x5 regular mesh network



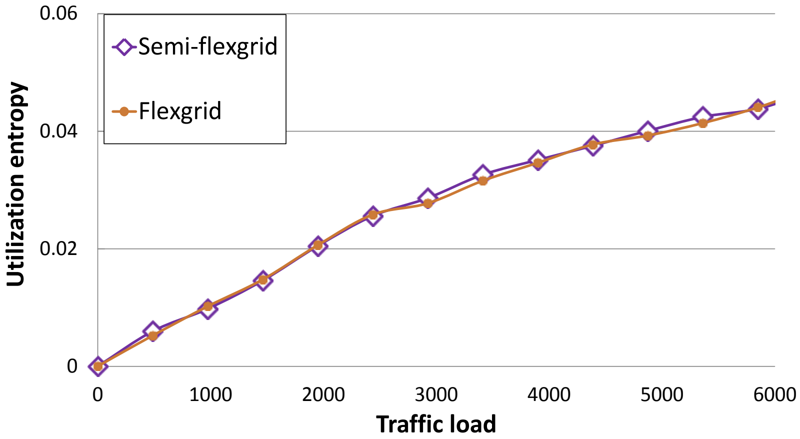
(b) COST266 pan-European network

Figure 6-14. Comparison of blocking ratio for SP1 with connection demand ratio GR1 tested on different network topologies.

As shown in Fig. 6-14, the blocking ratios of flexible grid and semi-flexible grid networks are compared and verified to be almost the same. This implies that the degree of fragmentation for both networks will be almost the same. To confirm this, Fig. 6-15 compares the fragmentation level of flexible grid and semi-flexible grid networks. Here, as a criterion, utilization entropy is utilized to show the level of resource fragmentation in the networks. The value is calculated based on the frequency slot usage status changes (See Fig. 6-7) for all the frequency slots on the link following the method shown in [6-15]. A low utilization entropy value indicates that the resource is used with fewer spectral gaps in slot usage in the fiber (low level of fragmentation). The results confirm that both flexible grid and semi-flexible grid networks give almost the same level of fragmentation over a wide range of traffic loads.



(a) 5x5 regular mesh network



(b) COST266 pan-European network

Figure 6-15. Comparison of utilization entropy for SP1 with connection demand ratio GR1 tested on different network topologies.

Figures 6-16 and 6-17 summarize the results tested over different parameter settings (Section 6.6.1). The graph plots the normalized maximum/minimum/average differences between the results for semi-flexible and flexible grid networks, tested on two different connection demand ratios (GR1 and GR2) and 6 different network topologies shown in Section 6.6.1. Figure 6-16 compares the traffic volume that can be accommodated when the total path setup blocking ratio is 1% for different network topologies with different slot assignment patterns (SP1-SP4, Table 6-1) and different connection demand ratios (BR1 and BR2). The vertical axis plots the relative accepted traffic volume (R_{trf}) for "Semi-Flex" grid to "Flex" grid network, which is calculated by:

$$R_{trf} = (trf_{SF} - trf_F)/trf_F \qquad (6\text{-}2)$$

where trf_{SF} and trf_F represent the accepted traffic volume (the number of optical paths) permitted in semi-flexible and flexible grid networks. The results demonstrate that semi-flexible grid networks can achieve almost the same blocking performance as conventional flexible grid networks (The average gap is less than 3.5 %).

