

Architectures and Design of Multi-Granular Optical Path Networks

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Glossary of Acronyms

3R	Re-amplification, Re-timing, and Re-shaping
AWG	Arrayed Waveguide Grating
BXC	Waveband Cross-connect
DEMUX	Demultiplexer
EDFA	Erbium Doped Fiber Amplifier
EO	Electrical to Optical converter
EXC	Electrical Cross-connect
FXC	Optical Fiber Cross-connect
HOXC	Hierarchical Optical Cross-connect
ILP	Integer Linear Programming
MEMS	Micro-ElectroMechanical System
MUX	Multiplexer
OE	Optical to Electrical converter
OXC	Optical Cross-connect
PLC	Planar Lightwave Circuit
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RWA	Routing and Wavelength Assignment
TDM	Time Division Multiplexing
WBSS	Waveband Selective Switch
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch
WXC	Wavelength Cross-connect

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Chapter 1

Introduction

1.1 Background

Communication traffic in backbone networks has been increasing exponentially due to the rapid growth of the Internet and broadband services such as ADSL, FTTH and mobile wireless access. Moreover, video oriented traffic is expected to be dominant in near future backbone networks [1-1][1-2]. Progress in high-definition and ultra-high-definition TV (more than 33M pixels) is steadily advancing [1-3], and the expected source video bit rate will reach 72 Gb/s per channel. The impact of broadband video is thus significant, and so will be a major factor in designing future networks. The global IP traffic growth forecast from 2010 to 2015 is shown in Figure 1-1 [1-4].

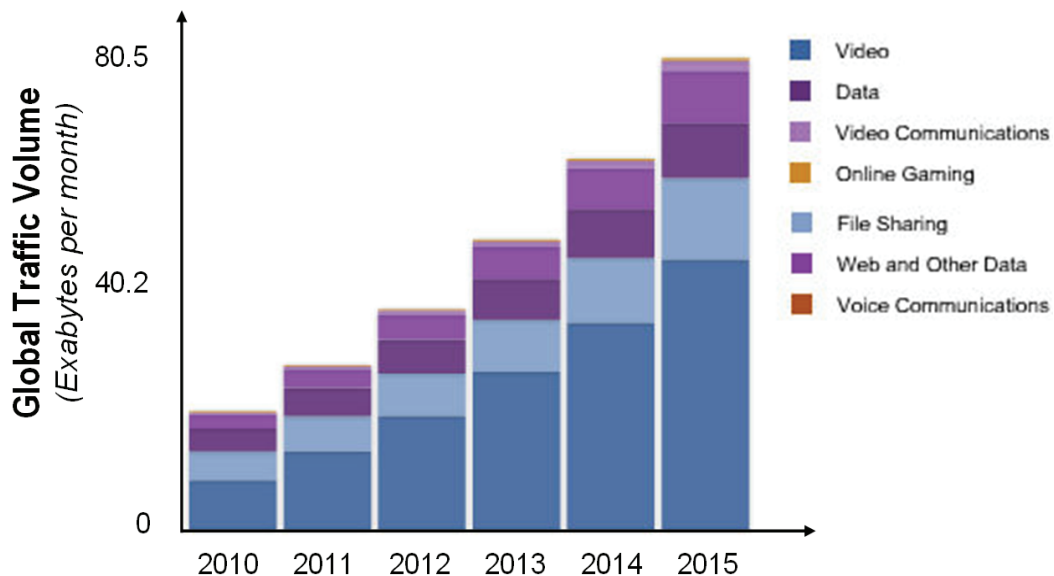


Figure 1-1. Global IP traffic growth forecast [1-4]. The compound annual growth rate of the data traffic is estimated about 32%. Broadband video and file sharing services will be dominated.

According to this forecast, global IP traffic in 2010 stands at 20.2 Exabytes per month and quadruples by 2015, to reach 80.5 Exabytes per month. Consumer IP traffic will reach 70 Exabytes per month and business IP traffic will surpass 10 Exabytes per month. The compound annual growth rate (CAGR) of the data traffic is estimated about 32% of the global fixed networks in which broadband video and file sharing services are currently dominating [1-4].

The power consumption and throughput limitation of IP in electrical routers deploying widely in current backbone networks will be more and more significant [1-5]-[1-8]. The inefficiencies of the present TCP/IP protocol will become more tangible given the advances in video oriented services. These challenges limit the scale of Internet expansion in terms of bandwidth and the number of users [1-9][1-10], and the approach of relying on only IP convergence will not be the best approach in creating future bandwidth abundant networks [1-1][1-2].

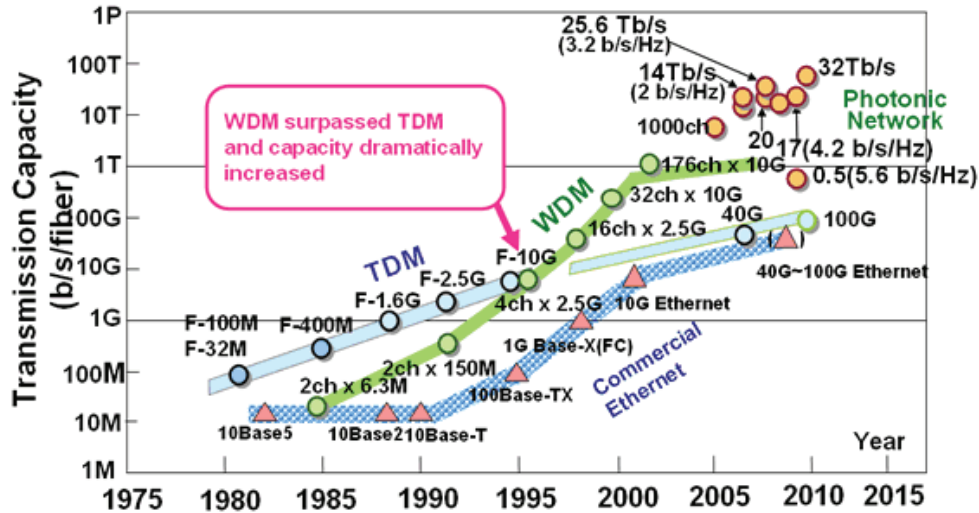


Figure 1-2. Developments in speed and capacity of transport technologies [1-11].

The WDM technology that makes use of the characteristics of optical communications technology surpassed the TDM technology and is now becoming the mainstream to provide ultra-large transmission capacity.

To cope with the future explosion of traffic demand, high-speed and large capacity optical transmission and the optical devices for optical transport networks have been developed. The development in the network transmission capacity is described in Figure 1-2 [1-11]. From 1980 to the beginning of the 1990s, electrical time division multiplexing (TDM) based on on-off keying was the major technology in optical transmission systems. In TDM systems, high-speed optical and electrical devices as well as optical fiber amplifiers were the keys to achieving high-speed long-haul transmission systems. The total transmission capacity reached 10 Gbit/s. In the 1990s, wavelength division multiplexing (WDM) technology, which divides the enormous fiber bandwidth into a large number of wavelengths, led to a rapid progress in transmission capacity owing to the appearance of optical filters providing optical multiplexing and/or demultiplexing functions. The latest 40-Gbit/s \times 40 wavelengths WDM system has been deployed in the core network, and total transmission capacity has reached 1.6 Tbit/s [1-12]. To keep up with the demand for rapid growth of communication traffic, new technologies supporting 10-Tbit/s optical transmission systems based on 100 Gbit/s per channel are investigating. One attractive candidate technology for 100-Gbit/s-based WDM systems is digital

coherent transmission, which combines coherent detection and digital signal processing [1-12].

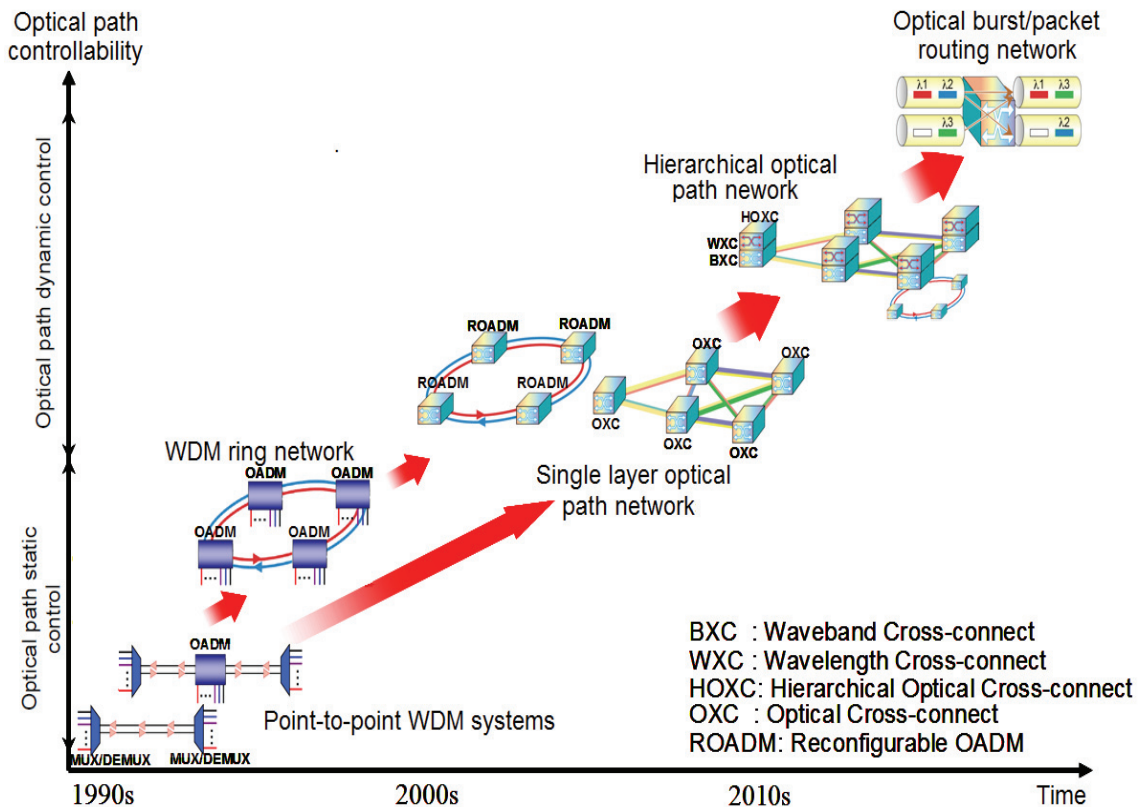


Figure 1-3. Development of photonic network technology

Recent developments in optical transmission and switching technologies have rapidly improved the functionality of optical networks. Optical networks become the key technology for creating cost-effective and bandwidth-abundant future backbone networks [1-2][1-13]. Figure 1-3 illustrates the evolution of optical network technologies based on optical switching technology. Optical network technology, which began as a way to establish a simple connection between two points as a point-to-point WDM transmission system, was accompanied by the development of optical switching technology. Ring based WDM networks employing optical add/drop multiplexers (OADMs) in cooperation with electrical IP routing systems and OEO (optical to electrical and electrical to optical) conversion [1-14][1-15] were introduced to support current broadband traffic demand.

However, because IP routing and OEO conversion will become a serious bottleneck in terms of electrical power consumption and cost for building large bandwidth networks, single layer optical path networks that utilize wavelength path routing made possible with optical cross-connects (OXCs) and reconfigurable OADMs (ROADMs) have been developed [1-1][1-2][1-15] and a large number of ROADM ring networks have been deployed in North

America and Japan. In contrast to the fixed-type OADM, a reconfigurable ones (ROADMs/OXCs), which use optical path switching, support remote path setup, enable operational expenditures related to path provisioning to be reduced, and at the same time can efficiently decrease the provisioning time. These improvements allow optical paths to be provided to customers in a timelier and simpler manner [1-13].

As the WDM transmission technology matures and fiber deployment becomes ubiquitous, the ability to manage optical paths in WDM networks is becoming more and more critical and complicated. In particular, the rapid advances in dense wavelength division multiplexing (DWDM) technology with hundreds of wavelengths per fiber and world-wide fiber deployment have brought about a tremendous increase in the size (i.e., the number of ports) of optical cross-connects, as well as in the cost and difficulty associated with controlling such large cross-connects. Hierarchical optical path networks employing hierarchical optical cross-connects (HOXCs) that are capable of dealing with two different optical path granularities; one is the wavelength path, the other is the waveband path, have attracted attention for their practical importance in reducing the port count, associated control complexity, and cost of optical cross-connects [1-16]-[1-25]. The hierarchical optical path network technology can prevent the expected cost explosion stemming from optical switch scale increase in optical nodes. This work focuses on design and optimization issues of hierarchical optical path networks and a more detailed overview of hierarchical optical path networks will be provided in the next chapter.

In further stage, as the necessary optical technologies that can deal with processing and routing optical bursts/packets become mature, faster dynamic control of optical paths at the level of optical bursts or optical packets will be a next-generation technology. Optical burst/packet switching nodes need optical switches that can respond faster than for optical path routing and require high-level and high-speed optical processing technology.

1.2 Purpose of the thesis

Optical path technologies become critical to creating bandwidth-abundant and power-efficient networks. In future networks, optical paths will be utilized not only within networks but also for the provisioning of optical circuit switching or optical flow switching services. Extension of optical layer technologies and coordination with new transport protocols will be critical; hierarchical optical path technologies and optical circuit/flow switching will play key roles to support the ever-increasing traffic while avoiding the explosion in cost and complexity of optical switches. The large optical cross-connect node throughput and optical path tunneling functions required are both effectively attained with the introduction of higher order optical paths, wavebands. Previous studies have shown that the hierarchical optical path network utilizing hierarchical optical cross-connects, that manage two different optical path granularities: wavelengths and wavebands, can greatly reduce the total network cost (or total port count) and its efficiency strongly depends on the network design solution adopted. Another

critical technical development necessary to implement an efficient hierarchical optical path network is hierarchical optical cross-connect switch design. Hierarchical optical cross-connects require small switching fabric for switching higher-order optical paths (i.e. wavebands), while that required for switching lower-order optical paths (wavelength paths) is still relatively large. Such large optical switches are costly or not yet available in current technologies. Therefore, in order to minimize the HOXC switch size and make HOXCs efficiently realizable with current mature technologies, following challenges need to be resolved:

(1) Combination of network cost minimization and node size optimization.

(2) Development of new hierarchical optical cross-connect architecture that can be implemented by current mature technologies and associated network design solutions that are capable of effectively exploiting the advantages of hierarchical optical path networks.

This thesis aims to resolve the above challenges, and to evaluate efficiency of hierarchical optical path networks under different network conditions and clarify the impacts of network parameters in hierarchical optical path networks. The main objectives are;

(1) Development of effective network design solutions that are capable of incorporating the node size optimization into network cost minimization.

(2) Proposals of cost-effective hierarchical optical cross-connect architectures which can overcome current technical challenges to be efficiently realized by utilizing present technologies, and corresponding network design solutions for the hierarchical optical path network employing the proposed HOXCs under various network conditions.

1.3 Organization of the thesis

This thesis presents the research results of our work with the proposals and the developments of the effective network design solutions and node architecture for realizing future hierarchical optical path networks. The thesis includes 6 chapters. Firstly, the first chapter provides an introduction to our thesis contents. Research background and literature review are then described in Chapter 2. Chapter 3 is to deal with network design solutions that are capable of incorporating the node size minimization into the network cost optimization. Chapter 4 and 5 are for introducing proposals of a new node architecture and appropriate network design algorithms to build a cost-effective, large-capacity and low-power-consumption network. In order to develop a new hierarchical optical cross-connect architecture that can be realized with current mature technologies, a hybrid-HOXC architecture has been proposed in Chapter 4. Moreover, this chapter also includes effective developed network design algorithms for hybrid hierarchical optical path networks employing the proposed hybrid-HOXC. On the other hand, Chapter 5 is to tackle the design problem of large-scale translucent hierarchical optical path networks while making full use of the advantages of the proposed hybrid-HOXC. Finally, the last chapter summarizes the work and its contributions.

Main contents of chapters in the thesis are organized as follows:

Chapter 1 - Introduction gives an introduction of the thesis.

Chapter 2 - Hierarchical optical path networks presents an overview of hierarchical optical path networks and summarizes conventional related works. Firstly, the main concepts of waveband paths and hierarchical optical cross-connects are described. It then explains how waveband routing in hierarchical optical path networks differs from wavelength routing in conventional single layer optical path networks. Major advantage of introducing waveband paths and HOXCs to reduce network cost and total switch size is introduced. Furthermore, the theoretical analysis of the port count reduction attained by hierarchical optical path networks is then presented. Finally, some conventional studies that have precisely evaluated and clarified the effectiveness of hierarchical optical path networks and other studies on the developed HOXCs for waveband path routing are summarized.

Chapter 3 - Hierarchical optical path network design with waveband add/drop capability constraint is to develop effective network design solutions that consider the node size optimization. Chapter 3 firstly clarifies the effect of waveband add/drop ratios, the ratio of number of added/dropped waveband paths to that of outgoing/incoming waveband paths, on switch size reduction of HOXC nodes, and then proposes two new network design algorithms which incorporate a restrictions on waveband add/drop capability according to different capability of adding/dropping waveband paths in specific HOXC architectures. Their effectiveness is evaluated by conducting extensive numerical experiments. The effects of the network parameters, which include network size, link distance and network topology, on total network cost are also elucidated. On the other hand, impact of selecting waveband capacity to minimize total cost of hierarchical optical path networks is evaluated. It is shown that the developed algorithms will play a key role in maximizing node-scale reduction and realizing the resultant network cost reductions when the waveband switching is to be fully utilized.

Chapter 4 - Design of hybrid-hierarchical optical path networks is for proposing a cost-effective hierarchical optical cross-connect architecture, which can overcome technical challenges to be efficiently realized by utilizing present technologies, and effective network design solutions for the corresponding hierarchical optical path network. In Chapter 4, a hybrid-hierarchical optical cross-connect that employs a waveband cross-connect for routing waveband paths and an electrical cross-connect for grooming wavelength paths in order to make HOXCs possible with current technologies has been firstly proposed. After that, network design algorithms for the corresponding hierarchical optical path networks utilizing the proposed hybrid-hierarchical optical cross-connects are developed. At first, an integer linear programming model to solve the network design problem is introduced. Then a 2-stage ILP optimization based design algorithm for medium size networks and a heuristic algorithm employing the neighbor source and destination grouping method for large networks are proposed. Performances of the proposed algorithms and hybrid-hierarchical optical path network efficiency are evaluated through numerical experiments. Finally, impact of the critical network parameters on total network cost is investigated.

Chapter 5 - Impact of electrical grooming and regeneration of wavelength paths in

creating hierarchical optical path networks assesses the impact of utilizing electrical cross-connects in the proposed hybrid-hierarchical optical cross-connect architecture of Chapter 4 for intermediate grooming and 3R regeneration of wavelength paths in the hybrid hierarchical optical path networks. A heuristic network design algorithm that considers the optical transparent reach limit is developed. Its effectiveness is verified by simulation results. Moreover, dependencies of the network cost with an optical transparent reach restriction on important network parameters including electrical switch port cost, and waveband capacity are also studied. It is demonstrated that selecting the waveband capacity properly plays an important role in minimizing the total network cost.

Chapter 6 – Conclusions summarizes the work presented in the thesis and its future prospects.

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Chapter 2

Hierarchical optical path networks

This chapter presents a comprehensive review of hierarchical optical path networks utilizing waveband switching that are a key technology to create future bandwidth abundant networks. Firstly, waveband switching technique and associated hierarchical optical cross-connect node architectures are briefly introduced. Major benefits of using HOXCs in hierarchical optical path networks are also explained. And then, differences between waveband switching in hierarchical optical path networks and wavelength routing in conventional single layer optical path networks are clarified. Finally, significant conventional studies on the design problem of hierarchical optical path networks are summarized.

2.1 Introduction

The transport network paradigm is moving toward next-generation networks that aim at IP convergence and technologies/architectures divergence. To meet the traffic increase driven by world-wide deployment of broadband access including xDSLs and FTTx, routing functions in the optical domain with optical paths were first put into commercial use by utilizing reconfigurable optical add/drop multiplexers (ROADMs) in optical ring networks [2-1][2-2]. Recently, GMPLS-controlled optical cross-connects (OXC), that can greatly enhance network throughput and reduces energy consumption, have been used for creating nation-wide testbed networks [2-3][2-4] and will be deployed soon to interconnect multiple ROADM rings or to create mesh-based single layer optical path networks. One of the salient features of optical paths, optical circuit switching, is that switch complexity does not depend on the bit rate carried by the optical paths. With electrical technologies, switching becomes more difficult and consumes more electrical power as the bit rate increases. Thus, the wide deployment of optical path technologies will be driven by the traffic increase and the limits created by power consumption and throughput, both of which are inherent in electrical switching.

New video technologies such as IP-TV and High/Ultra-High Definition TV are steadily advancing, and they are expected to be dominant in future transport networks [2-2]. The envisaged traffic growth will cause a significant increase in the number of wavelength paths, which requires large scale OXCs if optical paths are only switched at the wavelength path level. One important and promising approach to cope with these difficulties is the introduction of higher-order optical paths, the waveband paths (groups of multiple wavelengths), and corresponding hierarchical OXCs (HOXCs) that are capable of switching both waveband and wavelength paths [2-1][2-2][2-5]-[2-21]. Coarse granular routing provided by introducing

waveband paths is maximally utilized and fine granular routing at wavelength path level is only applied if necessary. The introduction of coarse granular routing could reduce the optical port count and is also effective in providing optical circuit or flow switching. Hierarchical optical path network and node technologies and network architectures that fully harness the power of optical transmissions to enhance network throughput and reduce energy consumption are of great importance.

In this chapter, we first briefly introduce about waveband switching technique and hierarchical optical cross-connect node architectures, and summarize the major benefits of using HOXCs in hierarchical optical path networks. We then explain how waveband switching in hierarchical optical path networks differs from wavelength routing in conventional single layer optical path networks. Finally, we reviewed conventional studies on the design problem of hierarchical optical path networks.

2.2 Waveband switching

The main concept of waveband switching is to group several wavelengths together as a group of multiple wavelength paths (i.e. waveband path) and route the waveband path using a single port whenever possible. Waveband switching networks deal with two different optical path granularities; one is the wavelength path, the other is the waveband path as shown in Figure 2-1. The waveband path is a group of multiple wavelength paths which are routed together as one entity. In waveband switching networks, switching of wavelength paths is performed only at two end nodes or nodes which require waveband grooming function. Along the waveband paths, waveband switching nodes route only waveband paths instead of each individual wavelength path as in traditional wavelength routed networks, as a result, some or most of the wavelength paths do not have to pass through individual wavelength filters and the design of multiplexers and demultiplexers is simplified as well. Hence, waveband switching can bring about tremendous benefits in terms of reducing the size (i.e., the necessary number of ports) of optical cross-connects as well as the cost and difficulty associated with controlling them. In addition to reducing the port count, the use of waveband paths reduces the number of entities that have to be managed in the system, and enables hierarchical and independent management of the information relevant to waveband and wavelength paths. This translates into reduced system footprint, power consumption and simplified network management.

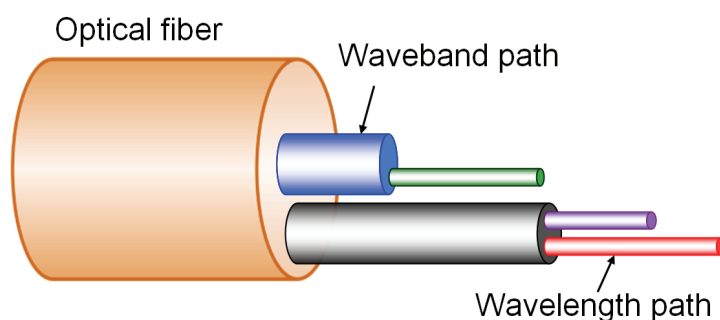


Figure 2-1. Optical path granularities: waveband paths and wavelength paths

Assume that a fiber can carry up to B waveband paths and each waveband path accommodates W wavelength paths. Figure 2-2 gives a waveband-configuration classification of waveband switching schemes based on whether the number of wavebands per fiber (B), the number of wavelengths per waveband (W), and the set of wavelengths (λ s) are fixed or not. Firstly, waveband switching schemes are classified into two variations depending on whether the number of wavebands in a fiber, B , is fixed or variable. Each variation is then further classified according to whether the number of wavelengths in a waveband, W , is fixed or variable. For a given fixed value of the set of wavelengths in waveband can be further classified depending on whether they are pre-determined (e.g., consists of consecutively numbered subset of wavelengths) or can be adaptive (dynamically configured). For example, one variation, could be to allow a variable number of wavelengths in a waveband at different nodes, with these wavelengths being selected randomly (not necessarily consecutively). Such a variation may result in more flexibility (efficiency) in using waveband switching node architecture than the variation shown shaded, on the other hand, the waveband switching node architecture (especially its part to deal with routing waveband paths) required to implement this variation may be too complex to be feasible with the current and near-future technology.

Moreover, with the fixed B , W and predefined wavelength set, however, variations exist based on whether the number of wavelengths per band is the same or uniform for all the wavebands or not. In specific, waveband granularity refers to the number of wavelengths that are aggregated into a waveband. When the waveband granularity is the same for all the wavebands, the corresponding waveband switching scheme is known as the uniform waveband switching. In contrast, if the granularity for the different waveband can vary, the resulted WBS scheme is referred to as non-uniform waveband switching. It is worth noting that the non-uniform waveband switching requires the hardware support from hierarchical optical cross-connects as well as appropriate waveband filters and MUXs/DEMUXs.

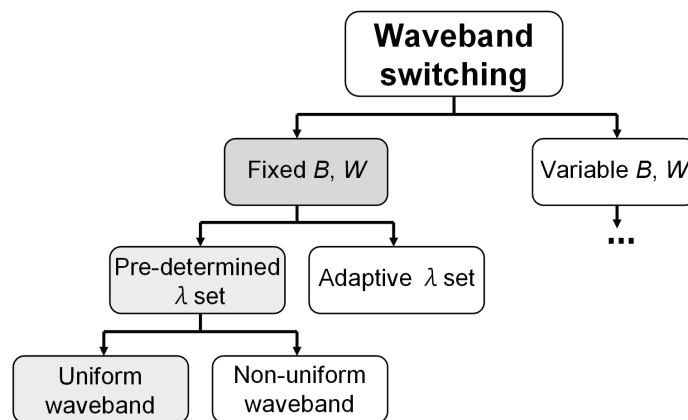


Figure 2-2. Classification of the waveband switching schemes

In our work, we only concentrate on the variation shown shaded in Figure 2-2, where each fiber has a fixed number of bands and each band has a fixed number as well as a fixed set of wavelengths, though the principles to be discussed can be extended to other waveband switching variations as well.

2.3 Hierarchical optical path networks

2.3.1 Hierarchical optical cross-connects

Hierarchical optical path networks which are WDM optical path networks utilizing waveband switching have been intensively investigated as an important technology that will prevent the expected network cost explosion stemming from optical switch scale increase in optical routing nodes [2-1]-[2-2]. The node system which is capable of switching different optical path granularities including wavelength paths and waveband paths is a key element for routing high speed data traffic in hierarchical optical path networks, is called hierarchical optical cross-connect (HOXC) or multi-granular optical cross-connect (MG-OXC). Generally, hierarchical optical cross-connects consist of 2 major functional parts: waveband cross-connect (BXC) and wavelength cross-connect (WXC). The waveband cross-connect part is to route waveband paths and the wavelength cross-connect part is for adding/dropping or grooming wavelength paths. Besides the cross-connects for waveband/wavelength paths, hierarchical optical cross-connects may also include fiber cross-connect (FXC) part which deals with switching whole fibers from inputs to outputs. Several architectures of hierarchical optical cross-connects have been proposed and extensively studied [2-5]-[2-12]. Proposed HOXCs can be classified into 2 main categories according to structure: single-layer HOXCs or multi-layer HOXCs.

A. Single-layer HOXCs

Studies in [2-9]-[2-12] proposed several architectures of single-layer hierarchical optical cross-connects in which wavelength cross-connect and waveband cross-connect are parallel to each other. Figure 2-3 shows a typical single-layer HOXC architecture which includes all three logical parts corresponding to FXC, BXC and WXC respectively. The single-layer HOXC architecture also requires multiplexers/demultiplexers of wavebands and fibers. The waveband demultiplexers are used to demultiplex wavebands into wavelengths, while the waveband multiplexers are employed to multiplex wavelengths into wavebands. The fiber demultiplexers and fiber multiplexers are used to demultiplex input fibers to wavebands, and multiplex wavebands to output fibers respectively. In the single-layer hierarchical optical cross-connects, optical paths (wavelength and waveband paths) are passed across only one of cross-connects (WXC, BXC or FXC). Some incoming fibers are pre-configured as designated fibers. Only the designated fibers may carry some wavebands which are requested to be dropped while all other

non-designated incoming fibers can only bypass entirely or drop all their wavebands. Similarly, within the designated fibers, only designated wavebands can have some of the wavelengths dropped while the remaining other wavebands pass through the node.

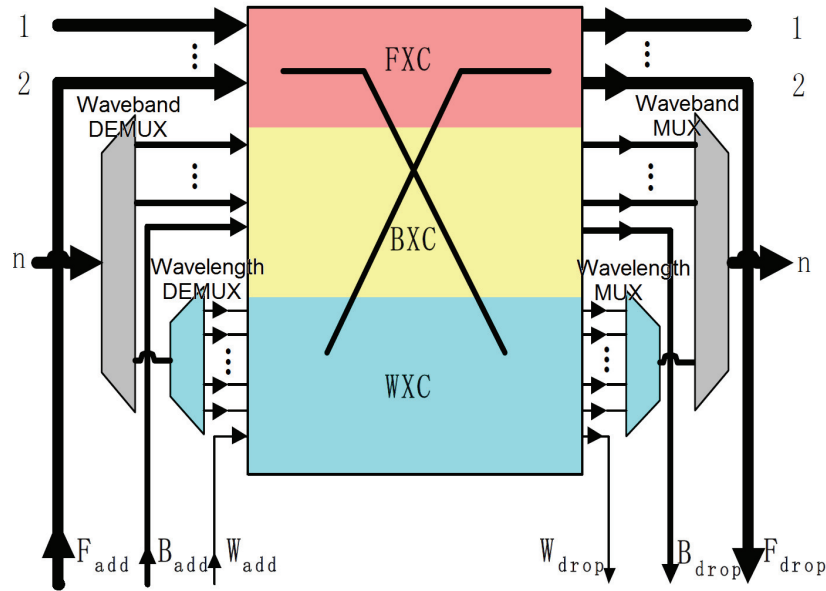


Figure 2-3. Single-layer HOXC architecture

B. Multi-layer HOXCs

Figure 2-4 describes a general architecture of three-layer hierarchical optical cross-connects [2-8][2-10][2-11]. It consists of three switching layers for wavelength, waveband and fiber switching. The WXC, BXC layers consist of a cross-connection and waveband/fiber multiplexers/demultiplexers. Wavelength cross-connection of the wavelength switching layer is employed to bypass/add/drop wavelength paths. At the BXC layer, waveband cross-connection is implemented to route waveband paths. Similarly, at the fiber cross-connections (FXC) layer fiber cross-connections are used to switch fibers entirely. Multi-layer HOXCs permit selecting dynamically fibers for multiplexing/demultiplexing from FXC layer to the BXC layer, and wavebands for multiplexing/demultiplexing from BXC to the WXC layer. For example, at the FXC layer, as long as there is a free waveband demultiplexer, any fiber can be demultiplexed into wavebands. Similarly, at the BXC layer any waveband can be demultiplexed to wavelengths using a free waveband demultiplexer by appropriately configuring the FXC, BXC cross-connections and associated demultiplexers. In order to reduce the number of necessary switching ports, the multi-layer HOXC switches a fiber using one port (space switching) at the FXC cross-connection if none of its wavelengths/wavebands is required to be added or dropped. Otherwise, it will demultiplex the fiber into wavebands, and switch an entire waveband using one port at the BXC cross-connection if none of its wavelengths needs to be added or dropped.

other words, only the wavebands whose wavelengths need to be added or dropped will be demultiplexed, and only the wavelengths in those wavebands that carry bypass traffic requested to be switched using the WXC. This is in contrast to the conventional OXCs that switch every wavelength individually using one port.

Although the single-layer hierarchical cross-connect architecture can route waveband paths and wavelength paths in parallel, and consequently have simpler and more compact designs, which may result in better signal quality, the single-layer HOXCs are not as flexible as the multi-layer HOXCs since only the designated fibers and designated bands have the capability of multiplexing/demultiplexing. One of the advantages of the multi-layer HOXC architectures is their capability for dynamic selection of fibers (or wavebands) for multiplexing/demultiplexing from the FXC (or BXC) layer to the BXC (or WXC) layer. However, in the 3-layer hierarchical optical cross-connects, because optical paths have to travel through all 3 cross-connect layer and grooming optical paths must pass BXC and FXC twice, the switched optical paths are affected by high loss and delay. On the other hand, crossing a whole fiber at FXC is rarely required due to ultra-high capacity of DWDM transmission system, as a result almost all input fibers must be demultiplexed into wavebands and routed to the BXC. Hence, 2-layer hierarchical optical cross-connects [2-5][2-7][2-13]-[2-16] that are desirable in terms of cost, loss and flexibility are intensively investigated.

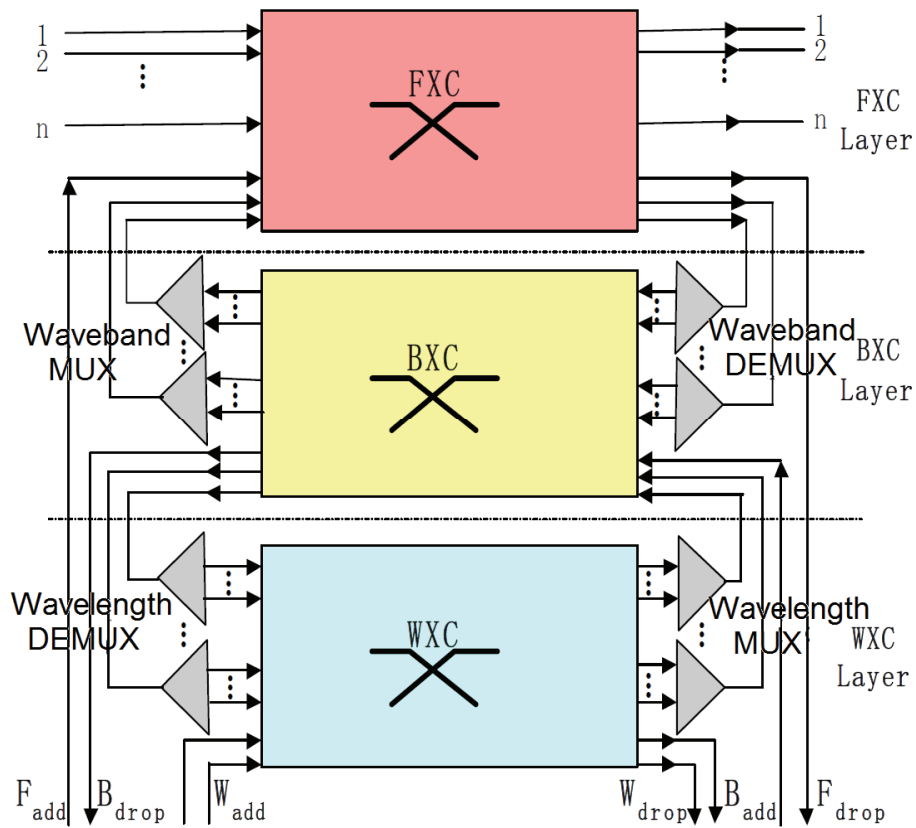


Figure 2-4. Three-layer HOXC architecture

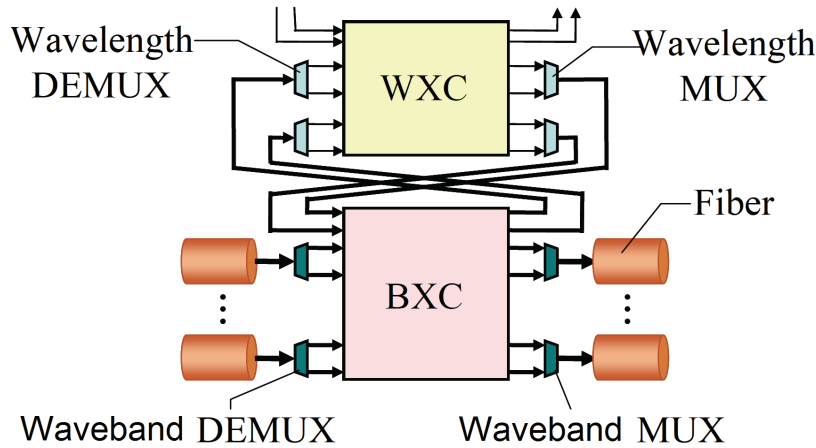


Figure 2-5. Two-layer HOXC architecture

The 2-layer hierarchical optical cross-connect consists of 2 parts; a waveband cross-connect (BXC) part and a wavelength cross-connect (WXC) part as shown in Figure 2-5. The former consists of a BXC switch and waveband multiplexers/demultiplexers for routing higher-order waveband paths, and the latter includes a WXC switch and wavelength multiplexers/demultiplexers to route lower-order wavelength paths. The HOXC architecture adds and drops optical paths at wavelength level only. All incoming fibers are demultiplexed into wavebands and switched at waveband level by the BXC. Only wavebands that are to be groomed or dropped are routed to the WXC. These wavebands are then demultiplexed into wavelengths and switched at the WXC. In the HOXC node, optical paths are mainly switched in the BXC layer with waveband granularity. When wavelength path level routing (which is called “grooming”) or termination is necessary for some wavelength paths in waveband paths, the waveband paths are sent to the WXC layer where they are groomed or terminated at the wavelength path granularity. Hereafter, we focus on the 2-layer hierarchical optical cross-connect architecture only in our work since it simplifies network OAM (Operation Administration and Maintenance) [2-1][2-2][2-17].

Similar to that for implementing conventional ROADMs/OXCs, two different optical switching systems are utilized to construct an HOXC node; matrix switch based and wavelength selective switch/waveband selective switch (WSS/WBSS) based architectures (WBSSs; analogous to WSS for switching with waveband granularity) [2-13]-[2-16]. Matrix switch based architectures consist of simple components that can be realized with integrated optical waveguide technologies such as planar lightwave circuit (PLC) technologies such as optical filters and optical switches each of which is dedicated to each function. Moreover, matrix switch based architectures include a number of components and thus, interconnections among the components are rather complicated. In contrast with the matrix switch based architectures, the interconnections in WSS/WBSS based HOXC architectures are much simpler since they require much less components. In addition, WSS/WBSS based HOXC architectures have the advantage

of modular growth capability, that is, the number of input/output fiber ports is incrementally increased as traffic demand increases, similar to that in the WSS based single-layer OXC node architecture.

2.3.2 Routing and assignment of optical paths in hierarchical optical path networks

Although routing of wavelength paths is still fundamental to waveband switching networks, waveband switching much differs from conventional wavelength routing. The objective and techniques used for hierarchical optical path networks utilizing waveband switching are different from that for single layer optical path networks. Single layer optical path networks employing ordinary-ROADMs/OXCs deal with the routing and wavelength assignment (RWA) problem that is to find a suitable route for each requested optical path and assign a wavelength to it. One of the main objectives of the traditional RWA algorithms in single layer optical path networks is to minimize the total number of wavelength-hops or the maximum number of wavelengths required to satisfy a given set of optical path requests, which is known to be NP-complete [2-1][2-2][2-17]. However, hierarchical optical path networks handle two different optical path granularities including wavelength and waveband paths, and as a result, routing and assignment of not only wavelength paths but also waveband paths must be taken into account. In addition, general objective for hierarchical optical path networks is to minimize the network cost, i.e. number of ports required by the HOXCs. Therefore, techniques developed for the RWA in single layer optical path networks (including for example, those for traffic grooming) cannot be directly applied to hierarchical optical path networks. New routing and assignment of wavelength/waveband paths need to be developed in order to effectively achieve the objective.

In RWA of wavelength and waveband paths of hierarchical optical path networks, selection of source and destination nodes of waveband paths plays an important role because the placement of waveband paths heavily impacts not only the efficiency of wavelength path routing but also the number of required switch ports [2-19]. Depending on the way to decide the nodes to group wavelengths into wavebands and disaggregate the waveband into wavelengths, the selection strategies can be classified into several categories as shown in Figure 2-6.

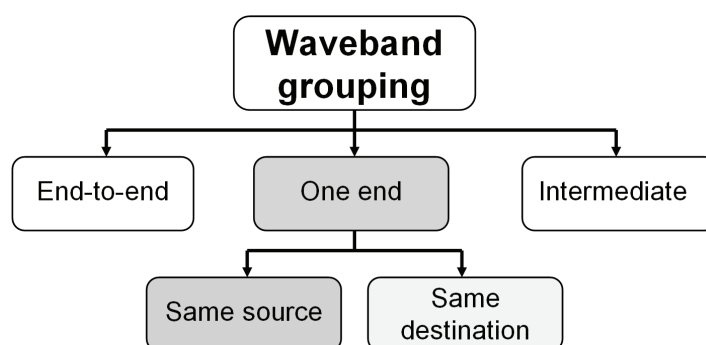


Figure 2-6. Waveband grouping strategies

The end-to-end grouping is the most straightforward form of waveband paths where the wavelength paths between the same source and destination nodes are grouped as waveband(s). Other waveband grouping strategies can be referred to as intermediate grouping since the aggregation or disaggregation can happen at the intermediate nodes. In specific, the same-source (destination) grouping policy groups the wavelength paths with the same source (destination) node (but various destination (source) nodes) into waveband(s). The most flexible grouping strategy is known as the intermediate grooming, in which optical paths with common subpath (from any source to any destination) are grouped. The aggregation and disaggregation of wavelength paths are allowed to happen at selected intermediate nodes along the subpath. Obviously, this strategy is the most powerful and efficient (in terms of being able to maximize the benefits of waveband switching) although it is also the most complex to be implemented in waveband switching routing algorithms.

2.3.3 Efficiency of hierarchical optical path networks

The hierarchical optical path networks utilizing hierarchical optical cross-connect have been intensively investigated as an important technology that will prevent the expected network cost explosion stemming from optical switch scale increase in optical routing nodes [2-1][2-2]. In a single-layer optical path network, each optical cross-connect switch port is allocated on a wavelength path basis along the paths which optical paths are routed. On the other hand, in a hierarchical optical path network, multiple wavelength paths are routed as a whole and one waveband cross-connect port of each intermediate node is used. Coarse granular routing at waveband level made possible by waveband cross-connects is maximally utilized and very fine granular routing, wavelength switching, is performed only at originating/terminating nodes if necessary. Therefore, the number of necessary switch ports in a network can be substantially decreased. Figure 2-7 schematically shows the difference of optical path switching in single-layer and hierarchical optical path networks, where only one fiber between nodes is illustrated for simplicity.

Suppose that H is the average number of hops in the networks. The port count ratio, R , between the hierarchical and single-layer optical path network is evaluated in [2-19] as following,

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

where parameter α is the waveband utilization ratio that represents the inefficiency of wavelength accommodation into wavebands in the hierarchical optical path network.

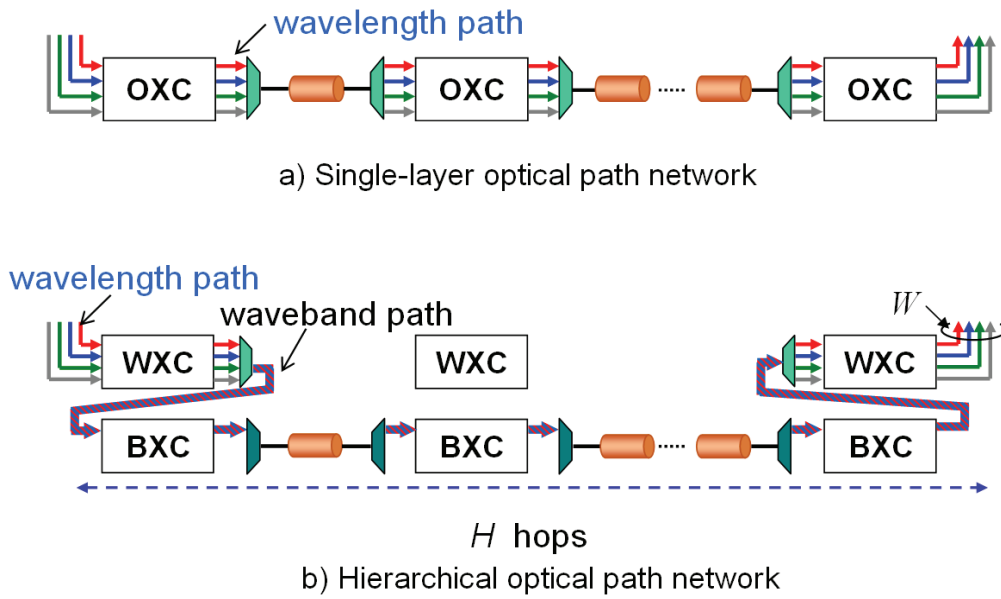


Figure 2-7. Wavelength routing vs. waveband switching.

- a) Wavelength routing in single layer optical path networks;
- b) Waveband switching that is capable of switching several wavelengths in a waveband as one entity at BXC's in hierarchical optical path networks.

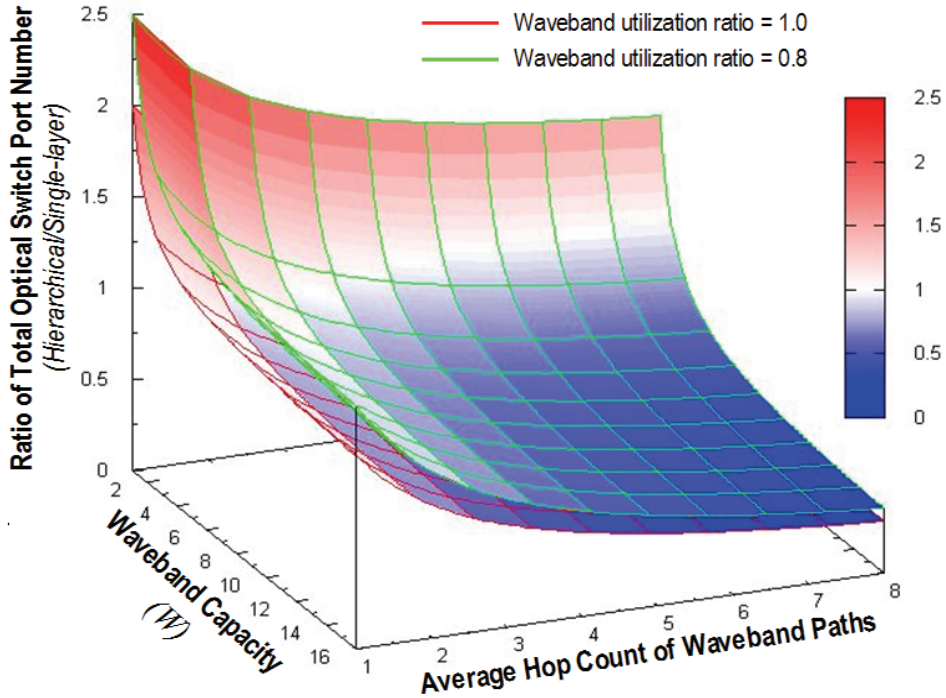


Figure 2-8. Relative port count ratio

Figure 2-8 shows the relation among the port count reduction that is attained by introducing

wavebands, waveband capacity (W) and average hop count (H) for a hierarchical optical path network with different values of α [2-19]. The two horizontal axes are the number of wavelength paths per waveband, W , and the average number of hops in the network, H . The vertical axis is the ratio, R , of total cross-connect switch ports required in hierarchical to those of single-layer optical path network. In Figure 2-8, the blue area means $R < 1$ and indicates the area wherein the hierarchical optical path network can reduce the necessary switch ports compared with the single-layer optical path network. The figure shows that introduction of waveband path routing is effective over a wide parameter range of H and W . For example, when H is 4 and W is 8, R is about 0.5. If the traffic volume is not enough, efficient intermediate grooming strategies are necessary. The effectiveness of introducing wavebands has been proven more precisely by applying efficient hierarchical optical path network design algorithms [2-17][2-19] which are reviewed later.

2.4 Design of hierarchical optical path networks

Effectiveness of hierarchical optical path networks utilizing hierarchical optical cross-connects strongly depends on the network design algorithm applied, especially when each traffic demand is not enough to fill the waveband capacity. Effective design algorithms for hierarchical optical path networks are much more difficult to develop than those for single layer optical path networks. The design objective aims at minimizing cost functions under waveband and wavelength continuity constraints. Even for single-layer optical path networks, the routing and wavelength assignment problem is known to be NP-complete [2-19]. Hierarchical optical path network design becomes much harder problem due to routing and waveband assignment for waveband paths and accommodating wavelength/waveband paths within wavebands/fibers, where they must be optimized simultaneously. Therefore, it is computationally impossible to obtain the optimal solution for practical network scales.