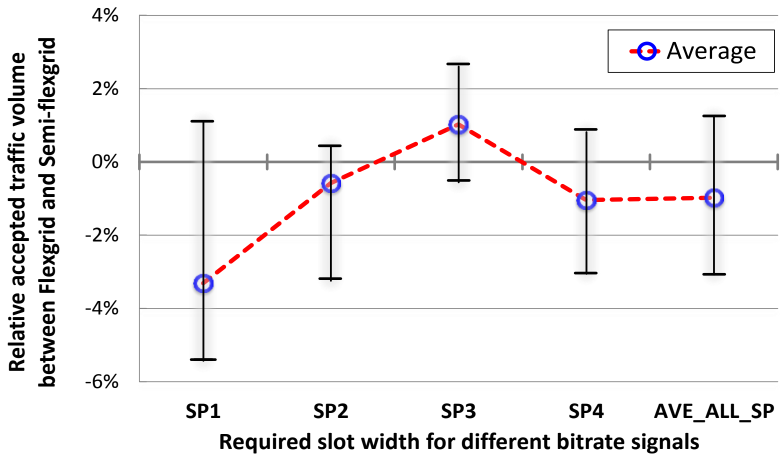


Figure 6-16. Comparison of accepted traffic volume
between flexible and semi-flexible grid networks for different slot requirement patterns.

Figure 6-17 compares the relative blocked bandwidth ratios for semi-flexible grid networks and flexible grid networks at the blocking ratio of 1% with different slot assignment patterns (SP1-SP4, Table 6-1). The blocked bandwidth ratio is defined as the ratio of total blocked connection request bandwidth over total connection request bandwidth. Obtain the results where the exclusive spectrum area size for 1 Tbps signal is optimal. The vertical axis of Fig. 6-17 is given by:

$$R_{BW} = (BW_{SF} - BW_F) / BW_F \quad (6\text{-}3)$$

where BW_{SF} and BW_F represent the blocking bandwidth ratios of the proposed semi-flexible grid network and the conventional flexible grid network, respectively. The results confirm that our proposed semi-flexible grid network offers almost the same blocked bandwidth ratios (The gap is less than 4 %) as the conventional flexible grid network.

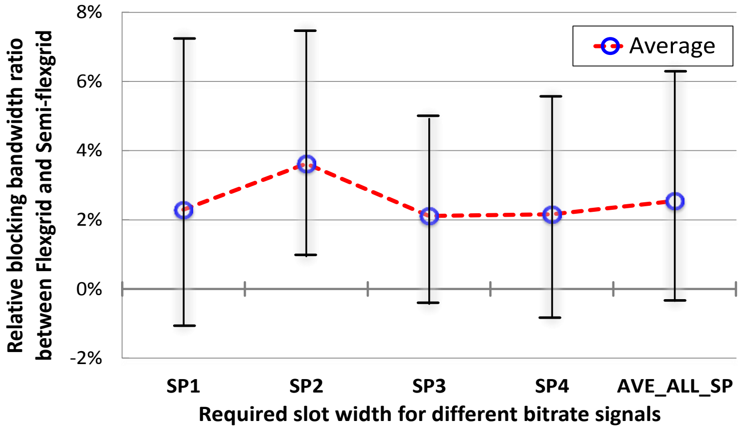


Figure 6-17. Comparison of blocking bandwidth ratio
between flexible and semi-flexible grid networks for different slot requirement patterns.

Figure 6-18 shows how the network topology size (Number of nodes: *N*) affects the relative blocked bandwidth ratios for semi-flexible grid and flexible grid networks for different slot assignment patterns (SP1-SP4, Table 6-1) when the blocking ratio is 1%. The results also demonstrate that our proposed semi-flexible grid network can attain almost the same blocked bandwidth ratios as the flexible grid ones, irrespective of network topology size.

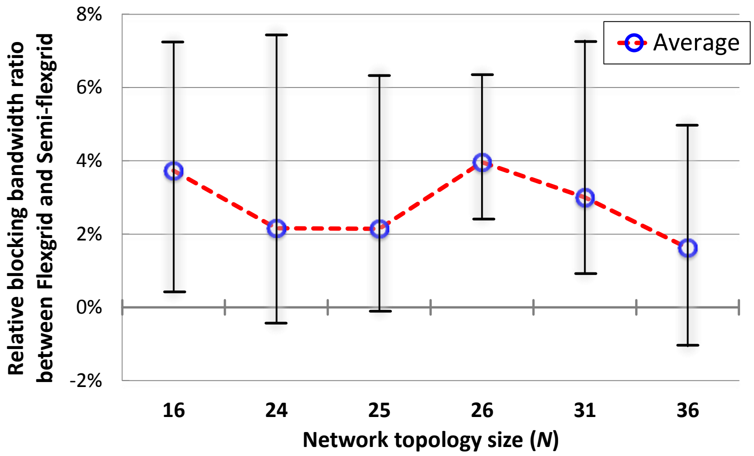


Figure 6-18. Comparison of blocking bandwidth ratio
between flexible and semi-flexible grid networks for different network topology sizes.