Various network design algorithms for hierarchical optical path networks have recently been developed considering different requirements [2-8]-[2-10][2-12] [2-19]-[2-26] and have verified the significant network cost reduction compared with single-layer optical path networks. They fall into two main categories: ILP based approaches and heuristic approaches. Integer Linear Programming (ILP) formulations are widely used in single layer optical path networks to solve the routing and wavelength assignment problem, and several ILP formulations are introduced for hierarchical optical path networks in the studies of [2-8][2-9]. The incorporated constraints in ILP models of hierarchical optical path networks are more than that of single layer optical path networks. Besides necessary constraints for wavelength paths, they include constraints for waveband paths and incorporate additional constraints for grouping wavelength paths and demultiplexing/multiplexing. The ILP models generally should be aware of the waveband grouping strategy, the specific HOXC architecture and the waveband configurations. Authors in [2-8] formulated an ILP model based on intermediate grouping policy for three layer HOXCs based networks. While for the ILP model presented in [2-9], the waveband grouping was restricted between the optical paths with the same destination for hierarchical optical path

networks utilizing two layer HOXCs. Study in [2-10] also introduced different ILP models corresponding to the three-layer and single-layer HOXC architectures.

Although ILP formulations can provide the optimal solutions for the RWA problem, it can be applicable only to very small networks and its performance becomes intractable when the size of the problem becomes larger due to the extremely high computational complexity. Hence, for designing large hierarchical optical path networks, heuristic algorithms are proposed to provide more practical solutions. Several heuristic or relaxation based algorithms were proposed [2-8]-[2-10][2-19]-[2-26]: they fall into three main categories. The first category covers relaxation-based methods [2-9][2-20]. To reduce the computational complexity induced by ILP formulations, the original design problem is approximated by using a combination of three sub-problems [2-9], or employing the Lagrangean relaxation [2-20]. These approaches are useful mainly for small networks where the sub-optimal solutions can be derived with a slight degree of relaxation, however, huge computational loads are generally incurred for large scale networks since the task is still a numerically hard problem.

The second category constructs wavelength paths first and then waveband paths are established [2-8][2-21]-[2-24]. In [2-8][2-21][2-22], wavelength paths having partially shared routes are groomed. The method in [2-23] accommodates wavelength paths within existing waveband paths. On the other hand, in [2-24], the authors proposed two greedy heuristics; one based on wavelength-path-first assignment and the other on waveband path-first assignment, and showed that the former outperforms the latter. This method is simple because it is almost equivalent to a well-accepted design method for single-layer optical path networks. However, further aggressive grooming is necessary to improve the waveband utilization ratio, especially when traffic demand is not large.

In the last category, heuristic network design algorithms set up waveband paths first and then wavelength paths are accommodated into existing waveband paths [2-9][2-25][2-26]. In [2-9][2-25], the traffic flowing into each node is defined as “potential” and employed as a criterion for setting up waveband paths. In [2-26], each waveband path is established so as to reduce the sum of hops between endpoints of the waveband path and wavelength paths. Further optimization of the placement of waveband paths can be done by setting an explicit relation between each waveband path and the wavelength paths to be accommodated. Authors in [2-19] proposed a very efficient network design algorithm that uses the cluster-search method in a source–destination Cartesian product space. The Cartesian space can be applied to effectively locate waveband paths that can reduce total cost. For each set of wavelength paths, a waveband path is first constructed so as to maximize the degree of cost reduction. The wavelength paths that are not accommodated in the first step are finally accommodated in wavebands by identifying the shortest paths in a multilayered graph considering waveband tunnels [2-19].

Because of the inherent difficulty of the design problem, instead of pursuing direct mathematical cost optimization, heuristic approaches that iteratively establish wavelength/waveband paths as those in the second and the third categories are practical to design large scale hierarchical optical path networks. Moreover, despite the fact that waveband

switching schemes are node-architecture-dependent and network-architecture -dependent, existing network design works have mainly focused on the cost minimization (or total port count). In order to make the HOXC nodes possible with current technologies, design algorithms that incorporate the node optimization in the network design problem are critical.

2.5 Summary

In this chapter, a review of waveband switching, node technology and related conventional studies on the network design for hierarchical optical path networks are described. Hierarchical optical path networks that employ waveband switching and hierarchical optical cross-connects are proposed to realize cost-effectively a large capacity optical path networks. It was shown that waveband path routing made possible with HOXCs could theoretically reduce total number of required optical switch ports of optical node systems. Conventional studies have also verified that hierarchical optical path networks can greatly reduce the network cost. Moreover, further advanced network solutions that incorporate the node optimization in order to make the HOXC nodes possible with current technologies are necessary to exploit the advantages of waveband switching and create near future bandwidth-abundant networks.

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Chapter 3

Hierarchical optical path network design with waveband add/drop capability constraint

In this chapter, for the first time to our knowledge, effective network design solutions that are capable of incorporating the node size minimization into the network cost optimization for hierarchical optical path network have been proposed. Two new network design algorithms that consider a restriction on waveband add/drop capabilities of nodes have been developed. Their effectiveness is then evaluated by conducting extensive numerical experiments. The effects of the network parameters, which include network size, link distance and network topology, on total network cost are also elucidated. The results show that the proposed algorithms are especially effective for large networks and large traffic demands. It is also demonstrated that choosing the waveband capacity properly is critical in minimizing total cost of the hierarchical optical path networks. The developed algorithms will play a key role in maximizing node-scale reduction and realizing the resultant network cost reductions when the waveband switching is to be fully utilized.

3.1 Introduction

To avoid explosions in the cost and complexity of the switches, hierarchical optical path networks that employ hierarchical optical cross-connects using waveband switching have been developed [3-1]-[3-22]. A critical technical development necessary to implement the hierarchical optical path networks is hierarchical optical cross-connect switch design. Detailed analyses of HOXC switch sizes in [3-7]-[3-9] revealed that total switch size strongly depends on the required waveband add/drop capability that is represented by the waveband add/drop ratio which is defined as the ratio of the number of added/dropped waveband paths to the total number of outgoing/incoming waveband paths. In order to reduce the switch scales of the hierarchical optical cross-connect systems, restricting the waveband add/drop ratios is essential. This is because node architectures or necessary devices are determined by the limitation of waveband add/drop capability. Depending on the hardware technologies and specific architectures applied, the HOXC can or cannot offer colorless waveband add/drop capability in

which any waveband(s) can be added or dropped from or to WXC regardless of the waveband indexes [3-7]. Accordingly the waveband add/drop ratio can be defined in two ways; colorless waveband add/drop ratio or waveband add/drop ratio on each waveband index (called colored waveband add/drop ratio). More details about the colored and colorless waveband add/drop ratios are explained afterward. However, conventional network design algorithms focused only on minimization of the network cost and assumed that optical cross-connect node cost is linear against the optical port count of the hierarchical cross-connect switches. In other words, the conventional network design algorithms attain network cost reduction using HOXCs, the waveband add/drop ratio of which is tailored to each node. To implement efficiently HOXCs, however, it is desirable to adopt a single or very limited numbers of maximum waveband add/drop ratios so as to simplify the switch fabrication, since this restriction impacts the component device architectures.

In this chapter, we, for the first time to our knowledge, have proposed two heuristic network design algorithms for hierarchical optical path networks subject to the colorless and colored waveband add/drop ratio restriction. Restricting the waveband add/drop ratio to a certain value can effectively reduce necessary optical path cross-connect switch scale as mentioned above. To attain these objectives, we introduce a preference function that is the sum of the square of the deviation from the restriction at every node along the selected route. The proposed algorithms first select several wavelength paths that can be carried efficiently by a waveband path, and then assign to the waveband path a waveband index and a route with the largest preference value. After optimization, for nodes that cannot satisfy the specified add/drop ratio restriction, additional spare through switch ports are added so that the restriction can be met (of course, this increases node cost, but this will be shown to be negligible in terms of total cost). Numerical experiments verify that our proposed algorithms can achieve almost the same cost as that without considering the restriction when the restriction is not so tight. Furthermore, we also detail sensitivity analysis results on the effects of network size, waveband/fiber capacity as well as the number of shortest path candidates on the total network cost.

3.2 Hierarchical optical path network cost model

Figure 3-1 shows the generic HOXC architecture which is considered in this chapter. Although the multi-granular non-hierarchical cross-connect architecture can route waveband paths and wavelength paths in parallel [3-5][3-10][3-11], we focus on the hierarchical architecture since it simplifies network OAM (Operation Administration and Maintenance) [3-3][3-4]. Note that, in the electrical realm, a hierarchical electrical path arrangement is adopted in SDH/SONET. The HOXC consists of a waveband cross-connect part and a wavelength cross-connect part. The former consists of a BXC switch and waveband multiplexers/demultiplexers for routing higher-order waveband paths, and the latter includes a WXC switch and wavelength multiplexers/demultiplexers to route lower-order wavelength

paths. Costly wavelength/waveband converters are not taken into consideration.

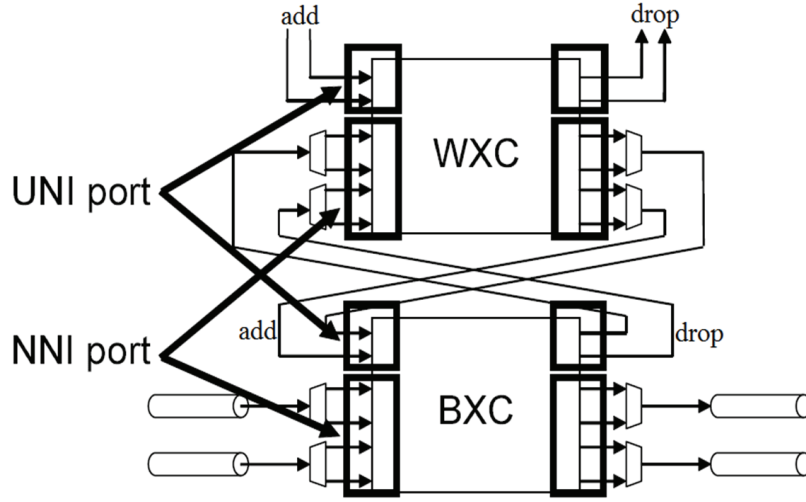


Figure 3-1. Generic HOXC architecture

Network cost is the sum of the costs of nodes (BXC and WXC) (see Figure 3-1) and links (optical fibers and fiber amplifiers). The node cost and link cost functions are expressed as follows by using the given parameters and variables listed in Tables 3-1 and 3-2. The functions also include constants that represent the costs of control systems and other overhead costs. Specific cost values used for the calculations are those up-dated from values given in [3-23].

Node cost:

$$C_{Node} = \sum_{i=1}^N (C_{B_NNI} \times B_NNI_i + C_{B_UNI} \times B_UNI_i + C_{BXC} + C_{W_NNI} \times W_NNI_i + C_{W_UNI} \times W_UNI_i + C_{WXC}) \quad (3-1)$$

Link cost:

$$C_{Link} = \sum_{i=1}^N \sum_{j=1}^N (C_{fiber}(i, j) \times F_{ij}) \quad (3-2)$$

with

$$C_{fiber}(i, j) = C_F \times D_{ij} + C_{AMP} \times \left\lceil \frac{D_{ij}}{D_{AMP}} \right\rceil \quad (3-3)$$

Table 3-1. Parameters for cost evaluation

Name	Description	Value
C_{B_NNI}	BXC NNI (network node interface) port cost per waveband	1
C_{B_UNI}	BXC UNI (User Network Interface) port cost per waveband	1.2
C_{BXC}	BXC switch base cost	4
C_{W_NNI}	WXC NNI (network node interface) port cost per wavelength	1
C_{W_UNI}	WXC UNI (User Network Interface) port cost per wavelength	1.2
C_{WXC}	WXC switch base cost	4
C_F	Optical fiber cost per km	0.012
C_{AMP}	Amplifier cost	2.04
D_{AMP}	Amplifier span	60
Network parameters		
N	Number of nodes in the network	
B	Maximum number of wavebands per fiber	
W	Maximum number of wavelengths per waveband	
D_{ij}	Distance between node i and node j ; $D_{ij}=0$ for node pair (i, j) that is not physically adjacent to each other.	

Table 3-2. Variables for cost evaluation

Name	Description
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
F_{ij}	Number of fibers between node i and node j

3.3 Waveband add/drop ratio restriction in hierarchical optical path network design

3.3.1 Waveband add/drop ratio

To realize the economical introduction of large scale optical cross-connects and the dynamic routing of optical paths, a sufficiently flexible add/drop capability and reduced switch scale must be realized simultaneously. Studies in HOXC architectures and dependences of switch sizes on HOXC parameters [3-7]-[3-9] showed that total switch size of the HOXC strongly

depends on the waveband add/drop ratio, denoted by y in Figure 3-2, which is defined as the ratio of the number of waveband paths added/dropped to the number of outgoing/incoming waveband paths at the waveband cross-connect (BXC) layer. Here, we also use symbol x to represent the ratio of all added/dropped wavelength paths from/to electrical systems to all outgoing/incoming wavelength paths at the HOXC (see Figure 3-2). In practical backbone networks, the value of x normally ranges from 0.2 to 0.4 [3-7]. For the HOXC in Figure 3-1, because the wavelength add/drop ratio x between optical switches and electrical systems is restricted through two switch stages, the BXC stage and WXC stage, the waveband add/drop ratio must be equal to or greater than the wavelength add/drop ratio x ($y \geq x$) and it is obviously related to the switch sizes of both BXC and WXC. In order to reduce the HOXC switch scale, decreasing y (equal to x) is the most effective approach if we assume x is a constant. Hereafter, we discuss the case where $x=y$.

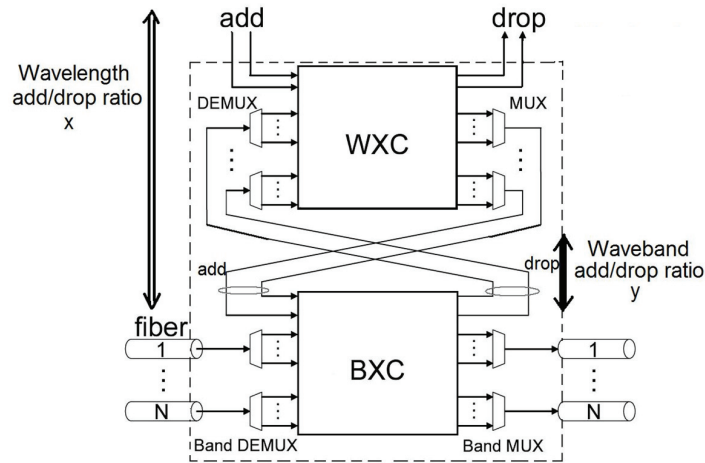


Figure 3-2. Add/drop ratio definitions

As mentioned before, depending on the hardware technologies used, the HOXC architecture can or cannot offer the “colorless” waveband add/drop capability in which any waveband(s) can be added or dropped from or to wavelength cross-connect (WXC) regardless of the waveband indexes [3-7][3-9]. Accordingly two different restriction schemes on the waveband add/drop ratios for different HOXC architectures are clarified as follows:

1) *Colored waveband add/drop ratio restriction*

For an HOXC node, let the number of added/dropped waveband paths in the i -th waveband be $b_{ad}^{(i)}$ and that of outgoing/incoming waveband paths to/from the other nodes be $b^{(i)}$. The colored waveband add/drop ratio for the i -th waveband is denoted as y_i^{each} . Then, for the given upper bound on colored waveband add/drop ratio, y , the HOXC node must satisfy,

$$\max_{b^{(i)} \neq 0} \left\{ y_i^{each} = \frac{b_{a/d}^{(i)}}{b^{(i)}} \right\} \leq y \quad (3-4)$$

2) Colorless waveband add/drop ratio restriction

This add/drop ratio restriction, y^{all} , is valid for all the waveband indexes and the restriction on the colorless waveband add/drop ratio is expressed as,

$$y^{all} = \frac{\sum_i b_{a/d}^{(i)}}{\sum_i b^{(i)}} \leq y \quad (3-5)$$

3.3.2 Impacts of waveband add/drop ratio

From the hardware realization point of view, it is desirable to fix the upper-bound of the waveband add/drop ratio, y , so as to not only reduce the WXC switch scale, but also simplify the HOXC architecture. Figure 3-3 and 3-4 show a typical WSS/WBSS based HOXC architecture and the dependence of the switch scales of WSS/WBSS based HOXC and OXC on the waveband add/drop ratio. Here, the switch scale is measured by the number of elemental 3D-MEMS mirrors needed to construct WSSs and WBSSs.

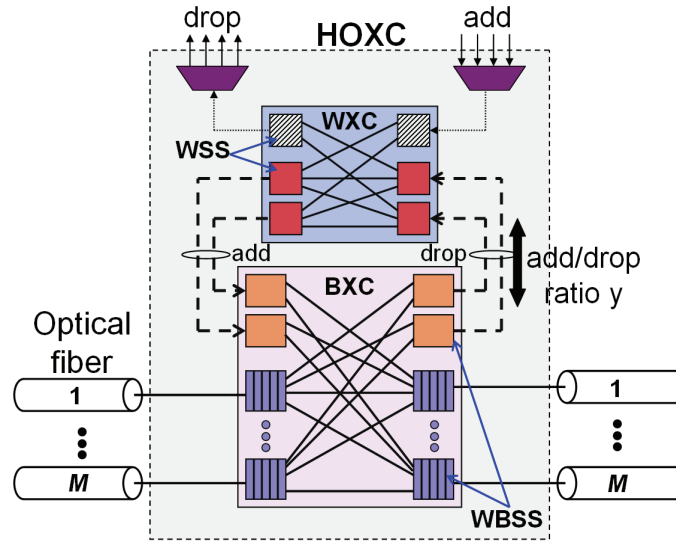


Figure 3-3. WSS/WBSS-based HOXC architecture

In terms of the number of elemental MEMS mirrors required for constructing WSSs/WBSSs, the HOXC is only more effective than the equivalent single layer OXC if the add/drop ratio, y , is less than a specific value y_{max} as shown in Figure 3-4 [3-8]. Figure 3-4 also indicates that the

larger y is, the greater number of required WSS/WBSS modules is, and therefore, limitation of the add/drop ratio is essential to effectively reduce hardware. Specifically, it was demonstrated that when the colored optical path add/drop ratio is 0.5-0.25 (between 50% and 25%), switch scale reduction of 21-48% is possible by introducing waveband technologies [3-3][3-8].

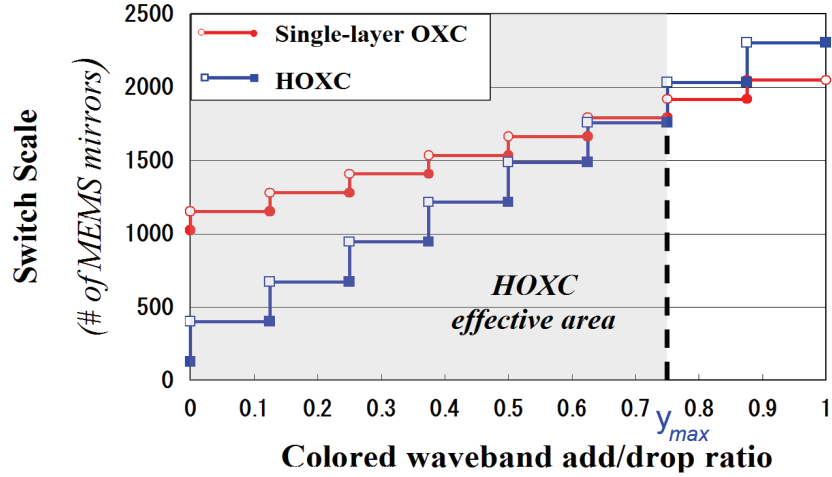


Figure 3-4. Comparison of switch size between WSS/WBSS based HOXC and OXC

The same discussion holds true for hierarchical optical cross-connect switches that utilize matrix-type switches. Unlike WSS/WBSS based HOXCs, depending on the utilized architectures, matrix-switch based HOXCs can provide colored or colorless waveband add/drop capability. A common matrix switch based HOXC with colorless add/drop capability is described in Figure 3-5. Figure 3-6 illustrates a switch size comparison between an HOXC and a single-layer OXC in terms of number of cross-point switches for matrix switches used with respects to the waveband add/drop ratio when both have the same number of input/output fibers [3-7]. The graph demonstrates that switch scale reductions of more than 50% have been attained when the colorless waveband add/drop ratio is less than 0.5 (50%) and the HOXC only has smaller switch size than the single-layer OXC when $y_{all} \leq 0.75$.

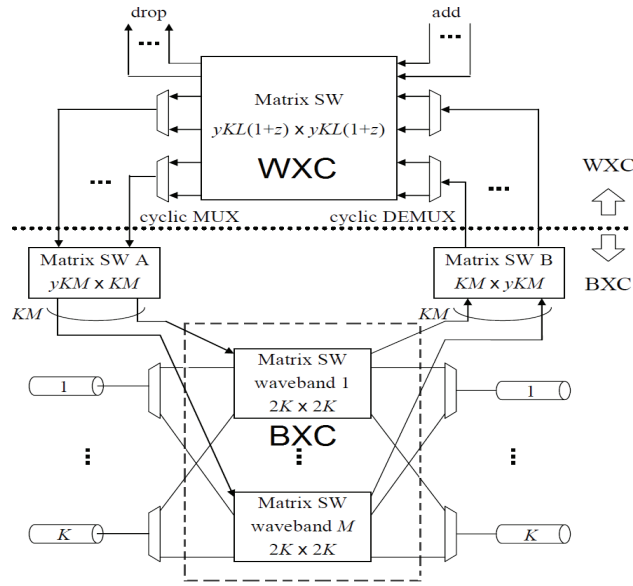


Figure 3-5. Matrix switch based HOXC architecture with colorless waveband add/drop capability

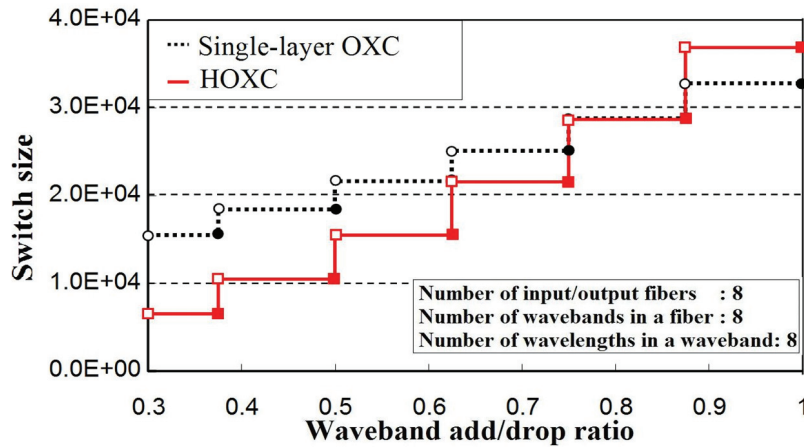


Figure 3-6. Dependence of HOXC and OXC switch scale on the colorless waveband add/drop ratio

Hereafter, we define symbols B and W as, respectively, the number of wavebands in a fiber and the number of wavelengths in a waveband. The total number of optical space switch ports required by a single-layer OXC when the input/output fiber number is M is $P_{OXC} = (1+x)MBW$, and total port count for an HOXC is $P_{HOXC} = (1+y)MB + (x+y)MBW$. The port count ratio between HOXC and a single-layer OXC is given by,

$$R = \frac{P_{HOXC}}{P_{OXC}} = 1 - \frac{(1-y)W - (1+y)}{(1+x)W} \quad (3-6)$$

, which is independent of the input/output fiber number and the number of wavebands in a fiber.