The aforementioned results prove that semi-flexible grid networks can basically match the performance of conventional flexible grid networks, which confirms the effectiveness of the proposed semi-flexible grid networks.

6.7 Summary

Spectral efficiency improvement, the major advantage of the flexible grid system has been intensively studied so far. To fully realize this merit, hardware requirements including flexible transponders, can be intense, and may more than offset the efficiency benefit. These requirements will worsen in the more flexible networking environment needed to support optical layer enhanced SDN or switched lambda services; the flexible C/D/C ROADMs necessitate fully tunable filters for coherent detection. To resolve these issues, novel semi-flexible grid networks are proposed, and one of the major objectives in this chapter is to prove the validity of semi-flexible networks over a much wide range of network conditions.

In this chapter, a novel disruption minimized rerouting and spectrum defragmentation mechanism that considers bitrate-dependent blocking ratio mitigation is presented. The proposed algorithm was verified to improve both the spectral efficiency and the blocking ratio equality among different bitrate signals. The results prove that semi-flexible grid networks can match the spectral efficiency of flexible grid networks over various parameter sets, while, as already mentioned in Chapter 6, the semi-flexible grid approach can almost match the hardware complexity of the present fixed grid system. These results suggest that our semi-flexible grid network technologies will be a viable solution in creating cost-effective flexible bandwidth networks.

References

[6-1] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, "Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies," *IEEE Communications Magazine*, vol. 47, no. 11, pp. 66-73, November 2009.

[6-2] O. Gerstel, M. Jinno, A. Lord, and S. J. B. Yoo, "Elastic optical networking: A new dawn for the optical layer?" *IEEE Communications Magazine*, vol. 50, no. 2, pp. 12-20, February 2012.

[6-3] S. Gringeri, B. Basch, V. Shukla, R. Egorov, and T. J. Xia, "Flexible architectures for optical transport nodes and networks," *IEEE Communications Magazine*, vol. 48, no. 7, pp. 40-50, July 2010.

[6-4] "Spectral grids for WDM applications: DWDM frequency grid," ITU-T Recommendations G.694.1, February 2012.

[6-5] A. Patel, P. Ji, J. Jue, and T. Wang, "Defragmentation of transparent flexible optical WDM (FWDM) networks," *OSA Optical Fiber Communication Conference (OFC)*, paper OTuI8, Los Angeles, USA, March 2011.

[6-6] F. Cugini, M. Secondini, N. Sambo, G. Bottari, G. Bruno, P. Iovanna, and P. Castoldi, "Push-Pull technique for defragmentation in flexible optical networks," *OSA Optical*

Fiber Communication Conference (OFC), paper JTh2A. 40, Los Angeles, USA, March 2012.

[6-7] T. Takagi, H. Hasegawa, K. Sato, Y. Sone, A. Hirano, and M. Jinno, "Disruption minimized spectrum defragmentation in elastic optical path networks that adopt distance adaptive modulation," *OSA European Conference and Exhibition on Optical Communication (ECOC)*, paper Mo.2.K.3, Geneva, Switzerland, September 2011.

[6-8] T. Ono, T. Ohara, N. Suzuki, S. Aisawa, and M. Tomizawa, "Novel ODU path switching for ODU reallocation without bit disruption using dynamic delay control scheme," *OSA Optical Fiber Communication Conference (OFC)*, paper JWA.7, Los Angeles, USA, March 2011.

[6-9] R. Wang, and B. Mukherjee, "Spectrum management in heterogeneous bandwidth optical networks," *Elsevier Journal of Optical Switching and Networking (OSN)*, vol. 11, pp. 83-91, January 2014.

[6-10] R. Scaraficci, and N. da Fonseca, "Alternative routing and zone-based spectrum assignment algorithm for flexgrid optical networks," *IEEE International Conference on Communications (ICC)*, paper ONS-02-1, Sydney, Australia, June 2014.

[6-11] P. Wright, M. C. Parker, and A. Lord, "Simulation results of Shannon entropy based flexgrid routing and spectrum assignment on a real network topology," *OSA European Conference and Exhibition on Optical Communication (ECOC)*, paper We.2.E.4, London, UK, September 2013.

[6-12] G. Shen, and Q. Yang, "From coarse grid to mini-grid to gridless: How much can gridless help contentionless?" *OSA Optical Fiber Communication Conference (OFC)*, paper OTuI3, Los Angles, USA, March 2011.

[6-13] T. Zami, "Illustration of the best synergy between grooming of static traffic and elastic spectral efficiency in the WDM networks," *OSA European Conference and Exhibition on Optical Communication (ECOC)*, paper Mo.1.D.3, Amsterdam, Netherlands, September 2012.

[6-14] M. De Leenheer, J. Buysse, C. Develder, and B. Mukherjee, "Isolation and resource efficiency of virtual optical networks," *Proceedings of IEEE International Conference on Computing, Networking and Communications (ICNC)*, pp. 840-844, Maui, USA, January 2012.

[6-15] X. Wang, Q. Zhang, I. Kim, P. Palacharla, and M. Sekiya, "Utilization entropy for assessing resource fragmentation in optical networks," *OSA Optical Fiber Communication Conference (OFC)*, paper OTh1A.2, Los Angeles, USA, March 2012.

Chapter 7
CONCLUSIONS

7.1 Research summary

Optical communication technologies are developing dramatically to cope with the continual increase in traffic growth. In 1990s, a significantly increase in the transmission capacity of optical fibers laid on the links is brought by the WDM technologies. In the currently backbone networks, point-to-point WDM transmission systems and electrical forwarding and routing systems have been widely utilized. Moreover, to resolve the bottlenecks of node throughput and energy consumption, the next generation optical-based node are also developing. In the 2000s, ROADMs, where the optical signals can cut through the electricity-intensive IP-routers as much as possible, are starting to be deployed. However, to support future traffic expansion where video-oriented traffic is dominant, further large-scale optical switches and large capacity optical fiber are required. To improve the limitation of the currently optical path networks, hierarchal optical path networks and elastic optical path networks which can reduce the node cost and link cost respectively are been actively studied.

This thesis presented analysis and results on the study focuses on the improvement of both hierarchical optical path networks and elastic optical path networks, and therefore, the topic is classified into two categories: For the first topic on the hierarchical optical path networks, the main objective is to analyze the cost reduction effectiveness possible with the introduction of wavelength/waveband convertors (the devices which can improve the fiber utilization efficiency) to the hierarchical optical path networks. For the second topic on the elastic optical path networks, the main objective is to propose a new optical path network which can almost match the performance of conventional flexible grid optical path networks (the verification of the performance by an effective network design algorithm is also required), while mitigates the hardware requirements by utilizing the cost-effective fixed grid based systems. The major contributions of this thesis are summarized as follows:

(1) Topic on the hierarchical optical path networks

Several novel optical path network design algorithms for hierarchical optical path networks introducing either or both of wavelength and waveband convertors are proposed. Since the original network design problem is known to be NP-complete, to obtain the sub-optimal solutions in a realistic calculation times, multi-stage ILPs (Integer Linear Programming) or heuristics practical are proposed. By using these algorithms, the cost reduction effectiveness achieved by introducing different types of convertors is verified. Compared with the conventional single-layer optical path networks, at most 40% of cost reduction effectiveness has been achieved while introducing both wavelength and waveband conversions. The allowable cost bound for different convertor use is also evaluated.