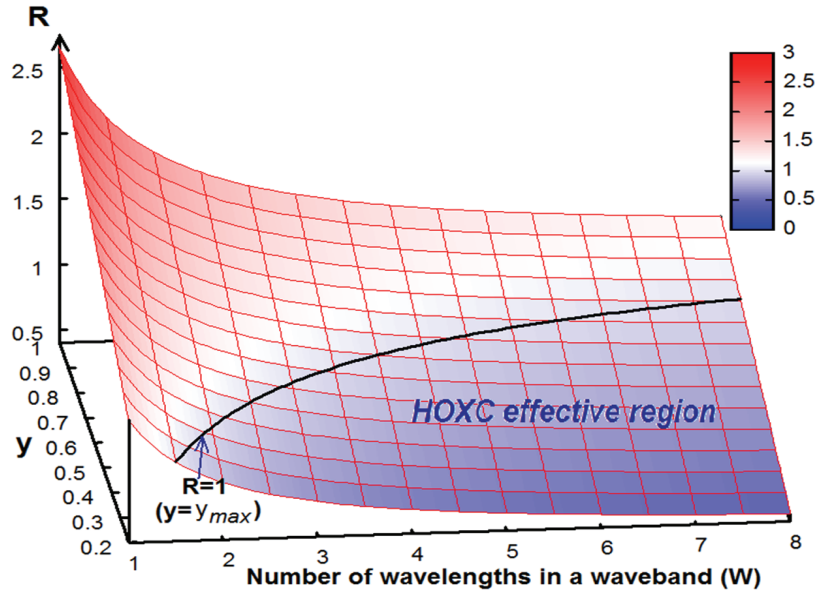


Figure 3-7. Port count ratio R

Because one of the main objectives for introducing the hierarchical optical cross-connects is to reduce the total number of ports required in optical space switches, the port count of HOXC should be less than that of a single-layer OXC. This means that R should be less than 1, so $y < \frac{W-1}{W+1} = y_{max}$. For example, if the wavelength number in a waveband is 8, y_{max} is 0.78. Figure 3-7 illustrates how the port count ratio R varies with waveband granularity (number of wavelengths in a waveband, W) and the waveband add/drop ratio when $x=0.2$. We assumed here that waveband paths are filled by wavelength paths, so this figure shows a theoretical bound. By reducing y or enlarging W , the degree of the switch size reduction in terms of port count is enhanced. Moreover, as mentioned before, the waveband add/drop ratio y must be greater than the added/dropped wavelength ratio, x , which is determined by the originating/terminating (added/dropped) traffic demand at the node. Therefore, y should be upper-bounded by a threshold that ranges between x and y_{max} , and the same node architecture (the same HOXC switch architecture that uses a specific y value) can be employed throughout the hierarchical optical path network while reducing the total port count of the network.

3.3.3 Analysis on waveband add/drop ratio in hierarchical optical path networks

In this section, we analyze the waveband add/drop ratio in relation to designing hierarchical optical networks. From the hardware realization point of view, it is not practical if the waveband add/drop ratios are completely variable, since this makes it essential to perform switch architecture optimization node by node. For greater economy, they should be set at one or a few specific values. In order to reduce the waveband add/drop ratios of nodes, grooming of wavelength paths should be minimized, which, on the other hand, may worsen the waveband

utilization and increase the total cost. The number of pass-through waveband paths at each node is related to the hop counts of the waveband paths, which are determined by the waveband routing strategy used.

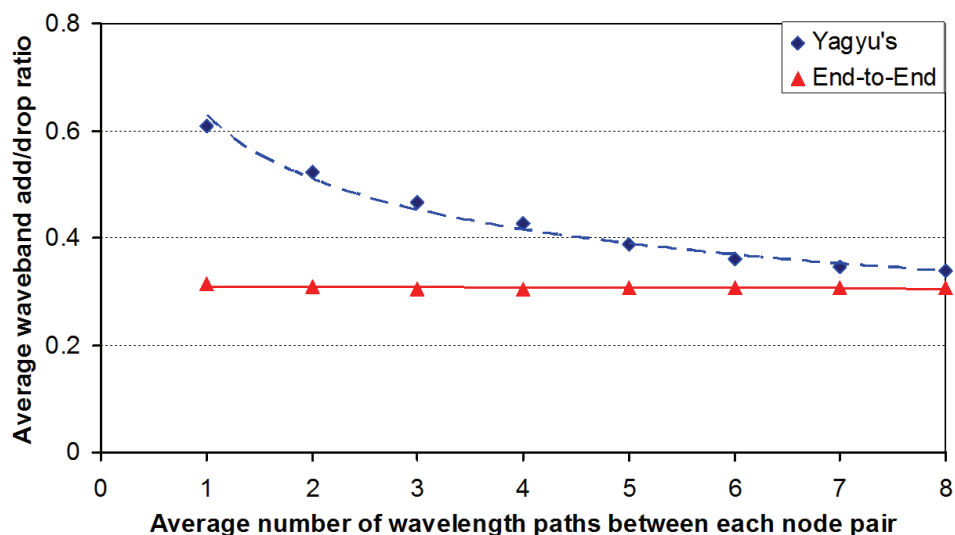
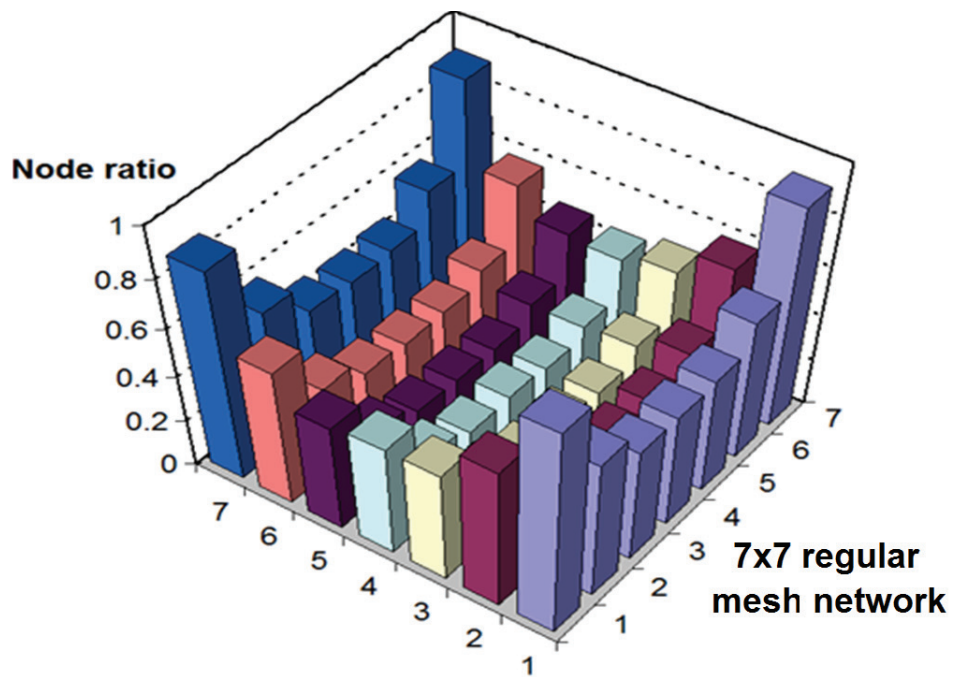
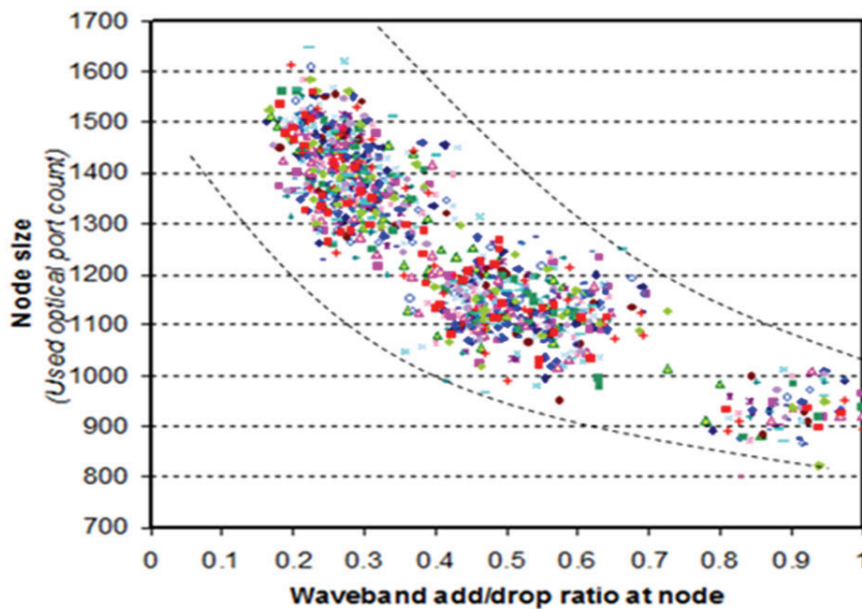


Figure 3-8. Average waveband add/drop ratio in a 7x7 regular mesh network

Figure 3-8 illustrates the average waveband add/drop ratio at each node in a 7x7 regular mesh network as derived by Yagyu's algorithm [3-22], which is known to be a very efficient algorithm, and an end-to-end algorithm that simply establishes direct waveband paths connecting source and destination nodes of the given wavelength path demands. Yagyu's algorithm achieves lower network cost than the end-to-end algorithm does while its average waveband add/drop ratio is greater than that obtained by the end-to-end algorithm. The ratio increment owes to the grooming strategy introduced by Yagyu's algorithm; it achieves a high utilization of waveband paths and a lower network cost as a result. A distribution of the waveband add/drop ratios at every node in the 7x7 regular mesh network obtained by Yagyu's algorithm, the average traffic demand is 4 (wavelengths), is shown in Figure 3-9.a. Figure 3-9.b plots the relationship between node size and the ratios in the 7x7 regular mesh network where 20 different random traffic patterns are tested at the average traffic demand intensity of 4. This result shows that the waveband add/drop ratio at each node distributes over a wide range from 0 to 1, and that the nodes that require large add/drop ratios are those with smaller node size. We, therefore, have to develop an algorithm that maximally reduces the network cost while restricting the add/drop ratio.



a) Waveband add/drop ratios at nodes



b) Switch size versus waveband add/drop ratio

Figure 3-9. A distribution of waveband add/drop ratio. a) Waveband add/drop ratio distribution at nodes in the 7x7 regular mesh network; b) Waveband add/drop ratio distribution with node sizes.

3.4 Proposed network design algorithm with a restriction on colorless waveband add/drop ratio

In this section, we focus on hierarchical optical cross-connect architectures that can offer the colorless waveband add/drop capability. Accordingly, we propose a new design algorithm for hierarchical optical path networks considering the colorless waveband add/drop ratio constraint. The algorithm combines the grooming technique with a waveband routing strategy and considers the add/drop ratio constraint on all wavebands by using multi-layer auxiliary waveband/wavelength graphs of the network.

3.4.1 Proposed network design algorithm

As discussed in Section 3.3, the colorless waveband add/drop ratio, y^{all} , should be upper-bounded and waveband paths need to be utilized efficiently to reduce the network cost. The proposed algorithm iteratively searches for groups of wavelength paths whose sources (and destinations) are located near to each other, and then establishes waveband paths to accommodate them. This waveband grooming scheme (see Figure 3-10) is based on that of [3-22] so that the proposed algorithm inherits the high utilization efficiency of waveband paths (Step 1 of the following algorithm). While routing the waveband paths, the algorithm controls the variation in waveband add/drop ratio at nodes by applying a preference function defined by current add/drop ratios at nodes. The routing and assignment of waveband/wavelength paths are based on the corresponding auxiliary multi-layer waveband/wavelength graphs whose arcs are weighted according to the availability of installed wavebands/fibers with free capacity.

Suppose that the given network can be expressed as a directed graph $G=(V, A)$ with N nodes, where $V=(v_k)_{k=1}^N$ is the vertex set that corresponds to all nodes, and A is the arc set that is related to all links in the network. The procedures of the proposed network design algorithm are summarized as follows:

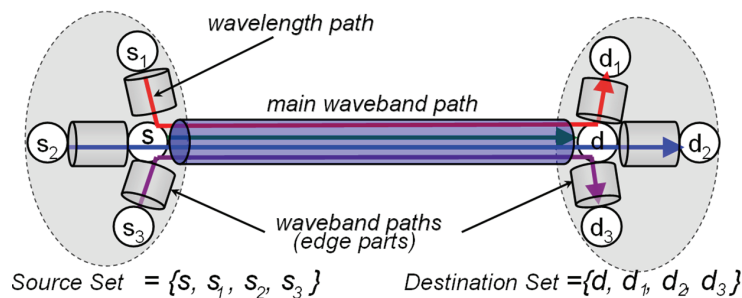


Figure 3-10. Waveband grooming scheme

<Design algorithm considering waveband add/drop ratio restriction>

Step 0- Selection of parameters

Select proper values for the following parameters:

- X_{wb} : Waveband construction threshold for establishing a new waveband path ($X_{wb} \in (0,1]$).
- K : Maximum number of route candidates for each node pair.
- y_{i0} : Upper-bounded value of the waveband add/drop ratio for node i in the given network.

Step 1- Waveband establishment

-- In descending order of hop count between source and destination nodes, search for a set of neighboring source/destination nodes $\nabla \subset V \times V$ subject to

$$W \geq \sum_{(s_i, d_j) \in \nabla} \{\# \text{ of wavelength paths requested between } s_i \text{ and } d_j\} \geq X_{wb}W .$$

-- Choose the source and destination pair $(s, d) \in \nabla$ of the main waveband path that maximizes the cost reduction function:

$$f(s, d) = \sum_{(v_k, v_l) \in \nabla} \frac{(\text{cost}_\lambda(v_k, v_l) - \text{cost}_{wb}(v_k, v_l; s, d))}{\text{cost}_\lambda(v_k, v_l)} \quad (3-7)$$

, where $\text{cost}_\lambda(v_k, v_l) > 0$ is the cost of implementing a wavelength path accommodated within a series of sequentially connected 1-hop waveband paths between v_k and v_l and $\text{cost}_{wb}(v_k, v_l; s, d) > 0$ is the cost of routing the wavelength path between v_k and v_l as a member of the waveband path that directly connects nodes (s, d) . The cost functions of $\text{cost}_\lambda(v_k, v_l)$ and $\text{cost}_{wb}(v_k, v_l; s, d)$ are given by,

$$\begin{aligned} \text{cost}_\lambda(v_k, v_l) &= 2C_{W_UNI} + 2C_{W_NNI} \text{hop}(v_k, v_l) \\ &+ \frac{2}{W} (C_{B_UNI} + C_{B_NNI}) \text{hop}(v_k, v_l) \end{aligned} \quad (3-8)$$

and

$$\begin{aligned} \text{cost}_{wb}(v_k, v_l; s, d) &= 2C_{W_UNI} + 2C_{W_NNI} (\text{hop}(v_k, s) + \text{hop}(d, v_l) + 1) \\ &+ \frac{2}{W} \{C_{B_UNI} (\text{hop}(v_k, s) + \text{hop}(d, v_l) + 1) \\ &+ C_{B_NNI} (\text{hop}(v_k, s) + \text{hop}(s, d) + \text{hop}(d, v_l))\} \end{aligned} \quad (3-9)$$

where C_{W_UNI} , C_{W_NNI} are, respectively, the UNI port cost and the NNI port cost of the WXC; and C_{B_UNI} , C_{B_NNI} are those of the BXC.

- If such a set does not exist, go to Step 3. Otherwise, go to Step 2.

Step 2- Routing Waveband

For the b^{th} waveband, $Band_b$ ($1 \leq b \leq B$), define a directed graph $G_b^{\text{Band}} = (V, A_b)$ where its arc set A_b is derived from all edges in G with modified arc weight $w_b^{\text{Band}} : V^2 \rightarrow R_+$, where R_+ is all non-negative real numbers and w_b^{Band} depends on the number of unoccupied wavebands in established fibers on the arc, denoted by f_b ($f_b \geq 0$). The weighting function for the arc set A_b is defined by,

$$w_b^{Band}(v_i, v_j) = \begin{cases} (1 - f_b \varepsilon) \left\{ 2C_{B_NNI} + \frac{C_{fiber}(v_i, v_j)}{B} \right\}; & \text{if } f_b > 0 \\ (1 + \Delta) \left\{ 2C_{B_NNI} + \frac{C_{fiber}(v_i, v_j)}{B} \right\}; & \text{else if } f_b = 0 \end{cases} \quad (3-10)$$

, where $C_{fiber}(v_i, v_j)$, the link cost connecting v_i and v_j including fibers and amplifiers, is as defined in Section 3.2, $\Delta \leq \frac{1}{\max_{(v_i, v_j) \in V \times V} \{hop(v_i, v_j)\}}$ in which $hop(v_i, v_j)$ is the hop count between v_i and v_j , and a very small constant $\varepsilon < (\max\{\text{number of fibers at a node}\})^{-1}$ is introduced to encourage the use of existing fibers as much as possible while minimizing the hop count. Stack the graphs $\{G_1^{Band}, \dots, G_B^{Band}\}$ and define a multi-layer waveband graph $G^{Band} = \{G_b^{Band} = (V, A_b) | 1 \leq b \leq B\}$ as shown in Figure 3-11. The dashed lines are the links that have some installed fibers with unoccupied waveband $Band_b$ and the solid lines represent the links that require a new fiber to accommodate the waveband.

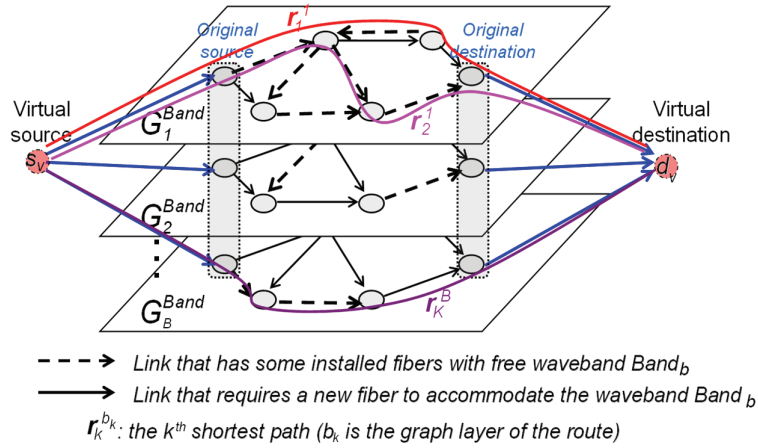


Figure 3-11. Multi-layer waveband graph of network

a) Routing the main waveband path

-- Add virtual source and destination nodes (s_v, d_v) which are respectively connected to the original source and destination nodes (s, d) on all layers and find K -shortest paths [3-24] ($r_1^{b_1}, \dots, r_K^{b_K}$) where b_k stands for the waveband index of the route $r_k^{b_k}$ from the source to the destination (see Figure 3-11).

-- For each route candidate $r_k^{b_k}$, calculate the square root of sum of squared deviations of add/drop ratio from y_{i0} at each node along the route, denoted by σ_k ;

$$\sigma_k = \sqrt{\sum_{n \in N(r_k^{b_k})} (\max\{y_n - y_{n0}, 0\})^2}$$

where $N(r_k^{b_k})$ is set of all nodes in the route candidate $r_k^{b_k}$; y_n

denotes the current waveband add/drop ratio of the node n .

-- Choose path $r_t^{b_t}$ with the largest σ_t among the candidates. If multiple paths are available, select one randomly.

b) Assignment of waveband paths

-- On the b_t^{th} layer $G_{b_t^{\text{th}}}^{\text{Band}}$, for each node pair $(s_i, d_i) \in \nabla$, if $s_i \neq s$ or $d_i \neq d$, find the shortest paths from s_i to s and from d to d_i , denoted as r_{Si} and r_{Di} , by applying Dijkstra's algorithm.

-- Assign each wavelength demand request between the node pair (s_i, d_i) to a wavelength $\lambda_k \in \text{Band}_{b_t^{\text{th}}}$ along route $r(s_i, d_i) = (r_{Si}, r_t^{b_t}, r_{Di})$, a set of concatenated waveband routes, in the first fit manner.

Go back to Step 1.

Step 3- Refinement

a) Accommodate remaining wavelength paths

-- Create a multi-layer wavelength graph including $B \times W$ layers $G^\lambda = \{G_k^\lambda = (V, A'_k) | 1 \leq k \leq B \times W\}$ of the network in which graph layer G_k^λ represents the graph for the wavelength λ_k . To encourage the use of existing waveband paths and fibers, each arc $a'_k(v_i, v_j) \in A'_k$ is weighted by considering the availability of waveband paths or fibers with free wavelength λ_k . The weight function for each arc connecting v_i and v_j $G_k^\lambda(v_i, v_j): A'_k \rightarrow R_+$ is defined by,

$$G_k^\lambda(v_i, v_j) = \begin{cases} 2C_{W_NNI} & \text{if waveband paths connecting } v_i \text{ and } v_j \text{ with} \\ & \text{free } \lambda_k \text{ are available;} \\ 2(C_{W_NNI} + C_{B_UNI} + C_{B_NNI}) & \text{else if installed fibers with} \\ & \text{free } \lambda_k \text{ are available on the arc } a'_k(v_i, v_j); \\ 2(C_{W_NNI} + C_{B_UNI} + C_{B_NNI}) + C_{\text{fiber}}(v_i, v_j) & \text{else if a new fiber} \\ & \text{is required on the physical link connecting } v_i \text{ and } v_j; \\ \infty & \text{else if there is neither established waveband path} \\ & \text{nor physical link connecting } v_i \text{ and } v_j. \end{cases} \quad (3-11)$$

-- For remaining traffic demands, in descending order of the hop count between source and destination nodes, find the shortest path based on the multi-layer graph G^λ so as to route each remaining wavelength path. Repeat this procedure until all remaining wavelength paths are accommodated.

b) Adding spare waveband ports

Add spare waveband ports to nodes whose ratios are greater than their upper-bound y_{i0} so that their ratios satisfy the restriction.

Remarks:

1. In step 2, the function σ_k is introduced to control the variation of the waveband add/drop ratios of nodes while suppressing the cost increase. We conducted numerical experiments using maximum ratio function $\sigma_k = \text{Max}_{n \in N(r_k^{b_k})} \{y_n\}$ and a root mean square deviation function

$$\sigma_k = \sqrt{\frac{\sum_{n \in N(r_k^{b_k})} (y_n - y_{n0})^2}{|N(r_k^{b_k})|}}$$

for different networks and found that the square root of sum of squared

deviations is the best choice for σ_k .

2. In Step 3, because only a small number of wavelength paths that are sparsely distributed and between node pairs mainly with short hop count remain and the RWA strategy that encourages the use of free wavelengths in the established waveband paths is applied, the newly established waveband paths are short and few in number. They rarely affect the waveband add/drop ratios of nodes. Hence, the shortest path algorithm Dijkstra is employed to route the remaining wavelength paths instead of the K-shortest path algorithm used in routing waveband paths.

3.4.2 Computational complexity of the proposed algorithm

Let N and M denote the number of nodes ($N = |V|$), and the number of arcs ($M = |A|$) in the network, respectively. The computational complexity of the proposed algorithm is evaluated as follows:

1) Computational complexity of Step 1

Let the total number of given wavelength paths be #path, which is proportional to the number of node pairs $N(N-1)$ as uniformly distributed traffic demand is assumed. Maximum number of search operations for the waveband establishment step is estimated to be $S_C = \frac{\#path}{X_{wb}W} + N(N-1)$,

which is $O(N^2)$.

Therefore, the computational complexity of Step 1 is $O(N^2)$. Then Step 2 is called once for each found set of neighboring source/destination nodes.

2) Computational complexity of Step 2

The complexity of Step 2 is mainly dominated by the K-shortest paths algorithm for routing waveband paths and the computational cost for each operation is $O(KN(M + M \log N))$ [3-24]. Because this step is required for each neighboring source/destination node set, the total computational complexity of Step 1 and Step 2 is $O(KN^3(M + M \log N))$.

3) Computational complexity of Step 3

The maximum number of wavelength paths W_A that are not accommodated in Step 1 and 2 are estimated by $W_A = \frac{X_{wb}W}{\min\#B_k} N(N-1)$, where $\min\#B_k$ stands for the minimum number of nodes in

the source/destination set. Dijkstra's algorithm is applied to find the optimal accommodation for each wavelength path and it requires $O(M + M \log N)$ operations. Hence, the time complexity of Step 3 is approximately $O(N^2(M + M \log N))$.

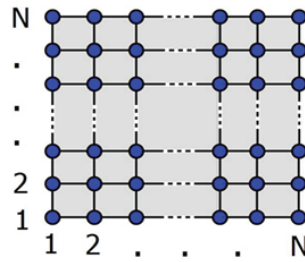
From the above discussion, we can conclude that the computational complexity of the proposed algorithm in the worst case is approximately $O(KN^3 (M + N \log N))$, when we have uniformly distributed traffic demand. The dominant element is N (the number of nodes), that is, network size.

3.4.3 Performance evaluation

A. Parameter setting

We have adopted the following parameters for the simulations:

- Physical network topologies: $N \times N$ regular mesh networks, pan-European network (COST266) and Japan's network [3-25] (Figure 3-12).
- Traffic demand: uniformly and randomly distributed.
- Capacity of fiber: $B \times W$ wavelengths per fiber; each fiber consists of B wavebands and each waveband includes W wavelengths.
- Parameter K : the number of shortest path candidates found by the K -shortest path algorithm.
- No wavelength/waveband conversion.



a) $N \times N$ regular mesh network



b) COST266 network



c) Japan network

Figure 3-12. Network topologies used for experiments

We also applied the proposed algorithm with all possible thresholds $X_{wb} \in \{1/W, 2/W, \dots, W/W\}$; one of the thresholds that minimizes the total network cost is then selected. For simplicity, we applied the same upper-bounded value of the waveband add/drop ratio y_0 for all nodes ($y_0 \in \{10\%, 20\%, \dots, 100\%\}$). Total network cost, which consists of node cost and link cost, is evaluated by linear functions of the total number of optical ports and the total length of fibers. Finally, the obtained total network costs of the hierarchical optical path networks are normalized by those calculated using the corresponding single-layer optical path networks. The algorithm was repeated 20 times for each traffic demand and each threshold X_{wb} ; their ensemble averages were determined and plotted.