(2) Topic on the elastic optical path networks

A novel semi-flexible grid optical path networks are proposed. For the proposal, each specific bitrate signal uses its own dedicated fixed grid and one edges of its frequency slot width is anchored at a specific frequency. Since each bitrate signal is aligned with a fixed grid that is specific to each bitrate, currently cost-effective fixed grid based hardware can be utilized. Moreover, to verify the effectiveness of the proposal networks, a novel disruption minimized rerouting and spectrum defragmentation mechanism that considers bitrate-dependent blocking ratio mitigation is proposed. By using this advanced control mechanism, the effectiveness of the proposed networks is confirmed. Compared with previous methods, the accommodated traffic volume in the networks can be improved by 25%.

The conclusions of each chapter are summarized as follows:

Chapter 1 – Introduction outlined the background of this thesis, including the advancement of photonic network technology, and issues to be addressed for realizing the next generation photonic networks - hierarchical optical path networks and elastic optical path networks more cost-effectively.

Chapter 2 – Hierarchical Optical Path Networks provided the fundamental review of hierarchical optical path networks which aim to reduce the node cost. The technologies enabling the waveband routing, the related node architectures and design problem for hierarchical optical path networks were also summarized.

Chapter 3 – Elastic Optical Path Networks provided the fundamental review of elastic optical path networks which aim to reduce the link cost. The technologies for realizing the flexible frequency grid granularity and the related node architecture, and design problem for elastic optical path networks were also summarized.

Chapter 4 – Hierarchical Optical Path Networks with Wavelength/Waveband Conversion presented novel hierarchical optical path network design algorithms to investigate the impact of either of both waveband/wavelength convertors. The results demonstrated that, by utilizing different types of convertors, hierarchical optical path networks can be cost-effective over a wide traffic demand area, and the wavelength/waveband convertor cost bound that makes the introduction of conversions effective was elucidated. The investigations done in this thesis will provide a useful guideline for the target cost that makes the conversion effective in creating cost-effective photonic networks.

Chapter 5 – Semi-flexible Grid Optical Path Networks proposed a novel semi-flexible grid network which utilizes an anchored frequency slot assignment that is defined selectively for each bitrate signal. Compared with the conventional flexible grid networks, the proposal can significantly mitigating hardware requirements by utilizing the currently cost-effective fixed grid based hardware. The proposed approach yields flexible grid systems with much reduced hardware requirements and will be a viable approach to realizing flexible bandwidth networks cost-effectively.

Chapter 6 – Development of Flexible/Semi-flexible Grid Networks Design Algorithm proposed a novel disruption minimized rerouting and spectrum defragmentation mechanism that considers bitrate-dependent blocking ratio mitigation is presented. The proposed algorithm was verified to improve both the spectral efficiency and the blocking ratio equality among different bitrate signals. The results prove that semi-flexible grid networks can match the spectral efficiency of flexible grid networks over various parameter sets, while, as already mentioned, the semi-flexible grid approach can almost match the hardware complexity of the present fixed grid system. These results suggest that our semi-flexible grid network technologies will be a viable solution in creating cost-effective flexible bandwidth networks.

7.2 Future prospects

The technologies of photonic networks have been rapidly developed in the last four decades. Since the first deployment of optical fiber communication in the 1970s, the fiber capacity of commercial networks has been increased by more than 1000 times, i.e., From 45 Mbps in 1977 (Corning Inc., 10 km) to 100 Gbps in 2009 (Verizon, between Paris and Frankfurt, around 500 km), and most of this improvement is brought by the introduction of WDM technologies. At the same times, Internet traffic is continually increasing, and this trend will be more obvious with the introduction of new video-oriented services including ultra-high definition video, the next generation photonic networks need to cope with this traffic expansion while the CAPEX/OPEX, as well as the power consumption should also be reduced as much as possible. The hierarchical optical path networks and elastic optical path networks are regarded as the potential candidates as the next generation photonic networks since they can significantly improve the network performances, especially in reducing the node cost and link cost respectively.

In this thesis, the potencies and bottlenecks of both hierarchical optical path networks and elastic optical path networks were analyzed, and different improvement strategies were proposed for each network: For the hierarchical optical path networks, to improve the low fiber utilization efficiency, the introduction impact of wavelength/waveband convertors were investigated, and the numerical results proved that by utilizing either or both wavelength/waveband convertors, hierarchical optical path networks can be cost-effective over a wide traffic demand area, and the target wavelength/waveband convertor cost that makes the introduction of conversions effective was elucidated. However, the technologies of wavelength/waveband conversion, in particular in the optical domain, are not mature yet, therefore, the hierarchical optical path networks are expected to create future photonic networks cost-effectively if the cost of related hardware components can be reduced to a reasonable level. On the other hand, for the elastic optical path networks, the proposed semi-flexible grid networks were verified to be effective in achieving a high spectral efficiency (link cost reduction effectiveness) while the hardware requirements (cost) can be significantly reduced compared with the conventional elastic optical path networks.

Apparently, with the development of related device technologies, an elastic optical path network introducing wavebands can be expected to be the best solution is to reduce the node cost and link cost at the same time. This new network architecture can be regarded as a combination of aforementioned hierarchical optical path networks and elastic optical path networks. There are two crucial issues for realizing this novel network architecture cost-effectively. The first issue is the optical path granularity. For the hierarchal optical path networks using wavebands, the minimum granularity is a wavelength (50 GHz/100 GHz), and a waveband is defined as group of several these wavelengths with a same granularity. However, for this new elastic optical waveband network, with the introduction of flexible bandwidth allocation with a much finer granularity (12.5 GHz), each bitrate signal can occupy different bandwidth during the fiber resource allocation; as a result, the waveband size can be varied. Obviously, the selection of wavebands has an enormous impact on the network performance. For this elastic optical waveband network, the design problem to be solved will be a routing, waveband selection, spectrum allocation and waveband assignment, which is certainly much more difficult than the conventional photonic network design problem. Here, efficient heuristic-based algorithm is expected to solve this problem. The second issue is the hardware requirement (cost). Assume this elastic optical waveband network utilize the same transceiver as the aforementioned semi-flexible grid networks, currently fixed grid based transponder can be utilized, however, for the OXC part which is used for switching the waveband signals is still in the development stage even for the conventional fixed grid networks. The same issue also happens to the wavelength/waveband convertors which are deployed to improve the fiber utilization efficiency, to realize them in a reasonable cost is still a challenging task. To address the above issues, the development in both optical path control scenario and photonic network technology is essential. Therefore, it is expected that the advance of the above issues will make a significant contribution to creating the next generation bandwidth abundant photonic networks cost-effectively.

ACKNOWLEDGEMENTS

Completion of this doctoral dissertation was possible with the support of several people over the past five years. Now it is the time to thank each of them.

First and foremost, I would like to express my sincerer gratitude to my supervisor Professor Ken-ichi Sato and Associate Professor Hiroshi Hasegawa for their patience, constant support and invaluable guidance. Without their directions and valuable comments for the last 5 years, this thesis would not have been possible. I am also deeply grateful to Professor Kenji Mase and Professor Masaaki Katayama for their insightful comments on this thesis.

I would also like to thank all my colleagues in Ken-ichi Sato's Laboratory, they have made tremendously support to my personal and professional time at Nagoya University. I am especially grateful for the Assistant Professor Yojiro Mori, Dr. Kiyo Ishii (currently with Network Photonics Research Center, AIST, Japan), Dr. Yoshiyuki Yamada (currently with Cloud System Research Laboratories, NEC Corporation, Japan), Dr. Hai Chau Le (currently with Next Generation Networking System Laboratory, UC Davis, USA) and Mr. Kazuteru Nakano (currently with NTT Network Service Systems Laboratory, NTT Corporation, Japan) for their helps and useful discussions.

Furthermore, I would like to acknowledge Nitori International Scholarship Foundation (founded by Nitori Co., Ltd., Japan), and MEXT (Ministry of Education, Culture, Sports, Science and Technology) of Japan for financial supports during the periods when I was studying in Japan. All my contributions in this thesis are for them and by them.