B. Network cost evaluation

1) NxN regular mesh networks

We applied the following values: $K=2$; the capacity of fiber is 8 wavebands ($B=8$) and each waveband consists of 8 wavelengths ($W=8$). Figure 3-13 shows the normalized network cost achieved by the proposed algorithm for the 7x7 regular mesh network. Here, we assumed that the traffic demand is randomly assigned with uniform distribution and is represented as the average number of wavelength paths between each node pair. This result shows that the proposed algorithm can offer up to 43% less cost than the corresponding single layer optical path networks while satisfying the waveband add/drop ratio constraint at all nodes. When the value of y_0 is larger than 30%, network cost increase over that where no add/drop ratio restriction was imposed was negligible.

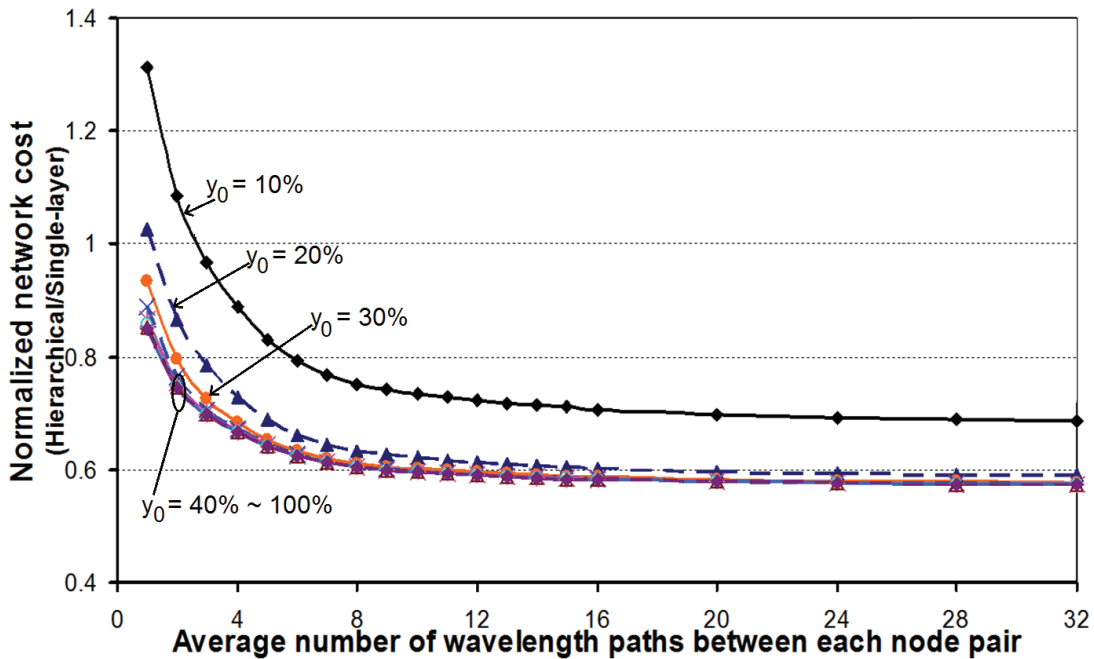


Figure 3-13. Normalized cost of the 7x7 regular mesh network

2) COST266 network and Japan's network

We investigated the cost reduction for COST266 network [3-25], that is the pan-European network with 26 nodes and 51 links, and Japan's network with its 18 nodes and 30 links. The traffic demand was randomly assigned with uniform distribution. The capacity of fiber was 8 wavebands ($B=8$) and each waveband consisted of 8 wavelengths ($W=8$). Figures 3-14 and 3-15 illustrate the normalized network costs of the COST266 and Japan's networks as yielded by the proposed algorithm where the average number of wavelength paths between each node pair was changed.

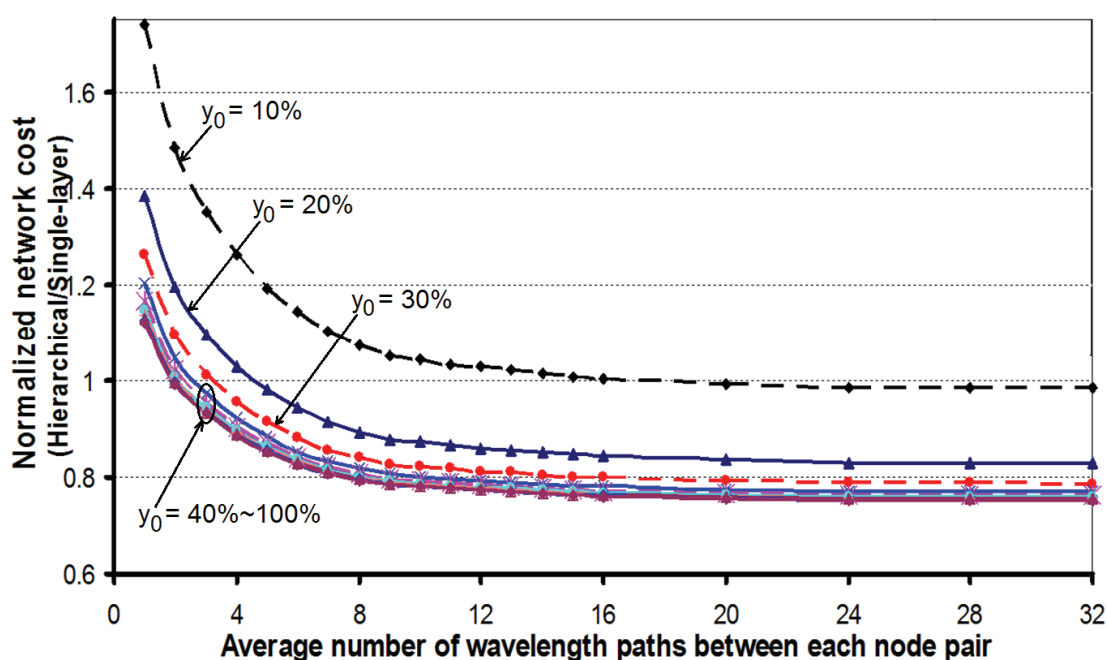


Figure 3-14. Normalized cost of the COST266 network

These results show that the proposed algorithm realizes up to 27% cost savings for the Japan's network topology and 23% for the COST266 network topology, compared to the conventional equivalent single-layer networks, while satisfying the waveband add/drop ratio constraint at all nodes. Except for the small traffic demand area or excessive small y_0 values, it is demonstrated that the hierarchical networks are more cost-effective than the conventional single-layer networks. Furthermore, mirroring the 7x7 regular mesh network results, when y_0 is greater than 30%, the network cost increase is negligible from that where no add/drop ratio restriction is imposed.

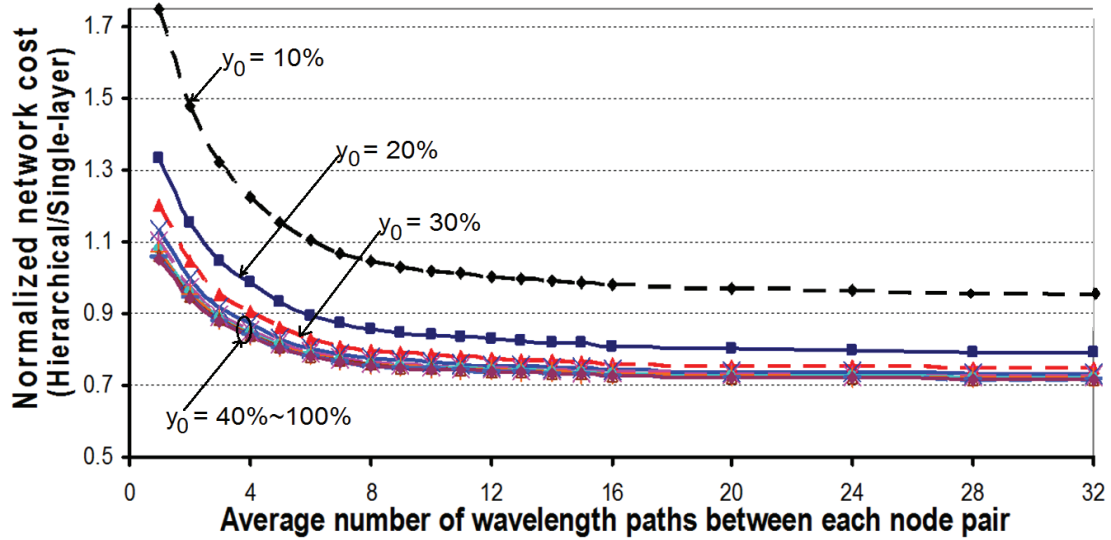


Figure 3-15. Normalized cost of the Japan network

3) Comparison with conventional algorithms

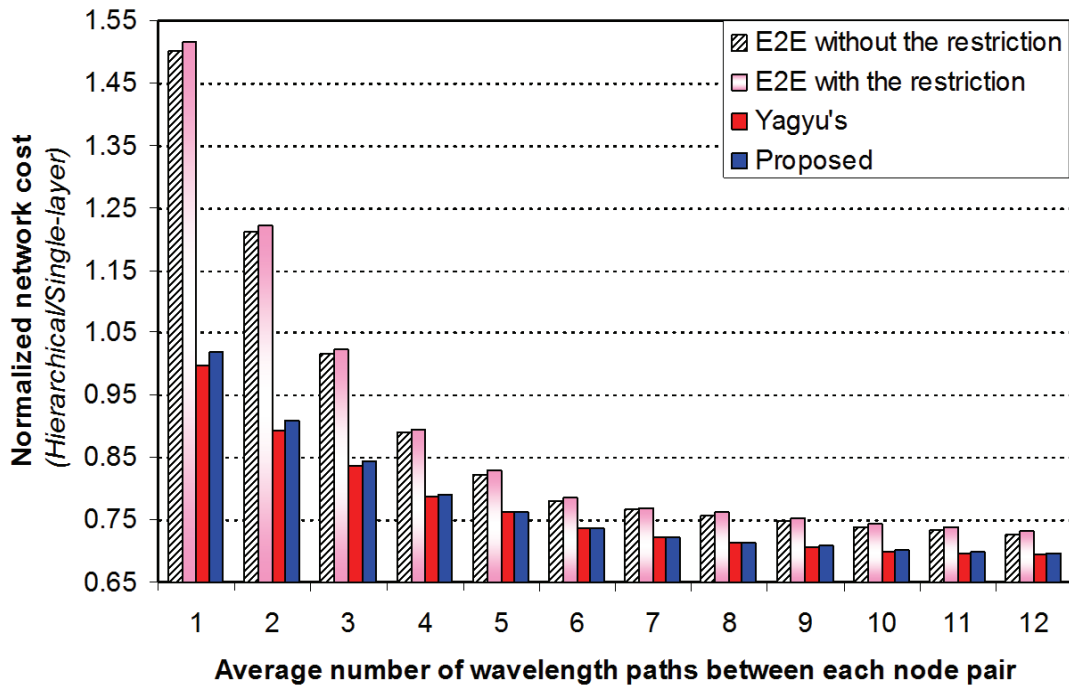


Figure 3-16. Network cost comparison with the conventional algorithms

For comparison, we also applied Yagyu’s algorithm, which is known to be very efficient and does not consider add/drop ratio restriction, and end-to-end algorithms without/with consideration of the waveband add/drop ratio restriction to the 5x5 regular mesh network

topology with the following input parameter values; waveband capacity $W=8$; fiber granularity $B=8$; the upper-bound value $y_0=50\%$. Figure 3-16 illustrates the normalized network costs yielded by the proposed algorithm with the upper-bound value $y_0=50\%$, Yagyu’s algorithm, and end-to-end algorithms (E2E) with and without the restriction ($y_0=50\%$) on the waveband add/drop ratio. Over all the traffic demands, although the proposed algorithm introduces the add/drop restriction constraint, it offers nearly the same cost as that of Yagyu’s, and much smaller cost than that achieved by the end-to-end algorithms with and without restriction on the waveband add/drop ratio.

4) Sensitivity analysis against network size

In this part, we study the dependence of the network cost on network size, changing the number of nodes and link distances. The assumptions are the traffic demands are uniformly and randomly distributed, each fiber consists of 8 wavebands ($B=8$) and the waveband capacity is 8 wavelengths ($W=8$), the upper-bounded value of the waveband add/drop ratio y_0 is fixed at 50% for all nodes. Figure 3-17 shows the normalized network costs of $N \times N$ regular mesh networks ($N=3, 4, 5, 6, 7$ and 8) when the link distance between nodes is 500 km and the traffic demand between each node pair is 2, 4, and 8. The normalized network cost decreases as network size or traffic demand increases. Because the ratio of WXC cut-through is strongly related to the average hop count, determined by the network size, while larger traffic demands help improve the utilization efficiency of waveband paths in the networks, both of them play important roles in enhancing the total network cost reduction.

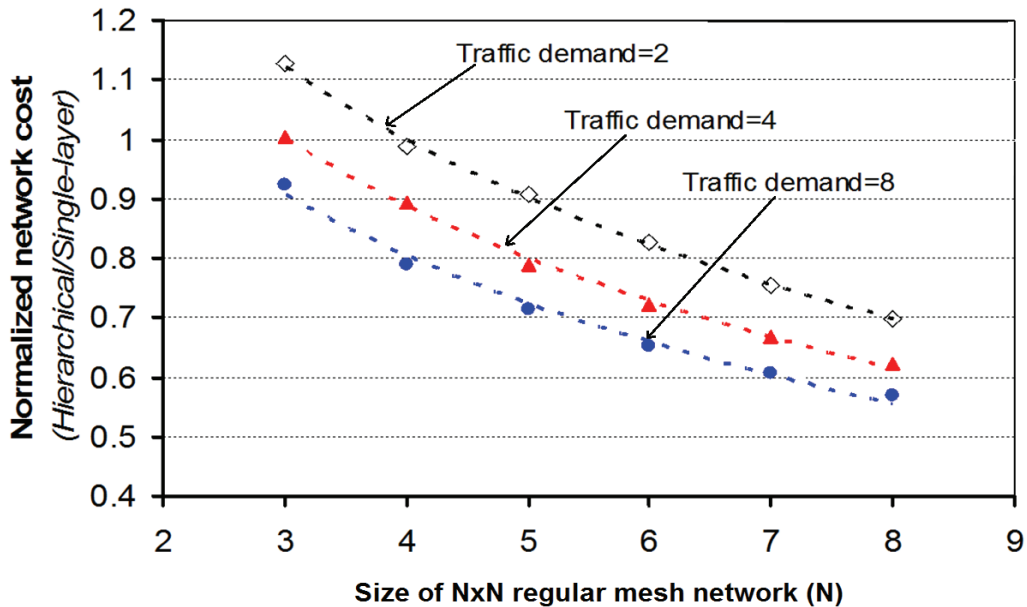


Figure 3-17. Network cost versus size of $N \times N$ regular mesh network

Figure 3-18 plots the 5x5 regular mesh network cost versus the average traffic demand between node pairs for four link distances: 100 km, 300 km, 500 km and 1000 km. The normalized network cost slightly increases as the link distance is enlarged due to the increase in link cost. As shown by these results, the hierarchical optical path network is demonstrated to be more cost effective than the single layer one over a wide range of parameter values.

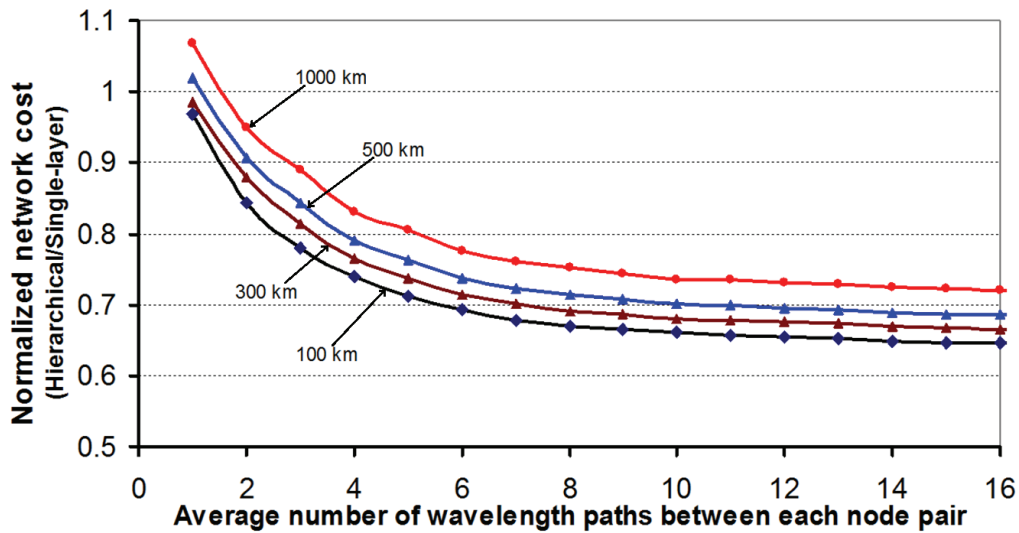


Figure 3-18. 5x5 regular mesh network cost for various link distances

5) Effect of route candidate number, K

The obtained network cost reduction achieved by the proposed algorithm can be improved by enlarging K , the number of shortest route candidates that are derived by the K -shortest algorithm. This is because raising K makes more shortest route candidates available which enhance the possibility of cost optimization. The improvement in COST266 network cost when the average wavelength path number between node pairs is 10 for K values of 2 and 4 is shown in Figure 3-19. Computational load increases with K due to the complexity of the K -shortest path algorithm. The figure indicates that the obtained network cost can be reduced slightly by setting K to a large value. There is a trade off between the obtained network cost and required calculation time. We can obtain a near-optimal solution in reasonable time by choosing a suitable K value.

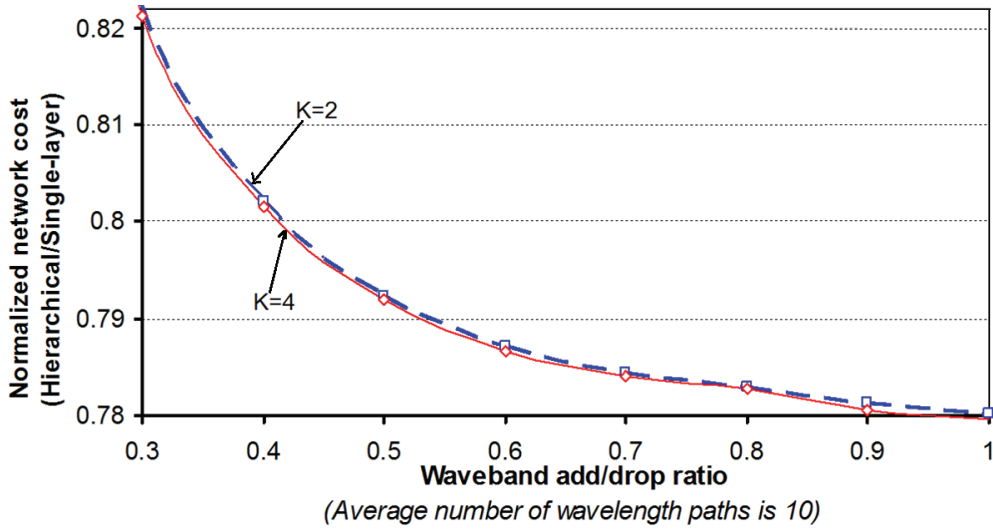


Figure 3-19. Effect of parameter K on the COST266 network cost

6) Dependence of network costs on waveband capacity

As we explained in Section 2, waveband capacity W has a strong impact on the total port count, a key determiner of total network cost. Hierarchical optical path networks theoretically offer larger cost reductions if W is increased. In this part, we set the add/drop ratio upper-bound value, y_0 , to 50%, hold the fiber capacity constant ($B \times W = 64$), and change the waveband capacity, W , to values of 4, 8, 16, and 32. The normalized network costs where the average traffic demand between each node pair is changed are described in Figure 3-20.

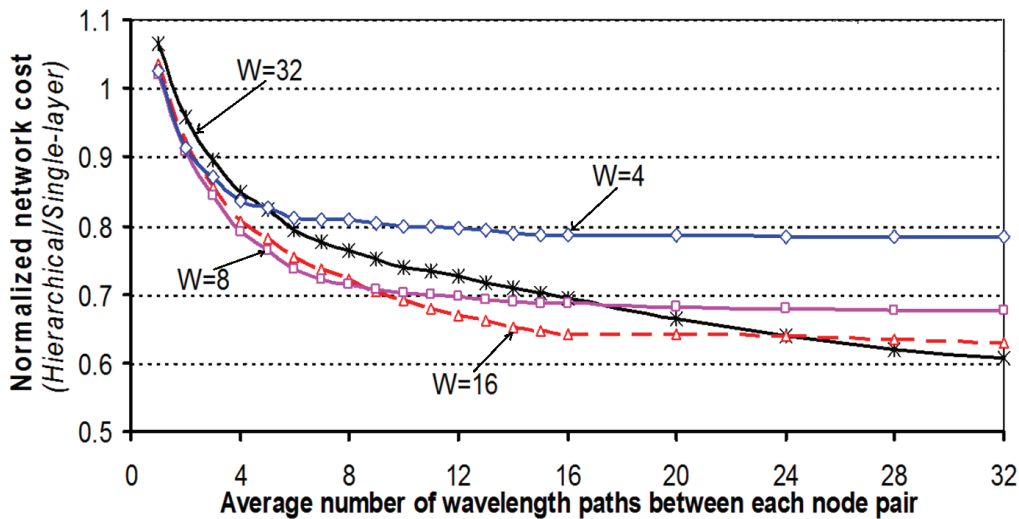


Figure 3-20. Effect of the waveband capacity on the 5x5 regular mesh network cost

Figure 3-20 shows that the smallest capacity $W=4$ offers a slight network cost reduction but only in a very restricted traffic region. Because of the fixed fiber capacity, selecting a smaller

waveband capacity can help improve the waveband utilization efficiency but may increase the number of waveband paths (waveband cross-connect switch ports) needed to carry the same given traffic demand, and as a result, the total network cost is increased. On the other hand, the largest waveband capacity ($W=32$) reduces the network cost less significantly given that the traffic demands may not be sufficient (less than 24) to fill such huge waveband paths; the result is a fall in waveband utilization efficiency. For intermediate waveband capacities, while $W=8$ provides the largest network cost reduction with traffic demands less than 9, the most effective traffic demand area for $W=16$ runs from 9 to 24. These results confirm that the optimal waveband path granularities, in terms of maximizing the network cost reduction, depend on the traffic demand in the network.

7) Effect of fiber granularity on the network cost

Figure 3-21 plots the impact of fiber capacity on the curves of network cost versus the average traffic demand between node pairs; the waveband granularity is constant ($W=8$). For larger fiber capacities with larger waveband bandwidths ($B \times W=16, 32, 64, \text{ and } 128$), the proposed algorithm offers larger total network cost reduction, and the network cost reduction obtained is gradually enhanced as the traffic demands increase. When fiber capacity increases, the number of fibers required is reduced, which results in reduced link cost and hence network cost. Increasing fiber capacity beyond a certain value may, however, require more expensive optical devices and more advanced technologies, factors that are not addressed by our proposed cost functions.

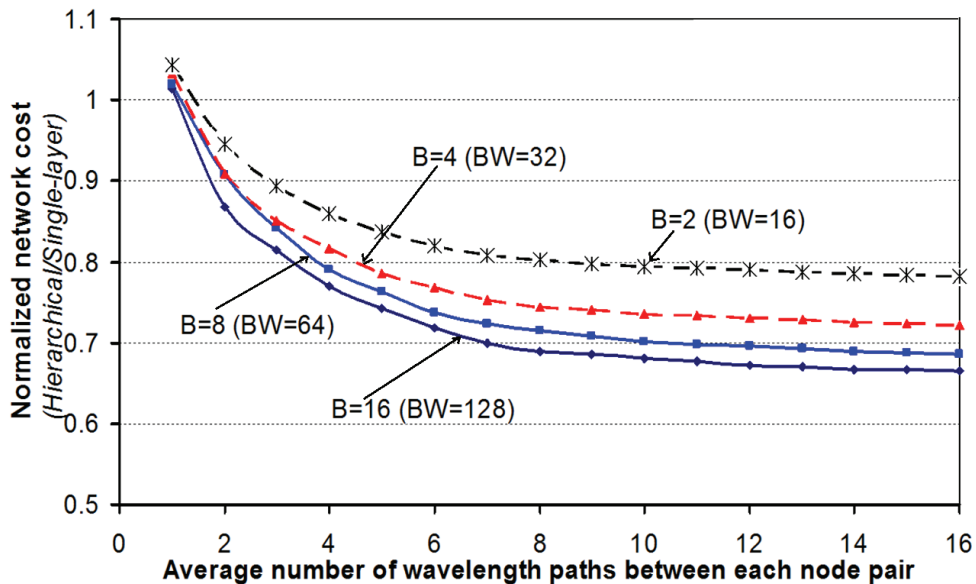


Figure 3-21. Dependence of 5x5 regular mesh network cost on fiber capacity

3.5 Proposed network design algorithm with a restriction on colored waveband add/drop ratio

A design algorithm considering the colored waveband add/drop ratio constraint has been introduced here for hierarchical optical path networks which employ optical matrix switches or WSS/WBSS components based HOXC architectures that can exploit only the colored waveband add/drop capability. The proposed method is based on our previously developed design strategy given in Section 3.4 that grooms wavelength paths with neighboring source and destination nodes. The algorithm uses multi-layer auxiliary waveband/wavelength graphs of the network to utilize the waveband routing strategy and the consideration on the add/drop ratio constraint for on each waveband index.

3.5.1 Proposed network design algorithm

To cope with both the network cost minimization and node size reduction, our proposed network design algorithm not only minimizes the total network cost but also simultaneously satisfies the given waveband add/drop ratio constraint on each waveband index. The proposed method iteratively grooms wavelength paths requested by nearby source and destination node pairs into a waveband, and then routes, and assigns the waveband path with consideration of the waveband add/drop ratio restriction on each waveband index by using multi-layer waveband/wavelength graphs of the network.

Suppose that the given network can be expressed as a directed graph $G=(V, A)$ with N nodes, where $V = (v_k)_{k=1}^N$ is the vertex set that corresponds to all nodes, and A is the arc set that is related to all links in the network; a fiber consists of B wavebands and each waveband can carry up to W wavelengths. The procedures of the proposed network design algorithm are summarized as follows:

<Design algorithm considering colored waveband add/drop ratio constraint>

Step 0- Selection of parameters

Select proper values for the following parameters:

- X_{wb} : Waveband construction threshold for establishing a new waveband path ($X_{wb} \in (0, 1]$).
- K : Maximum number of route candidates for each node pair.
- y_{i0} : Upper-bounded value of the colored waveband add/drop ratio for node i in the given network.

Step 1- Waveband Selection

- In descending order of hop count between source and destination nodes, search for a set of neighboring source/destination nodes $\nabla \subset V \times V$ subject to

$$W \geq \sum_{(s_i, d_j) \in \nabla} \{\# \text{ of wavelength paths requested between } s_i \text{ and } d_j\} \geq X_{wb} W$$

- Choose the source and destination pair $(s, d) \in \nabla$ of the main waveband path that

maximizes the cost reduction function:

$$f(s, d) = \sum_{(v_k, v_l) \in \nabla} \frac{(\text{cost}_\lambda(v_k, v_l) - \text{cost}_{wb}(v_k, v_l; s, d))}{\text{cost}_\lambda(v_k, v_l)} \quad (3-12)$$

, where $\text{cost}_\lambda(v_k, v_l) > 0$ is the cost of implementing a wavelength path accommodated within a series of sequentially connected 1-hop waveband paths between v_k and v_l and $\text{cost}_{wb}(v_k, v_l; s, d) > 0$ is the cost of routing the wavelength path between v_k and v_l as a member of the waveband path that directly connects nodes (s, d) . The cost functions of $\text{cost}_\lambda(v_k, v_l)$ and $\text{cost}_{wb}(v_k, v_l; s, d)$ are given by,

$$\begin{aligned} \text{cost}_\lambda(v_k, v_l) &= 2C_{W_UNI} + 2C_{W_NNI} \text{hop}(v_k, v_l) \\ &+ \frac{2}{W} (C_{B_UNI} + C_{B_NNI}) \text{hop}(v_k, v_l) \end{aligned} \quad (3-13)$$

and

$$\begin{aligned} \text{cost}_{wb}(v_k, v_l; s, d) &= 2C_{W_UNI} + 2C_{W_NNI} (\text{hop}(v_k, s) + \text{hop}(d, v_l) + 1) \\ &+ \frac{2}{W} \{C_{B_UNI} (\text{hop}(v_k, s) + \text{hop}(d, v_l) + 1) \\ &+ C_{B_NNI} (\text{hop}(v_k, s) + \text{hop}(s, d) + \text{hop}(d, v_l))\} \end{aligned} \quad (3-14)$$

, where C_{W_UNI} , C_{W_NNI} are, respectively, the UNI port cost and the NNI port cost of the WXC; and C_{B_UNI} , C_{B_NNI} are those of the BXC.

- If such a set does not exist, go to Step 3. Otherwise, go to Step 2.

Step 2- Routing and Waveband Assignment

- For the b^{th} waveband, $Band_b$ ($1 \leq b \leq B$), define a directed graph $G_b^{\text{Band}} = (V, A_b)$ where its arc set A_b is derived from all edges in \mathbf{G} with modified arc weight $w_b^{\text{Band}} : V^2 \rightarrow R_+$, where R_+ is all non-negative real numbers and w_b^{Band} depends on the number of unoccupied wavebands in established fibers on the arc, denoted by f_b ($f_b \geq 0$). The weighting function for the arc set A_b is defined by,

$$w_b^{\text{Band}}(v_i, v_j) = \begin{cases} (1 - f_b \varepsilon) \left\{ 2C_{B_NNI} + \frac{C_{\text{fiber}}(v_i, v_j)}{B} \right\}; & \text{if } f_b > 0 \\ (1 + \Delta) \left\{ 2C_{B_NNI} + \frac{C_{\text{fiber}}(v_i, v_j)}{B} \right\}; & \text{else if } f_b = 0 \end{cases} \quad (3-15)$$

, where $C_{\text{fiber}}(v_i, v_j)$, the link cost connecting v_i and v_j including fibers and amplifiers, is as defined in Section 3.2, $\Delta \leq \frac{1}{\max_{(v_i, v_j) \in V \times V} \{\text{hop}(v_i, v_j)\}}$ in which $\text{hop}(v_i, v_j)$ is the hop

count between v_i and v_j , and a very small constant $\varepsilon < (\max\{\text{number of fibers at a node}\})^{-1}$ is introduced to encourage the use of existing fibers as much as possible while minimizing the hop

count. Stack the graphs $\{G_1^{\text{Band}}, \dots, G_B^{\text{Band}}\}$ and define a multi-layer waveband graph

$$G^{\text{Band}} = \{G_b^{\text{Band}} = (V, A_b) \mid 1 \leq b \leq B\}.$$

a) Routing the main waveband path

- Add virtual source and destination nodes (s_v, d_v) which are respectively connected to the original source and destination nodes (s, d) on all layers and find K -shortest paths ($r_1^{b_1}, \dots, r_K^{b_K}$) where b_k stands for the waveband index of the route $r_k^{b_k}$ from the source to the destination.

- For each route candidate $r_k^{b_k}$, calculate the corresponding preference function value σ_k that is square root of sum of squared deviations of add/drop ratios from the upper-bound value at each node along the route: $\sigma_k = \sqrt{\sum_{n \in N(r_k^{b_k})} (\max\{y_n^{b_k} - y_{n0}, 0\})^2}$ where $N(r_k^{b_k})$ is set of all nodes in the

route candidate $r_k^{b_k}$; $y_n^{b_k}$ denotes the current waveband add/drop ratio of the node n on the waveband index b_k .

- Choose path $r_t^{b_t}$ with the largest σ_t among the candidates. If multiple paths are available, select one randomly.

b) Assignment of waveband paths

- On the b_t^{th} layer $G_{b_t}^{Band}$, for each node pair $(s_i, d_i) \in \nabla$, if $s_i \neq s$ or $d_i \neq d$, find the shortest paths from s_i to s and from d to d_i , denoted as r_{Si} and r_{Di} .

- Assign each wavelength demand request between the node pair (s_i, d_i) to a wavelength $\lambda_k \in Band_{b_t}$ along the route $r(s_i, d_i) = (r_{Si}, r_t^{b_t}, r_{Di})$, a set of concatenated waveband routes, in the first fit manner.

Go back to Step 1.

Step 3- Routing Sparse Wavelength Paths

a) Accommodate remaining wavelength paths

- Construct a multi-layer wavelength graph including $B \times W$ layers $G^\lambda = \{G_k^\lambda = (V, A'_k) \mid 1 \leq k \leq B \times W\}$ of the network in which each graph layer G_k^λ represents the network graph for the wavelength λ_k . The weight function for each arc connecting v_i and v_j $G_k^\lambda(v_i, v_j) : A'_k \rightarrow R_+$ is defined by,

$$G_k^\lambda(v_i, v_j) = \begin{cases} 2C_{W_NNI} & \text{if waveband paths connecting } v_i \text{ and } v_j \text{ with} \\ & \text{free } \lambda_k \text{ are available;} \\ 2(C_{W_NNI} + C_{B_UNI} + C_{B_NNI}) & \text{else if installed fibers with} \\ & \text{free } \lambda_k \text{ are available on the arc } a'_k(v_i, v_j); \\ 2(C_{W_NNI} + C_{B_UNI} + C_{B_NNI}) + C_{fiber}(v_i, v_j) & \text{else if a new fiber} \\ & \text{is required on the physical link connecting } v_i \text{ and } v_j; \\ \infty & \text{else if there is neither established waveband path} \\ & \text{nor physical link connecting } v_i \text{ and } v_j. \end{cases} \quad (3-16)$$

- For remaining traffic demands, in descending order of the hop count between source and

destination nodes, find the shortest path based on the multi-layer graph G^λ so as to route each remaining wavelength path. Repeat this procedure until all remaining wavelength paths are accommodated.

b) Refinement

- For each waveband index, add spare waveband ports to nodes whose colored waveband add/drop ratios are greater than their upper-bound y_{i0} so that their ratios satisfy the restriction at all waveband indexes.

3.5.2 Computational complexity of the proposed algorithm

Assume that N and M are the number of nodes ($N=|V|$) and the number of arcs ($M=|A|$) in the network, respectively. Similar to the algorithm considering the restriction on colorless waveband add/drop ratio, evaluation of computational complexity of the proposed algorithm is based on the computational complexities of 3 component steps. Computational complexity of Step 1 is $O(N^2)$. Moreover, computational cost for Step 2 is $O(KN(M + M\log N))$ since the complexity of Step 2 is mainly dominated by the K -shortest path algorithm applied for routing main waveband paths. Hence, total computational complexity of Step 1 and Step 2 is $O(KN^3(M + M\log N))$. On the other hand, because maximum number of remaining wavelength paths is estimated by $W_A = \frac{X_{wb}W}{\min\#B_k} N(N-1)$, which is $O(N^2)$, where $\min\#B_k$ stands for the minimum number of nodes in the source/destination set and Step 3 iteratively accommodates each remaining wavelength path by using Dijkstra's algorithm which requires $O(M+N\log N)$ operations, the time complexity of Step 3 is approximately $O(N^2(M + M\log N))$. Hence, the computational complexity of this algorithm in the worst case is $O(KN^3(M + M\log N))$, equivalent to that of the proposed algorithm considering the colorless waveband add/drop ration constraint.

3.5.3 Performance evaluation

We assume the following parameters in numerical experiments of the proposed network design algorithm:

- ✧ Physical network topologies: pan-European network (COST266) and $N \times N$ regular mesh networks.
- ✧ Traffic demand represented as the average number of wavelength paths requested between each node pair: uniformly and randomly distributed.
- ✧ Fiber capacity: $B \times W$ wavelengths per fiber; each fiber consists of B wavebands and each waveband can carry up to W wavelengths.
- ✧ Parameter K : the number of shortest path candidates found by the K -shortest path algorithm.
- ✧ No wavelength/waveband conversion.

The proposed algorithm is applied with all possible thresholds $X_{wb} \in \{1/W, 2/W, \dots, W/W\}$; one of the thresholds that minimizes the total network cost is then selected. For simplicity, we employed the same upper-bounded value of the colored waveband add/drop ratio, y_0 , for all nodes ($y_0 \in \{10\%, 20\%, \dots, 100\%\}$). The obtained total network costs of the hierarchical optical path networks are normalized by those calculated using the corresponding single-layer optical path networks. In other words, to compare with the optical path network using single-layer OXCs, we evaluate the normalized network cost which is defined as the ratio of the obtained total network cost to the corresponding single layer network cost.

1) Network cost evaluation

We applied the following values: $K=4$; the capacity of fiber is 8 wavebands ($B=8$) and each waveband includes 8 wavelengths ($W=8$). Figure 3-22 shows the normalized network cost achieved by the proposed algorithm for the pan-European network, COST266, which consists of 26 nodes and 51 links. These results show that the proposed algorithm realizes up to 20% cost savings for the COST266 network, compared to the conventional equivalent single-layer networks, while satisfying the colored waveband add/drop ratio constraint at all nodes. Figure 3-22 also illustrates that the obtained network cost depends on the ratio upper-bound value, y_0 , and increasing y_0 above 50% slightly helps in reducing the normalized network cost. Except for the small traffic demand area or excessive small y_0 values, it is demonstrated that the hierarchical networks are more cost-effective than the conventional single-layer networks.

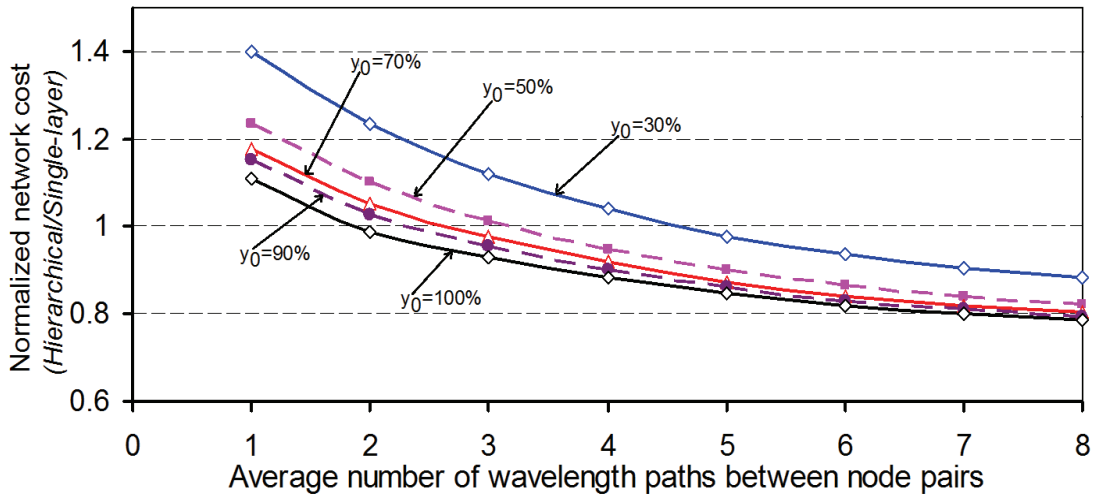


Figure 3-22. Cost reduction in COST266 network

2) Impact of waveband capacity

Waveband capacity W has a strong impact on the total port count, a key determiner of total network cost, and hierarchical optical path networks theoretically offer larger cost reductions if W is increased [3-22]. However, when W is enlarged, the node cost (in terms of port count) is

enhanced while the link cost, which depends on the utilization ratios of wavebands and fibers, may be decreased due to the establishment of inefficient wavebands that have large number of unused wavelengths. Therefore, a trade-off exists between node cost and link cost. To minimize the total network cost, depending on the traffic demands, the value of W that solves the trade-off should be selected. In this part, we set the add/drop ratio upper-bound value, y_0 , to 50%, hold the fiber capacity constant ($B \times W = 64$), and change the waveband capacity, W , to values of 2, 4, 8, 16, and 32. The normalized network costs as the average traffic demand is changed are described in Figure 3-23. The smallest waveband capacity ($W=2$) offers the worst cost reduction. Because of the fixed fiber capacity, selecting a smaller waveband capacity can help improve the waveband utilization efficiency but may increase both the number of waveband paths (waveband cross-connect switch ports) needed to carry the same given traffic demand and the number of waveband ports added to satisfied the restriction (in Step 3), and as a result, the total network cost is increased. Depending on the traffic demand areas, the greatest cost reduction is obtained by different waveband capacities. The biggest waveband capacity $W=32$ provides the largest network cost reduction with traffic demands less than 2, the most effective traffic demand area for $W=4$ runs between 2 and 3, and the best waveband capacity for the traffic demand larger than 3 is $W=8$. These results verified that the optimal waveband path granularities, in terms of maximizing the network cost reduction, depend on the average traffic demand requested.

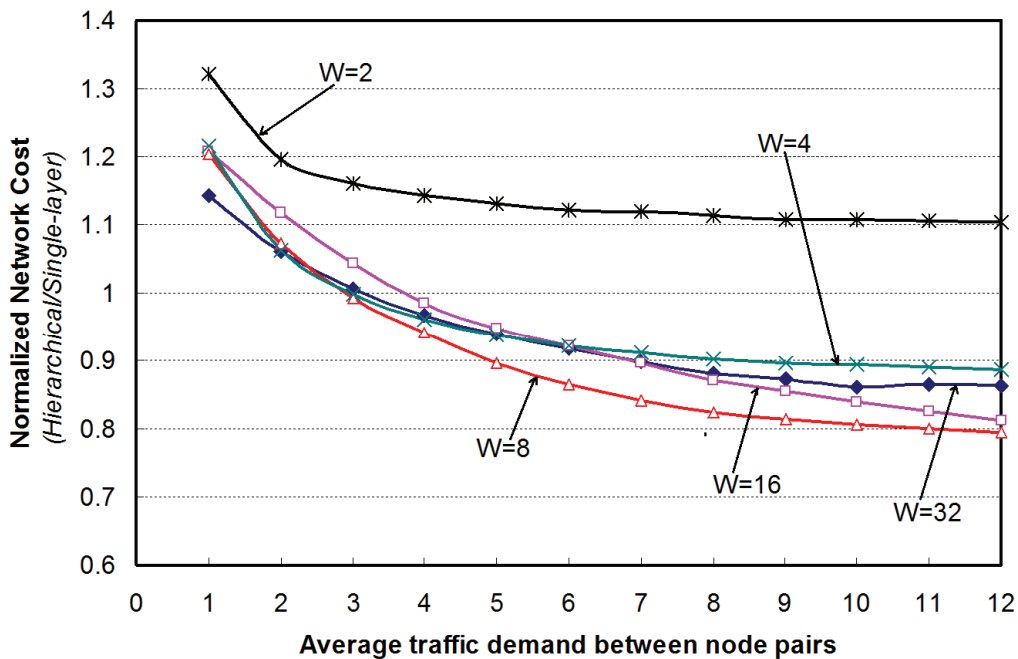


Figure 3-23. Effect of the waveband capacity on the COST266 network cost

3) Effect of network size

In this part, we study the dependence of the network cost reduction on network size (in terms of node count). We assume that each fiber carries 8 wavebands ($B=8$) and the waveband capacity is 8 wavelengths ($W=8$), the upper-bounded value of the waveband add/drop ratio y_0 is fixed at 30% and 50% for all nodes. Figure 3-24 illustrates the normalized network costs of $N \times N$ regular mesh networks ($N=3, 4, 5, 6, 7$ and 8) when the link distance is 500 km and the traffic demand between each node pair is 2, 4, and 8 respectively. The obtained network cost reduction becomes greater as the network size or the traffic demand increases. Because the ratio of WXC cut-through is strongly related to the average hop count, determined by the network size, while larger traffic demands help improve the utilization efficiency of waveband paths in the networks, both of them play important roles in enhancing the total network cost reduction.

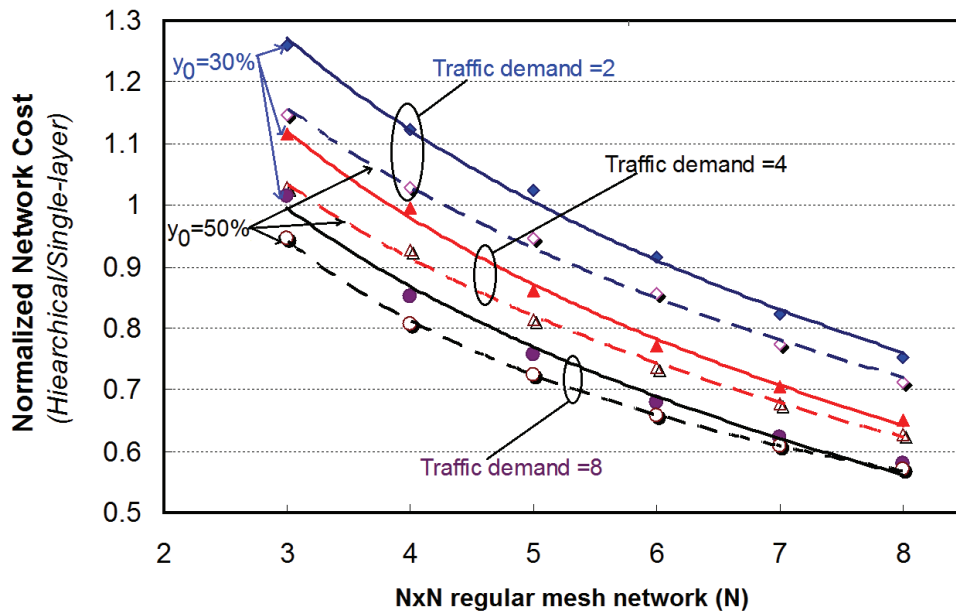


Figure 3-24. Network cost versus size of $N \times N$ regular mesh network

3.6 Summary

In this chapter, we, for the first time to our knowledge, have proposed two new hierarchical optical path network design algorithms that can incorporate a restriction on the waveband add/drop ratio to reduce the necessary switch size of HOXCs. The first proposed network design algorithm considering the colorless waveband add/drop ratio constraint is for the optical circuit/fast switching networks which utilize hierarchical optical cross-connects with full colorless waveband adding/dropping capability; and the second one with the consideration on the colored add/drop capability is applicable to the networks whose hierarchical optical cross-connect nodes are not capable of colorlessly adding/dropping wavebands from/to BXC layer. Numerical experiments verified that the proposed algorithms attain substantial network cost reduction while satisfying the constraint on each waveband add/drop ratio and they are

especially cost-effective for large networks and large traffic demands. The impacts of important network parameters such as network size, link distance, network topology and selection of waveband capacity on the total network cost are also investigated. We believe that the developed algorithms will play a key role in maximizing node-scale reduction and realizing the resultant network cost reductions when the waveband switching is to be fully utilized.

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Chapter 4

Design of hybrid hierarchical optical path networks

In this chapter, to make HOXCs possible with current mature technologies, we propose a hybrid hierarchical optical cross-connect that employs a waveband cross-connect for routing waveband paths and an electrical cross-connect for grooming wavelength paths. We also develop network design algorithms for hierarchical optical path networks that utilize the proposed hybrid-hierarchical optical cross-connects. At first, we present an integer linear programming model to solve the network design problem. We then propose a 2-stage ILP optimization based design algorithm for medium size networks and a heuristic algorithm employing the neighbor source and destination grouping method for large networks. Performances of hybrid-hierarchical optical path networks designed by the proposed algorithms are evaluated through numerical experiments. Furthermore, impact of the critical network parameters on total network cost is investigated.

4.1 Introduction

In conventional hierarchical optical cross-connect architectures [4-1]-[4-9], the switch scale of optical cross-connects required for switching waveband paths can be very small [4-10][4-11], and that for wavelength path cross-connects is dominant. As discussed in Chapter 3, the WXC size is determined by the necessary waveband add/drop ratio of the node, the ratio of number of added/dropped waveband paths to that of outgoing/incoming waveband paths, and therefore bounding the waveband add/drop ratio is the direct way of effectively reducing the WXC portion. Our proposed network design algorithms that consider colored/colorless waveband add/drop ratio restrictions reveal that even if the add/drop ratio is held to a small value, say 0.3, the increase in required network resources such as optical switch ports and fibers can be very small.