Last, but definitely not least, I would like to express my deepest gratitude to all my family members, especially to my parents, for their love, encouragement, understanding, and also their sacrifices to me. Thank you.

LIST OF PUBLICATIONS, PATENTS AND AWARDS

A. Journal Papers

[1] Z. Shen, H. Hasegawa, and K. Sato, "**Design of hierarchical optical path networks that utilize wavelength conversion and evaluation of the allowable cost bound,**" *Proc. SPIE-OSA-IEEE Asia Communications and Photonics (ACP)*, vol. 8310, p. 831007, November 2011. (Chapter 4)

[2] Z. Shen, H. Hasegawa, and K. Sato, "**An efficient heuristic waveband assignment algorithm for hierarchical optical path networks utilizing wavelength convertors,**" *Elsevier Journal of Optical Switching and Networking (OSN)*, vol. 10, pp. 54-61, January 2013. (Chapter 4)

[3] Z. Shen, H. Hasegawa, and K. Sato, **"Effectiveness of wavelength/waveband conversion and allowable cost bound evaluation for hierarchical optical path networks,"** *IEEE-OSA Journal of Optical Communications and Networking (JOCN)*, vol. 5, no. 11, pp.1262-1274, November 2013. (Chapter 4)

[4] Z. Shen, H. Hasegawa, K. Sato, and T. Tanaka, and A. Hirano, **"A novel elastic optical path network that utilizes bitrate-specific anchored frequency slot arrangement,"** *OSA Journal of Optics Express*, vol. 22, no. 3, pp. 3169-3179, February 2014. (Chapter 5)

[5] Z. Shen, H. Hasegawa, and K. Sato, **"Integrity enhancement of flexible/semi-flexible grid networks that minimizes disruption in spectrum defragmentation and bitrate-dependent blocking,"** Accepted for publication in *IEEE-OSA Journal of Optical Communications and Networking (JOCN).* (Chapter 6)

B. International conferences

[1] Z. Shen, H. Hasegawa, and K. Sato, **"Design of hierarchical optical path networks that utilize wavelength conversion and evaluation of the allowable cost bound,"** *SPIE-OSA-IEEE Asia Communications and Photonics (ACP)*, paper 8310-06, Shanghai, China, November 2011. (Chapter 4)

[2] Z. Shen, H. Hasegawa, and K. Sato, **"Effectiveness of waveband conversion for hierarchical optical path networks and the allowable cost bound,"** *IEEE Photonics in Switching (PS)*, paper Th-S34-O10, Ajaccio, France, September 2012. (Chapter 4)

[3] Z. Shen, H. Hasegawa, and K. Sato, **"Impact of wavelength/waveband convertors and the cost bound in hierarchical optical path networks,"** *OSA Optical Fiber Communication Conference and Exposition/The National Fiber Optic Engineers Conference (OFC/NFOEC)*, paper Mo.3A.2, Anaheim, USA, March 2013. (Chapter 4)

[4] Z. Shen, H. Hasegawa, K. Sato, T. Tanaka, and A. Hirano, **"A novel semi-flexible grid optical path network that utilizes aligned frequency slot arrangement,"** *IEEE European Conference and Exhibition on Optical Communication (ECOC)*, paper We.2.E.2, London, UK, September 2013. (Chapter 5)

[5] Z. Shen, H. Hasegawa, and K. Sato, **"A novel flexible Grid/semi-flexible grid optical path network design algorithm that reserves exclusive frequency slots for high bitrate signals,"** *IEEE International Conference on Optical Network Design and Modeling (ONDM)*, paper S10_3, Stockholm, Sweden, May 2014. (Chapter 6)

[6] Z. Shen, H. Hasegawa, and K. Sato, **"Disruption minimized spectrum defragmentation and equalization of bitrate dependent blocking in semi-flexible grid networks,"** *IEEE Photonics in Switching (PS)*, paper PW1B.2, San Diego, USA, July 2014. (Chapter 6)

[7] Z. Shen, H. Hasegawa, and K. Sato, **"A novel semi-flexible grid network utilizing aligned frequency slot assignment,"** *International Symposium on VICTORIES Project & workshop*, P4, Tsukuba, Japan, October 2014.