Another possible approach to reducing the switch size of HOXCs and realizing HOXCs with current technologies is utilizing electrical switches for handling wavelength paths. Subsequent works confirmed the effectiveness of hybrid hierarchical optical path networks that incorporate both optical cross-connects for higher order optical paths, waveband paths, and electrical cross-connects (EXCs) for lower order optical paths, wavelength paths [4-12]-[4-15]; the key is suppressing the electrical cross-connect portion. Although photonic switching technology offer

various advantages in terms of large throughput, and bit rate and protocol independence, electrical switching technology still offers notable advantages including wavelength conversion, 3R regeneration functions, and maturity of available commercial technologies used in creating SDH/SONET and OTN cross-connects. Utilizing electrical switches can also naturally provide wavelength conversion and 3R regeneration functions due to the necessity of using OE/EO converters at the inputs and outputs of the electrical switching matrices. Studies in [4-4][4-11] thus proposed hybrid-hierarchical optical cross-connect (hybrid-HOXC) architectures in which the optical wavelength cross-connect is entirely replaced by an electrical one or an electrical TDM switch at wavelength speeds. As a result, the required electrical switch scale must be as large as that of the wavelength cross-connect. However, since such relatively large electrical switches are costly and consume huge amounts of electrical power, their implementation should be limited. As will be discussed in Section 4.2, we divided the wavelength cross-connect layer into two functionally dedicated parts, and the electrical switch is only used for one part, which greatly reduces necessary electrical switch scale.

On the other hand, the optical path network design problem, minimizing the given network cost function, is known to be NP-complete even for single layer optical path networks due to the difficulties of solving the RWA (Routing and Wavelength Assignment) problem. In the hierarchical optical path network design, in addition to the difficulty of single-layer ones, we must deal with the establishment of waveband paths, which includes the selection of source/destination of waveband paths, and routing and waveband assignment. Optimal selection of ingress/egress nodes of waveband paths is of critical importance and very difficult to attain. These obstacles make network design much more difficult because the placement of waveband paths heavily impacts not only the routing efficiency of each wavelength path but also the number of required switch ports. As a result, cost-efficient implementation of waveband switching strongly depends on the network design algorithm applied [4-1][4-2]. Despite being able to obtain the optimal solution, conventional integer linear programming (ILP) approaches can be, in practice, applied only to very small networks due to their extremely high computational complexity. Heuristic approaches that can only provide sub-optimal solutions are applicable to large optical WDM networks.

In this chapter, to take advantage of electrical switches while carefully restricting the usage of expensive and power consuming OEs/EOs (or electrical switch ports), we have proposed a hybrid-hierarchical optical cross-connect architecture that separates the wavelength adding/dropping and grooming functions at the WXC layer and utilize small scale EXCs only for intermediate grooming of wavelength paths, which significantly reduces switch scale. The proposed hybrid-HOXC consists of an optical waveband cross-connect (BXC) for adding/dropping or routing large granular optical paths and an electrical cross-connect that is used only for intermediate grooming of wavelength paths. The architecture exploits the large throughput of the BXC while wavelength path grooming is accompanied by the 3R and wavelength conversion capabilities of the EXC at intermediate nodes. Sub-wavelength path level grooming is possible with the electrical cross-connect if necessary, but this lies outside the

scope of this work.

We, then, have developed network design algorithms for the proposed hybrid hierarchical optical path networks. To obtain the optimal solution, we newly introduced an integer linear programming model for the hybrid hierarchical optical path networks. Since the optimal ILP model can be solved for very small problem size (i.e. network size) only, we have proposed a more advanced heuristic 2-stage ILP optimization based design algorithm in order to make it applicable for larger hybrid-hierarchical optical path networks and to achieve good sub-optimal solutions. The proposed heuristic 2-stage ILP based algorithm divides the network design problem, subject to the goal of cost minimization, into 2 sub-problems and applies ILP formulations to solve each of them. Numerical results prove that the proposed algorithm can achieve near optimal cost and offer better cost reduction than conventional algorithms. We also extensively evaluate the impact of electrical/optical port cost ratios and waveband capacity on the total network cost, which are the most important parameters that determine the effectiveness of the proposed hybrid-HOXC architecture.

However, because the ILP optimization based approaches are still not applicable for designing large optical path networks due to the huge computational complexity requirements, we have developed a heuristic network design algorithm employing the neighbor source and destination grouping method for grooming wavelength paths. Efficiency of the proposed algorithm is verified through numerical experiments. The effects of important network parameters including network size, the electrical switch port cost and waveband capacity on the total network cost are investigated. The results show that the hybrid-HOXC based networks are especially effective for larger networks, as cheaper EXC port cost and in a wide range of the traffic demand. Moreover, depending on the given traffic demands in the network, selection of a suitable waveband granularity plays an important role to gain better cost reduction.

4.2 Hybrid hierarchical optical path network

4.2.1 Proposal of hybrid-hierarchical optical cross-connect

In order to realize the hierarchical optical cross-connects with current practical optical technologies, we have proposed a hybrid-HOXC architecture as shown in Figure 4-1. Different from conventional HOXC architectures [4-3]-[4-7], the large WXC part is divided into 2 separate parts for dedicated adding/dropping and grooming functions. The wavelength path added/dropped operations can be done with optical supplemental devices (i.e. WSSs) or they can be integrated into the switch portions required for attaining colorless/directionless capabilities (as in a single layer OXC). These issues are not discussed herein. The grooming part utilizes a flexible electrical switch with wavelength granularity, that is, an OTN electrical cross-connect (EXC) or simple electrical space switches. Hence, the hybrid-HOXC consists of 2 layer switching fabrics. One is a waveband cross-connect (BXC) that is capable of switching waveband paths in the optical domain. The other is an electrical cross-connect for grooming wavelength paths, and wavelength conversion and/or 3R functions required to rectify

accumulated optical impairments. In order to minimize cost and power consumption, the electrical cross-connect is only used to perform processing of lower-order optical paths, wavelength paths, to improve the utilization efficiency of high-order optical paths, wavebands, while the optical parts transfer most of the through traffic.

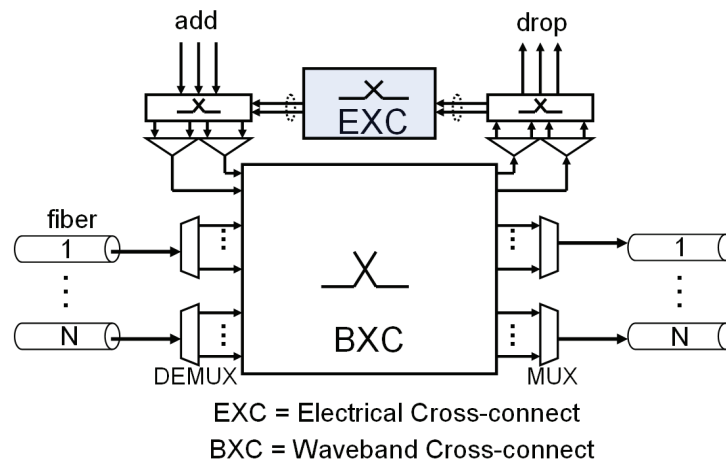


Figure 4-1. Proposed hybrid-hierarchical optical cross-connect

4.2.2 Hybrid hierarchical optical path network

In hybrid-hierarchical optical path networks which are hierarchical optical path networks utilizing the proposed hybrid-hierarchical optical cross-connects, waveband paths are added or dropped to/from the BXC at their originating/terminating nodes, and only wavelength paths that need to be groomed from the dropped waveband paths are routed to the EXCs of intermediate nodes, regenerated and/or converted into a new wavelength index if necessary, and then aggregated into their required outgoing waveband path. On the other hand, other added/dropped wavelength paths do not pass through the EXC, and bypass-waveband paths are switched only at the BXC layer. The basic operations of the hybrid hierarchical optical path networks is illustrated in Figure 4-2.

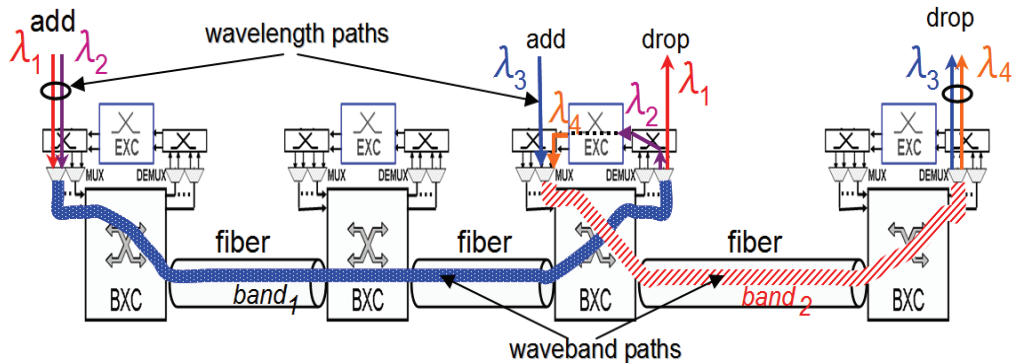


Figure 4-2. Combination of grooming and regenerating wavelength paths

4.3 Hybrid-hierarchical optical path network design problem

4.3.1 Network cost model

Similar to that of conventional hierarchical optical path networks, the total network cost of hybrid hierarchical optical path networks is calculated as the sum of total node cost and total link cost. The total node cost is evaluated by the sum of the cost of EXC ports required for grooming wavelength paths and that of BXC ports for originating/terminating and routing waveband paths, while the total link cost is the cost of all established fibers and amplifiers. In the hybrid-hierarchical optical path network, a grooming wavelength path requires 2 EXC ports and each waveband path needs a UNI port at each BXC of the originating/terminating nodes and 2 BXC NNI ports for each link that it passes through (see Figure 4-3). The node cost and link cost functions are expressed as follows by using the given parameters and variables listed in Table 4-1. The functions also include constants that represent the costs of control systems and other overhead costs. Specific cost values used for the calculations are those up-dated from values given in [4-10].

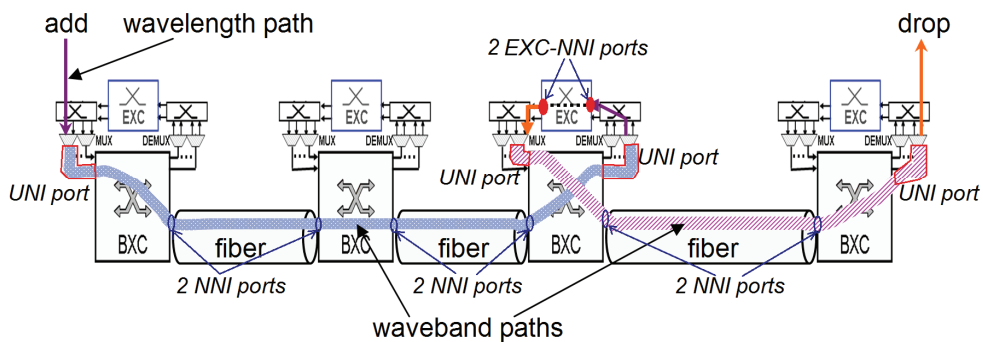


Figure 4-3. Cost model of the hybrid hierarchical optical path network

Node cost:

$$C_{Node} = \sum_{i=1}^N \{C_{BXC} + C_{BXC_NNI} \times BXC_NNI_i + C_{BXC_UNI} \times BXC_UNI_i + \gamma_i C_{EXC} + C_{EXC_NNI} \times EXC_NNI_i\} \quad (4-1)$$

where BXC_UNI_i , BXC_NNI_i and EXC_NNI_i are respectively the numbers of required BXC UNI ports, BXC NNI ports and EXC ports of node i ; and $\gamma_i = 1$ iff $EXC_NNI_i > 0$ else $\gamma_i = 0$.

Link cost:

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

where F_{ij} is the total number of fibers required on the link connecting node i and node j , and $C_{fiber}(i, j)$ is the cost of a fiber on the link (i, j) . $C_{fiber}(i, j)$ is given by,

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

Table 4-1. Parameters for cost evaluation

Name	Description	Value
C_{BXC_NNI}	BXC NNI (network node interface) port cost per waveband	1
C_{BXC_UNI}	BXC UNI (User Network Interface) port cost per waveband	1.2
C_{BXC}	BXC switch base cost	4
C_{EXC_NNI}	EXC port cost per wavelength	1
C_{EXC}	EXC switch base cost	4
C_F	Optical fiber cost per km	0.012
C_{AMP}	Amplifier cost	2.04
D_{AMP}	Amplifier span	60
Network parameters		
N	Number of nodes in the network	
B	Maximum number of wavebands per fiber	
W	Maximum number of wavelengths per waveband	
D_{ij}	Distance between node i and node j ; $D_{ij}=0$ for node pair (i, j) that is not physically adjacent to each other.	

4.3.2 Problem statement

A given hybrid-HOXC-based WDM mesh network of N nodes is modeled as directed graph

$G=G(V, A)$ in which V is the set of all nodes ($|V|=N$) and A is the set of all physical links ($|A|=L$) in the network. Each node is labeled by a number n , where $1 \leq n \leq N$. Link (i, j) connects node i to node j . Fibers are established only on the links and each link can consist of multiple fibers. The fiber and waveband capacity are fixed as constants in the network. The traffic demand represented as the number of wavelength paths requested between node pairs is given in advance. The problem is to route and assign all given traffic demands so as to minimize network resource requirements. In this paper, the objective of the design problem is to minimize the total network cost.

In order to minimize the total network cost of the hybrid-hierarchical optical path network, design strategies that maximally reduce both node cost and link cost are required. In fact, the node cost of the hybrid-hierarchical optical path network, which is dominated by the number of optical/electrical switch ports required, can be reduced by encouraging pass-through at the waveband path level and eliminating waveband grooming operations at the EXCs. On the contrary, although costly OE/EO and electrical switching ports must be used, EXC layer operations can help to increase the network resource utilization efficiency, and hence, reduce the link cost. Therefore, a tradeoff exists between the link cost and the node cost.

4.4 ILP model for hybrid hierarchical optical path networks

This section formulates the hybrid-hierarchical optical path network using the source flow ILP formulations that consider all the requests originating from a single source node as a single commodity [4-16][4-17].

A. Notations

- ✧ The physical topology is modeled by graph $G=G(V, A)$ where V is the set of nodes ($|V|=N$) and A is the set of physical links ($|A|=L$) in the network;
- ✧ D : Traffic demand matrix whose element d_{ij} is the number of wavelength paths requested between the node pair (i, j) ;
- ✧ B : Fiber capacity represented by the number of wavebands per fiber;
- ✧ W : Waveband capacity in terms of the number of wavelength paths per waveband;
- ✧ O_i / I_i are the sets of “unidirectional links” having node i as one extreme and that exit/enter the node.

B. ILP Variables

- ✧ $w_{l,k}^s$ is the number of wavelength paths between node pair (l, k) that have been allocated to the wavelength paths generated at node s ;
- ✧ $wb_{b,l,k}$ is the total number of waveband paths required between node pair (l, k) with waveband index b ;

- ✧ $b_{b,l,k}^s$ is the number of waveband paths on link (l, k) which have been allocated to waveband paths generated at node s on waveband index b ;
- ✧ $F_{l,k}$ is the number of fibers required on link (l, k) ;

C. Objective Function

The objective of network design is, subject to the fixed traffic demand, to minimize the total network cost, which can be formulated as:

$$\text{Min} \left\{ \sum_{s \in V} \sum_{l, k \in V; l \neq s, k \neq d} w_{l,k}^s \times 2C_{EXC_NNI} + \sum_{l, k \in V} \sum_{b=1}^B w b_{b,l,k} \times 2C_{BXC_UNI} \right. \quad (4-4)$$

$$\left. + \sum_{s \in V} \sum_{(l,k) \in A} \sum_{b=1}^B b_{b,l,k}^s \times 2C_{BXC_NNI} + \sum_{(l,k) \in A} F_{l,k} \times C_{fiber}(l,k) \right\}$$

D. Constraints

The set of constraints is the following:

$$\sum_{k \in V} w_{s,k}^s = \sum_{i \in V} d_{s,i} \quad \forall s \in V \quad (4-5)$$

$$\sum_{k \in V} w_{j,k}^s = \sum_{k \in V} w_{k,j}^s - d_{s,j} \quad \forall j, s \in V; j \neq s \quad (4-6)$$

$$\sum_{s \in V} w_{l,k}^s \leq W \times \sum_{b=1}^B w b_{b,l,k} \quad \forall l, k \in V; l \neq k \quad (4-7)$$

$$\sum_{(l,k) \in O_s} b_{b,l,k}^s = \sum_{d \in V} w b_{b,s,d} \quad \forall s \in V; \forall b = 1..B \quad (4-8)$$

$$\sum_{(l,k) \in O_j} b_{b,l,k}^s = \sum_{(l,k) \in I_j} b_{b,l,k}^s - w b_{b,s,j} \quad \forall j, s \in V; j \neq s; \forall b = 1..B \quad (4-9)$$

$$\sum_{s \in V} b_{b,l,k}^s \leq F_{l,k} \quad \forall (l,k) \in A; \forall b = 1..B \quad (4-10)$$

Constraints (4-5) and (4-6) are solenoidality constraints for the wavelength layer. Due to the wavelength conversion capability, the wavelength continuity constraint is ignored in the wavelength layer of the network. As a result, the wavelength index is not taken into account in the wavelength flow variables. Constraint (4-5) states that the total traffic flow (in terms of number of wavelength paths) generated by source node s and exiting from it must be equal to the sum of the traffic demands requested by node s as a source. Constraint (4-6) expresses the flow conservation condition, regardless of the wavelength index, for each node (except source node s) in which the total wavelength flow generated by s and leaving node j is given by the

total wavelength flow generated by s and incident on j minus the number of the traffic demands requested between node pair (s, j) . Capacity constraint (4-7) represents the restriction on the waveband capacity in which between each node pair (l, k) , total traffic flow of all sources in the network must be less than or equal to the total capacity of all wavebands established between the node pair.

Similarly to constraints (4-5) and (4-6) in the wavelength layer, constraints (4-8) and (4-9) are the solenoidality constraints for the waveband layer of the network. Constraint (4-9) is also the flow conservation constraint of the waveband flows. However, because no waveband conversion is available here, those constraints are applied for each waveband index to maintain waveband continuity.

Finally, in order to ensure a feasible resource allocation, capacity constraint (4-10) states that on each link the sum of waveband flows generated by all nodes does not exceed the product of number of fibers and the fiber capacity in terms of wavebands.

4.5 Network design algorithm based on 2-stage ILP optimization

4.5.1 Proposed algorithm

In this section, we describe the 2-stage ILP optimization based heuristic algorithm developed for hierarchical optical path networks with proposed hybrid-hierarchical optical cross-connects. Our approach divides the network design problem into two design stages according to the 2 network layers. The first stage is for grooming, routing, and wavelength assignment in the wavelength layer (the EXC layer); the second involves waveband routing and waveband index assignment and fiber establishment and so is related to the BXC layer. In each stage, the design task considers the layer as a single layer optical path network in which optical paths are wavelength/waveband paths for the wavelength/waveband layer, respectively, and employs the corresponding node-link ILP formulation approach, which yields optimization with less computational effort than other ILP approaches. The use of EXCs can provide wavelength conversion capability; no waveband conversion is available in the optical BXC layer. As a result, in the first stage, the node-link ILP formulations that minimize the total cost of grooming wavelength paths into waveband paths should be implemented. Here, on the wavelength path layer of the network, virtual wavelength paths which can have a different wavelength index on each distinct fiber along their routes are available, thus the design task is covers the full mesh network whose node pairs are linked by directional waveband links whose weight is cost of the end-to-end shortest waveband paths connecting the nodes. In the second stage, the objective is minimization of the total cost of the BXC ports and fibers needed to accommodate all required waveband paths and the node-link formulations are applied for the single waveband path network without waveband conversion where waveband path continuity constraints are set to guarantee that each waveband path has a fixed waveband index associated with it.

The proposed algorithm and the mathematical ILP formulations are summarized as follows:

<2-stage ILP Optimization based Design Algorithm>

Step 1: Grooming wavelength paths

a) Create a virtual full mesh waveband graph of the given network:

- Let G^{Band} be the original topology G with modified weight w^{Band} of the arc $a^{Band}(v_i, v_j)$: $w^{Band}(v_i, v_j): V^2 \rightarrow R_+$, where R_+ is set of all non-negative real numbers, which is calculated by,

$$w^{Band}(v_i, v_j) = \begin{cases} 2C_{BXC-NNI} + \frac{C_{fiber}(v_i, v_j)}{B} & \text{if there is a physical link connecting } v_i \text{ and } v_j \\ \infty & \text{otherwise} \end{cases} \quad (4-11)$$

where $C_{fiber}(v_i, v_j)$ is the cost of a fiber connecting v_i and v_j ; $2C_{BXC-NNI}$ represents the cost of 2 BXC NNI ports required for switching the waveband path at both ends of the physical link (v_i, v_j) .

- Based on graph G^{Band} , for each node pair (v_i, v_j) , calculate cost $w_b(v_i, v_j)$ of the shortest path from v_i to v_j .

- Define a full mesh waveband path network $G_b(V, A_b)$ in which each arc $a_b(v_i, v_j)$ is weighted by the value of $w_b(v_i, v_j)$.

b) On the full mesh network $G_b(V, A_b)$, apply the node-link ILP formulations for the single layer network with wavelength conversion capability to minimize the cost of grooming wavelength paths into waveband paths which is represented by total cost of EXC switch ports and wavebands required to accommodate all given traffic demands. The ILP formulations are shown as follows:

Input

- ✓ The full mesh network $G_b(V, A_b)$ with N nodes;
- ✓ The traffic demand requested between node i and node j is $d_{i,j}$. The total number of requested wavelength paths having source node i is denoted by WS_i ($WS_i = \sum_{j \in V} d_{i,j}$);
- ✓ Waveband capacity is W wavelengths.

Integer variables

- $w_{l,k}^s$ is the sum of wavelength paths originating from source node s and carried by link (l, k) ;
- $B_{l,k}$ is the total number of waveband paths required on link (l, k) .

Objective

$$\text{Min} \left\{ \sum_{s,l,k \in V} w_{l,k}^s \times 2C_{EXC-NNI} + \sum_{(l,k) \in A_b} B_{l,k} \times (2C_{BXC-UNI} + w_b(l,k)) \right\} \quad (4-12)$$

Constraints

$$\sum_{(l,k) \in O_s} w_{l,k}^s = WS_s \quad \forall s \in V \quad (4-13)$$

$$\sum_{(l,k) \in O_j} w_{l,k}^s = \sum_{(l,k) \in I_j} w_{l,k}^s - d_{s,j} \quad \forall j, s \in V; j \neq s \quad (4-14)$$

$$\sum_{s \in V} w_{l,k}^s \leq W \times B_{l,k} \quad \forall (l,k) \in A_b; k \neq s \quad (4-15)$$

Constraint (4-13) implies that sum of the wavelength flows that originate from source node s must be equal to the total traffic demands requested by node s . Constraint (4-14) ensures that the wavelength flow conservation conditions are satisfied regardless of the wavelength indexes. Moreover, the waveband capacity constraint, (4-15), is required to make sure that the total number of wavelength flows on each link must be smaller than or equal to the product of the waveband capacity and the number of wavebands established on that link.

Step 2: RWA of waveband paths and fiber setup

Input

- ✓ Network $G(V, A)$ with N nodes;
- ✓ The number of waveband paths requested between each node pair (i, j) is $B_{i,j}$ (results of Step 1).
- ✓ Fiber capacity is B wavebands.

Integer variables

- B_b^s is the total number of waveband paths requested by source node s on waveband index b ;

- $wb_{b,l,k}$ is the total number of waveband paths required between node pair (l, k) in waveband index b ;
- $b_{b,l,k}^s$ is the number of waveband paths on link (l, k) which have been allocated to carry waveband paths generated at node s on waveband index b ;
- $F_{l,k}$ is the number of fibers required on link (l, k) .

Objective

$$\text{Min} \left\{ \sum_{s,l,k \in V} \sum_{b=1}^B b_{b,l,k}^s \times 2C_{BXC-NNI} + \sum_{(l,k) \in A} F_{l,k} \times C_{fiber}(l,k) \right\} \quad (4-16)$$

Constraints

$$\sum_{b=1}^B B_b^s = \sum_{d \in V} B_{s,d} \quad \forall s \in V \quad (4-17)$$

$$\sum_{b=1}^B wb_{b,s,d} = B_{s,d} \quad \forall s, d \in V; s \neq d \quad (4-18)$$

$$\sum_{(l,k) \in O_s} b_{b,l,k}^s = B_b^s \quad \forall s \in V; \forall b = 1, \dots, B \quad (4-19)$$

$$\sum_{(l,k) \in O_j} b_{b,l,k}^s = \sum_{(l,k) \in I_j} b_{b,l,k}^s - wb_{b,s,j} \quad \forall j, s \in V; j \neq s; \forall b = 1, \dots, B; \quad (4-20)$$

$$\sum_{s \in V} b_{b,l,k}^s \leq F_{l,k} \quad \forall (l,k) \in A; \forall b = 1, \dots, B \quad (4-21)$$

In this stage, the solenoidality constraints are split into sets (4-17) and (4-19) in order to impose waveband flow conservation independently on each waveband index. Constraint (4-17) states that the sum of the waveband flows originated from source node s in all waveband indexes must be equal to the total number of waveband paths requested from node s . Constraint (4-18) implies that, between each node pair, the total number of waveband paths established in all waveband indexes must be the number of wavebands requested by the node pair. On the other hand, constraint (4-19) ensures that, on every waveband index, the sum of waveband paths generated from source node s is equal to the total number of waveband paths requested by that node. The waveband flow conservation constraint, then, is shown in (4-20). Finally, the capacity constraint, (4-21), is also

considered for each waveband index b .