[8] Z. Shen, T. Kusano, H. Hasegawa, and K. Sato, "**A novel routing and frequency slot assignment scheme that can adapt to transmission speed migration,**" *OSA Optical Fiber Communication Conference and Exposition (OFC)*, paper W1I.2, Los Angeles, USA, March 2015.

C. Domestic conferences

[1] 沈 志舒, 長谷川 浩, 佐藤 健一, "波長変換を考慮した多階層光パスネットワークの設計法," 電子情報通信学会総合大会, B-12-12, 東京都世田谷区, 2011 年 3 月.

[2] 沈 志舒, 長谷川 浩, 佐藤 健一, "波長変換を導入した多階層光パスネットワークの設計法と波長変換器コストの許容値評価," 電子情報通信学会ソサエティ大会, B-12-8, 札幌市, 2011 年 9 月.

[3] 沈 志舒, 長谷川 浩, 佐藤 健一, "波長変換・波長群変換器の導入による階層化光パスネットワークのコスト削減効果," 電子情報通信学会フォトニックネットワーク研究会, PN2013-5, pp. 25-30 , 郡山市, 2013 年 6 月.

[4] 沈 志舒, 長谷川 浩, 佐藤 健一, "複数の周波数グリッドを導入したエラスティック光パスネットワークアーキテクチャ," 電子情報通信学会ソサエティ大会, B-12-6,

福岡市, 2013 年 9 月.

[5] 沈 志舒, 長谷川 浩, 佐藤 健一, “ [奨励講演] 階層化光パスネットワークにおける波長変換・波長群変換器の導入効果,”電子情報通信学会フォトニックネットワーク研究会, PN2013-98, pp. 43-48 ,さぬき市, 2014 年 3 月.

[6] 沈 志舒, 長谷川 浩, 佐藤 健一, “エラスティック光パスネットワークにおける高ビットレート信号専用周波数領域を用いた信号割当法,” 電子情報通信学会総合大会, B-12-5, 新潟市, 2014 月 3 月.

[7] 草野 太希, 沈 志舒, 長谷川 浩, 佐藤 健一, “信号帯域幅毎の設定目標周波数を導入した光パス経路・周波数スロット割当法,”電子情報通信学会ソサエティ大会, B-12-11, 徳島市, 2014 年 9 月.

[8] 沈 志舒, 長谷川 浩, 佐藤 健一, “準フレキシブルグリッドネットワークにおけるパス再配置の効果,” 電子情報通信学会ソサエティ大会, B-12-12, 徳島市, 2014 年 9 月.

[9] 草野 太希, 沈 志舒, 長谷川 浩, 佐藤 健一, “将来のシステム更新に適応するエラスティック光パスネットワーク動的制御法,”電子情報通信学会ソサエティ大会発表予定, 草津市, 2015 年 3 月.

D. Patents

[1] 国内特許出願「多重化装置、光パスネットワーク、及び、多重化方法」, 佐藤 健一, 長谷川 浩, 小坂 駿, 沈 志舒, 田中 貴章, 平野 章, 特願 2013-181505 号, 2013 年 9 月.

E. Awards

[1] 文部科学省外国人留学生学習奨励費, 日本国内採用, 2010 年 4 月 1 日~2011 年 3 月 31 日.

[2] ニトリ国際財団奨学金採用, 2011 年 4 月 1 日~2012 年 3 月 31 日.

[3] Best Student Paper Award - Runner-up, *SPIE-OSA-IEEE Asia Communications and Photonics Conference (ACP)*, November 2011.

[4] 文部科学省外国人留学生奨学金 (国費)，日本国内採用，2012 年 4 月 1 日~2015 年 3 月 31 日.

[5] Best Student Paper Prize - Shortlist, *IEEE European Conference and Exhibition on Optical Communication (ECOC)*, September 2013.

[6] フォトニックネットワーク若手研究賞，社団法人電子情報通信学会フォトニックネットワーク研究会，2014 年 3 月.