4.5.2 Performance evaluation

In this section, we employ numerical simulations to investigate the performance of the proposed network design algorithm based on the 2-layer ILP approach. We first analyze the efficiency of the proposed algorithm in comparison with the optimal design approach that uses the ILP model for small networks. For larger networks such as Japan’s optical network and the pan-European optical network, the superiority of the hybrid-hierarchical optical path networks over the single layer optical path networks in terms of network cost efficiency is verified. We also compare the proposed algorithm with the non-grooming (end-to-end) algorithm [4-14] and the efficient conventional design algorithm for hierarchical optical path networks given in [4-10]. In the numerical experiments, the specific cost values, including the costs of BXC UNI and NNI ports, used in the calculations are those in [4-10] (see Section 4.2), and the ratio of the cost of an electrical switch port to that of an optical switch port is set as a parameter β ($\beta = C_{EXC-NNI} / C_{BXC-NNI}$). Finally, the waveband/fiber utilization ratios in the network and the impact of the waveband capacity are also investigated.

A. Comparison with the optimal solution

We applied the ILP model to find the optimal solution and the proposed 2-stage ILP optimization based algorithm (called 2-layer ILP) for a 2x3 regular mesh network consisting of 6 nodes and 7 links. The network size is due to the size limitation of the ILP model. The traffic demand is generated randomly and represented by average number of wavelengths requested between node pairs while β is fixed at 5. Each fiber has a capacity of 16 ($B \times W = 16$) wavelengths and the waveband capacity is set at 4 ($W = 4$). The simulation results are given in Table 4-2. From the table, we see that the performance of our proposed algorithm is very close to that of the ILP model. The differences between the cost offered by the proposed algorithm and the optimal one are very small; less than 2.2 % when traffic demand is larger than 2.

Table 4-2. Total network cost comparison

Algorithm	Traffic demand							
	1	2	3	4	5	6	7	8
<i>The optimal</i>	316.88	443.12	533.04	695.52	756.48	858.16	997.6	1098.08
<i>2-layer ILP</i>	342.48	450.72	538.88	698.96	770.4	865.76	1004.72	1122
<i>Relative ratio</i> <i>((2-layer-Optimal)/ Optimal)</i>	8.08%	1.72%	1.1%	0.49%	1.84%	0.89%	0.71%	2.18%

B. Heuristic algorithm performance analysis

1) Network cost evaluation

In this part, the numerical evaluation addressed the COST266 Pan-European optical network that consists of 26 nodes and 51 links, and Japan’s optical network with 18 nodes and 30 links. Randomly distributed traffic demands are applied, where each wavelength path demand between any node pair is assigned with equal probability; they are represented as the average number of wavelength paths requested between each node pair. We also assume that the waveband capacity is set at 8 (wavelengths) ($W=8$) and each fiber can accommodate up to 64 wavelengths ($B \times W=64$). The obtained costs, then, are normalized by that for the comparable single layer optical path network that employs corresponding single layer optical path cross-connects [4-18]. The network costs are evaluated with 20 different traffic patterns for each average traffic demand between node pairs, and their ensemble averages are plotted.

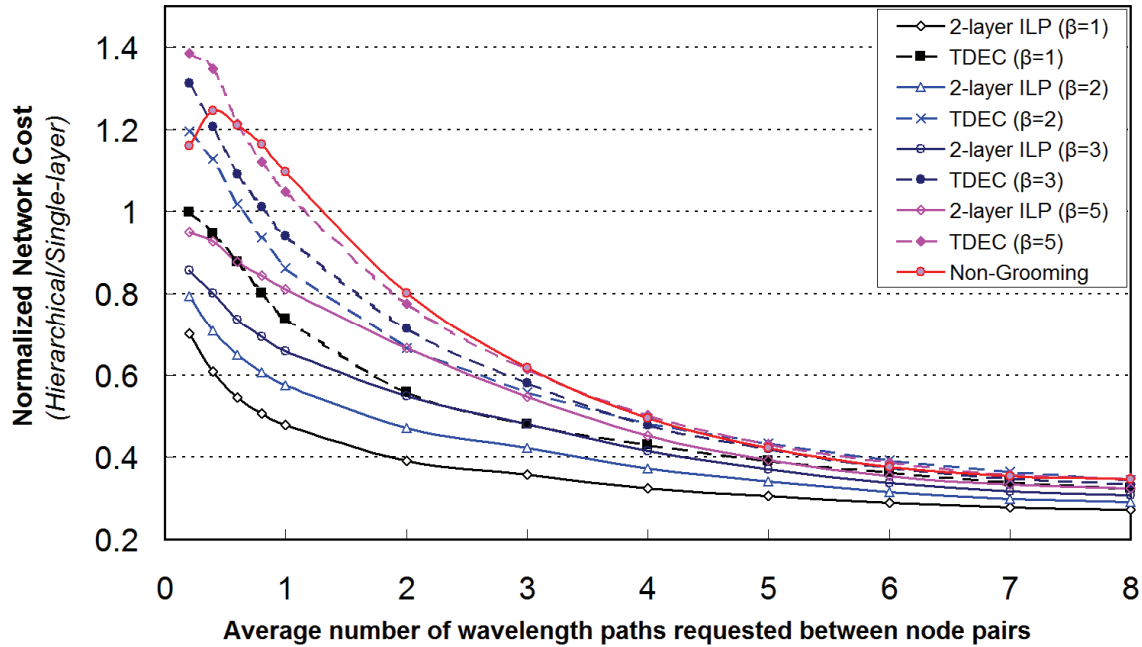


Figure 4-4. COST266 network cost versus traffic demand

Figures 4-4 and 4-5 illustrate the network costs obtained by the proposed algorithm for COST266 and Japan’s optical network, respectively, where the average traffic demand between node pairs is changed. The costs are compared to those achieved by the algorithm that is based on the Traffic Demand Expression in a Cartesian product space (TDEC) [4-10], which is known to be one of the most efficient heuristic algorithms, and the end-to-end algorithm (Non-Grooming), which accommodates wavelength paths with the same source and destination nodes; i.e. wavelength paths are not groomed at intermediate nodes (please refer to [4-10] or [4-14] for details). The results demonstrate that the hybrid-hierarchical optical path network cost is strongly dependent

on the network design algorithm employed and applying hybrid-hierarchical optical path networks can reduce the network cost comparing to corresponding single-layer optical path networks (normalized costs are less than 1). This cost reduction depends on both the traffic demand and EXC port cost ratio, β , and increases as the traffic demand increases or β decreases. Our proposed algorithm outperforms the conventional algorithms (TDEC and Non-Grooming) and always offers the best cost reduction for all traffic demands and values of β ($\beta=1$ to 5).

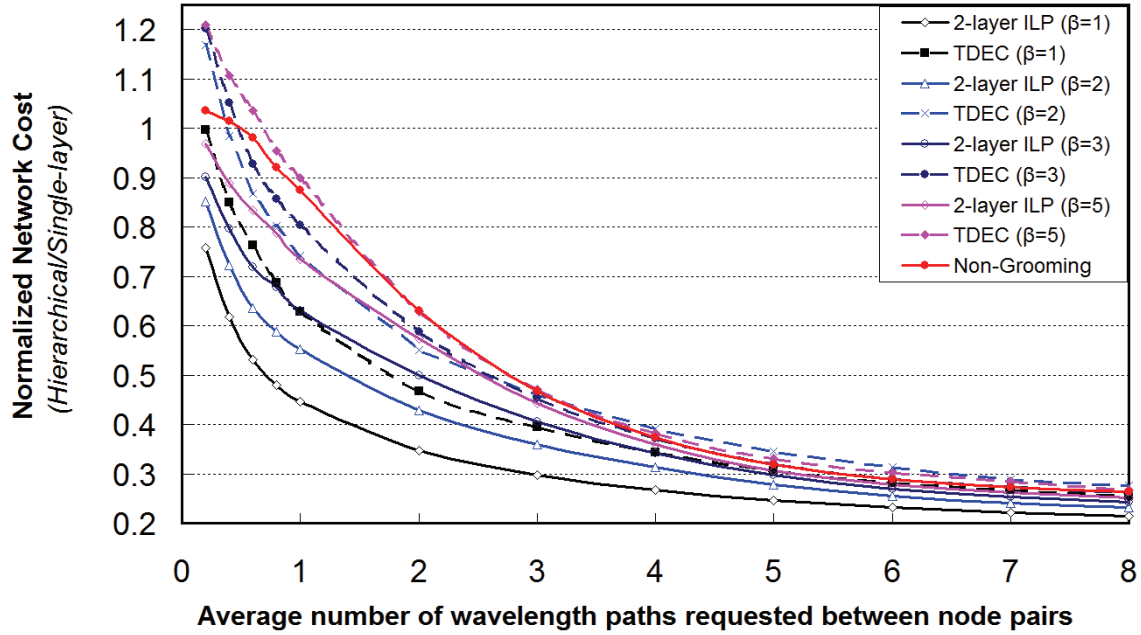
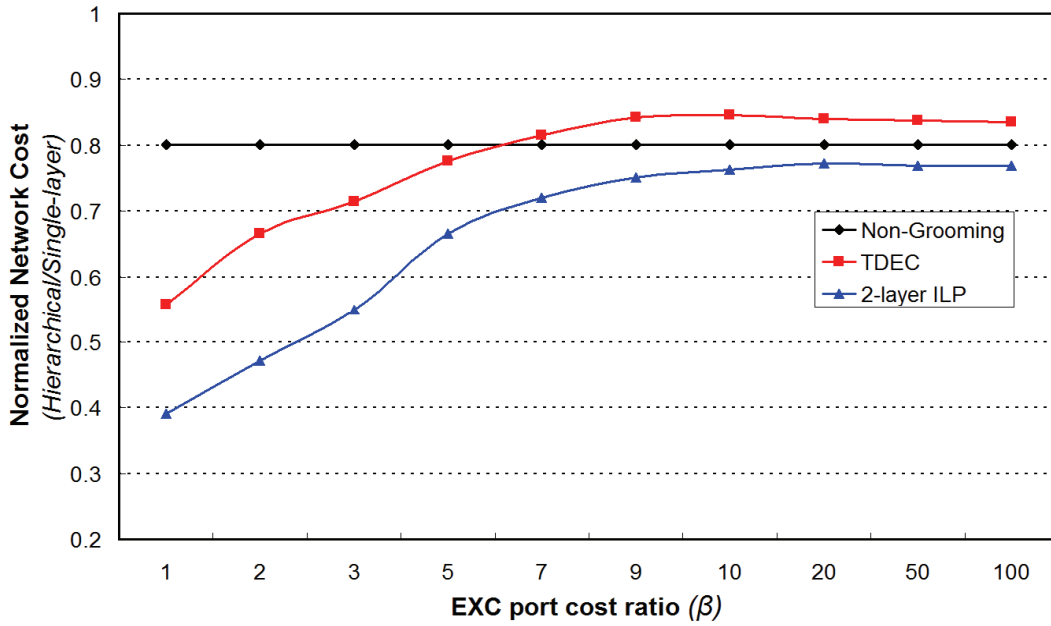


Figure 4-5. Japan's optical network cost versus traffic demand

Moreover, the impact of the EXC port cost ratio, β , on the total network cost for the COST266 network with the average traffic demand between node pairs of 2 is described in Figure 4-6. Because the Non-Grooming algorithm does not groom wavelength paths at intermediate nodes, EXC implementation is not required. As the result, its cost (Non-Grooming) is not affected by the variation of β . For the hybrid-hierarchical optical path network, the network cost increases with β since higher EXC port cost reduces wavelength path grooming. However, even though β is relatively large, say 10, the proposed algorithm still reduces the cost and offers lower cost than the Non-Grooming and TDEC algorithms.

Figure 4-6. Network cost versus parameter β

2) Impact of electrical grooming on utilization ratios

The link utilization efficiency of the hybrid-hierarchical optical path networks is determined by both the waveband and fiber utilization ratios. The fiber utilization ratio (in terms of wavebands) is defined as the ratio of number of used wavebands to the total number of wavebands that can be accommodated in a fiber, while the waveband utilization ratio is the ratio of occupied wavelength number to waveband capacity. Although grooming wavelength paths can help to improve the utilization ratio of waveband paths, grooming operations at the EXC must be considered carefully due to the high cost of EXC ports. Figures 4-7 and 4-8 plot the average utilization ratios of waveband and fiber, respectively, obtained by the proposed algorithm in the COST266 network. Figure 4-7 shows that the average waveband utilization ratio decreases as β increases and is always greater than that of the non-grooming network. That is because, as β reduces, grooming of wavelength paths is encouraged resulting in an enhancement in waveband path utilization. When the EXC port cost becomes too expensive, all grooming operations at the EXCs are limited, therefore, the waveband utilization ratio is reduced towards that of Non-Grooming. Figure 4-8 illustrates that, in large traffic demand areas, the average traffic demand between node pairs is greater than 2, smaller β also offers greater fiber utilization ratio in terms of wavebands.

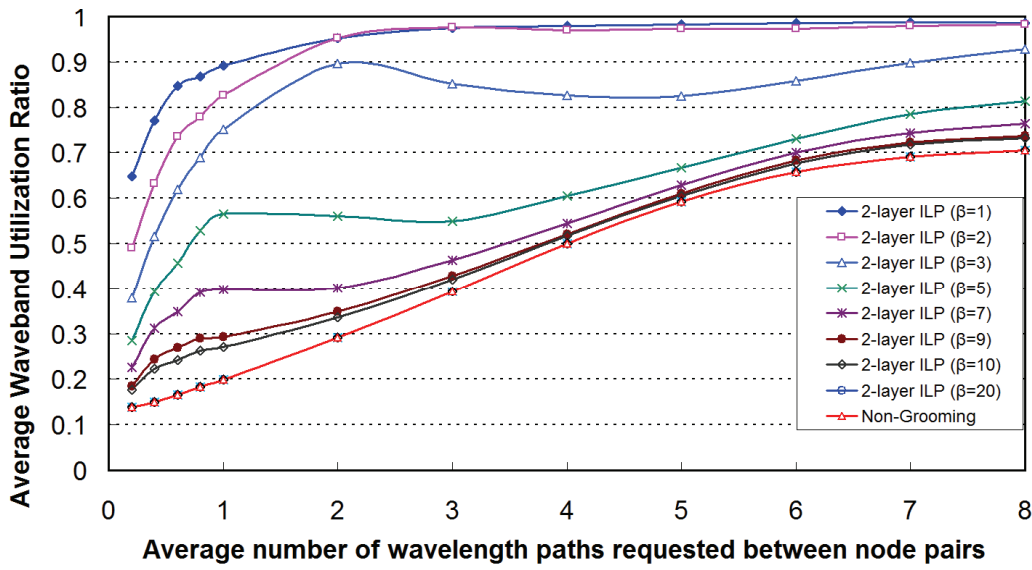


Figure 4-7. Waveband utilization ratio

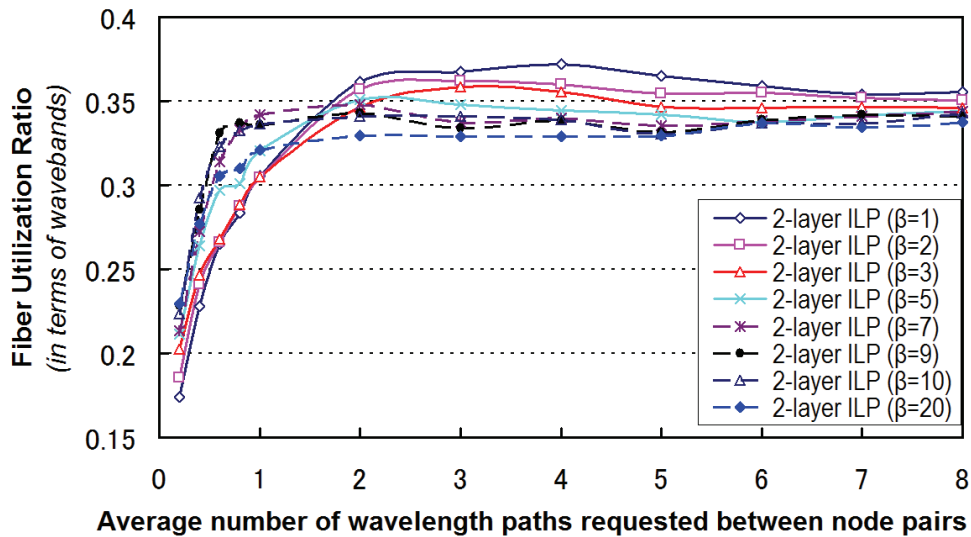


Figure 4-8. Fiber utilization ratio

3) Impact of waveband capacity

In order to examine the effect of waveband capacity selection on total network cost, we change the waveband capacity of the network ($W=2, 4, 8, 16$ and 32) while keeping the fiber capacity as a constant ($B \times W=64$). The total costs of the COST266 network obtained by the proposed algorithm and the Non-Grooming algorithm when the waveband capacity is varied, with different values of β and the traffic demand of 2, are shown in Figure 4-9. The results prove that the waveband capacity value greatly affects the network cost, and the optimal waveband capacity, i.e. that which offers the best cost reduction, depends on EXC port cost and

algorithm adopted. Among the waveband capacity values tested, the optimal waveband capacity of Non-Grooming is 4 while the optimal waveband capacity given by the proposed algorithm varies with β . For example, with $\beta=1$ or 2, the optimal value is 8, however, with other values of β , it is 4, the same as that with Non-Grooming.

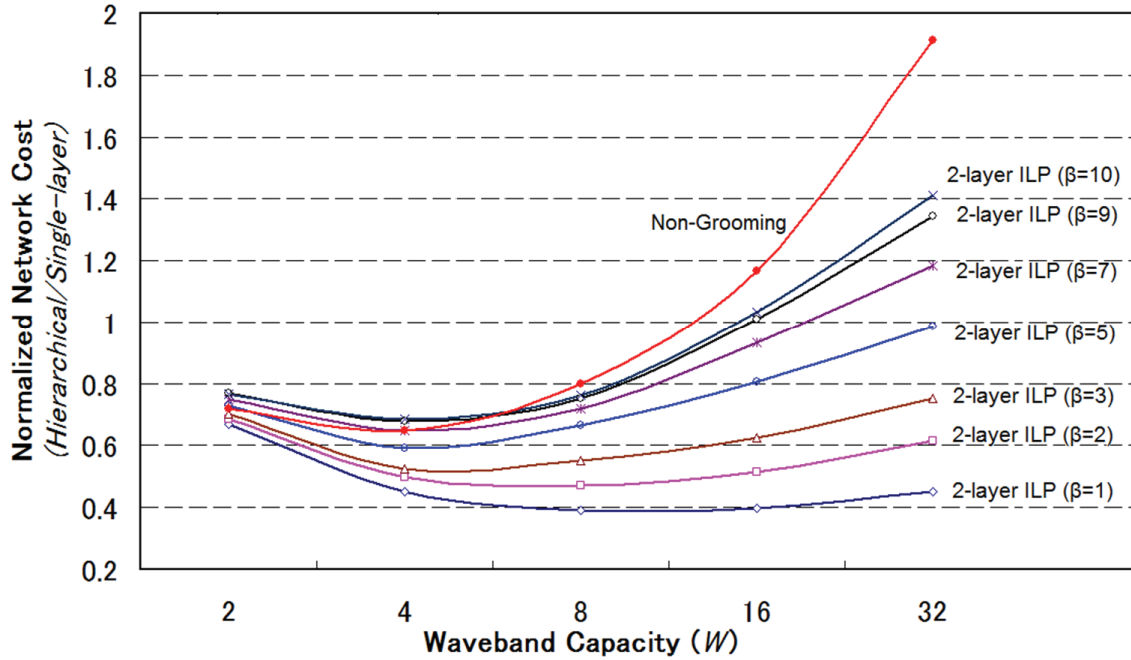


Figure 4-9. Impact of waveband capacity

4.6 Heuristic design algorithm based on neighbor source and destination grouping method

4.6.1 Proposed network design algorithm

In the hybrid-HOXC based optical path networks, taking benefits of introducing waveband, direct passing-through of highly utilized waveband paths can effectively reduce the node cost while waveband grooming should be used to accommodate sparse wavelength paths that can not form wavebands to improve the utilization of waveband paths, to minimize the total network cost while fully utilize the advantages of the hybrid-nodes, we propose a design algorithm, called Neighbor Source-Destination Grouping based algorithm, that employs a waveband grouping method based on grooming wavelength paths having neighbor sources and destinations. The proposed algorithm iteratively searches for a group of the traffic demands (wavelength paths) whose sources and destinations are located nearby, and then establishes a main waveband path connecting the source and destination at the centers. All traffic demands in the group are firstly concentrated to the center source node, then accommodated into the main

waveband path to the center destination node, and finally distributed to their expected destinations. After that step, only few traffic demands in the networks are not satisfied with a sparse distribution. The RWA of these wavelength paths are performed by using a full mesh virtual wavelength graph based on a consideration of the established waveband paths and new end-to-end waveband paths.

Denote X_{wb} ($X_{wb} \in (0,1]$) as a waveband construction threshold for establishing a new waveband path. The procedures of the proposed network design algorithm are summarized as follows:

<Neighbor Source-Destination Grouping based Algorithm>

Step 1- Neighbor source-destination waveband grooming

a) Neighbor source-destination waveband grooming

- In descending order of hop count between source and destination nodes, choose the source and destination pair (s, d) . Search for a set of neighboring source and destination nodes of the selected node pair (s, d) $\nabla \subset V \times V$ subject to

$$W \geq \sum_{(s_i, d_i) \in \nabla} \{\text{number of wavelength paths from } s_i \text{ to } d_i\} \geq X_{wb} W .$$

- If such a set does not exist, go to Step 2.

b) RWA of main waveband paths (s, d)

- Let G_b^{Band} ($1 \leq b \leq B$) be the original topology G with modified weight w_b^{Band} of the arc $a(v_i, v_j)$: $w_b^{Band}(v_i, v_j): V^2 \rightarrow R_+$, where R_+ is all non-negative real numbers, which is calculated by

$$w_b^{Band}(v_i, v_j) = \begin{cases} (1 - f_b \varepsilon) \left\{ 2C_{BXC-NNI} + \frac{C_{fiber}(v_i, v_j)}{B} \right\}; & \text{if there exists } f_b \text{ free wavebands} \\ (1 + \Delta) \left\{ 2C_{BXC-NNI} + \frac{C_{fiber}(v_i, v_j)}{B} \right\}; & \text{otherwise} \end{cases} \quad (4-22)$$

where $C_{BXC-NNI}$ is the NNI port cost at BXC, and $C_{fiber}(v_i, v_j)$ is the cost of a fiber connecting v_i and v_j . Small constants Δ and ε are introduced to encourage using the existing fibers as much as possible while minimizing the hop count. Stack the graphs $\{G_1^{Band}, \dots, G_B^{Band}\}$ and define a multi-layer waveband graph $G^{Band} = \{G_b^{Band} = (V, A_b) | 1 \leq b \leq B\}$.

- Add virtual source and destination nodes (s_v, d_v) which are respectively connected to the original source and destination nodes (s, d) on all layers and find the shortest path from the source to the destination. If more than one path are available, select one randomly.

c) RWA of wavelength paths in the edge parts

- Create a full mesh virtual wavelength graph G^λ of the network based on the established waveband paths with free capacities and new end-to-end waveband routes (see Figure 4-10). The arc weight w^λ of G^λ , where $w^\lambda : V^2 \rightarrow R_+$, is given by

$$w^\lambda(v_i, v_j) = \text{Min}\{C_{\text{existed wb}}(v_i, v_j), C_{e2e\text{-wb}}(v_i, v_j)\} \quad (4-23)$$

, where $C_{e2e\text{-wb}}(v_i, v_j)$ is cost of routing a wavelength by employing a new end-to-end waveband path directly connecting v_i and v_j , and $C_{\text{existed wb}}(v_i, v_j)$ is the cost by using an established waveband path with free capacity between v_i and v_j , is given by

$$C_{\text{existed wb}}(v_i, v_j) = \begin{cases} 2C_{\text{EXC-NNI}}; & \text{if there exists an established} \\ & \text{waveband with free wavelength(s);} \\ \infty & ; \quad \text{otherwise} \end{cases} \quad (4-24)$$

, where $C_{\text{EXC-NNI}}$ be the cost of the electrical switched port of the EXC, so as to encourage the use of existing waveband paths and fibers.

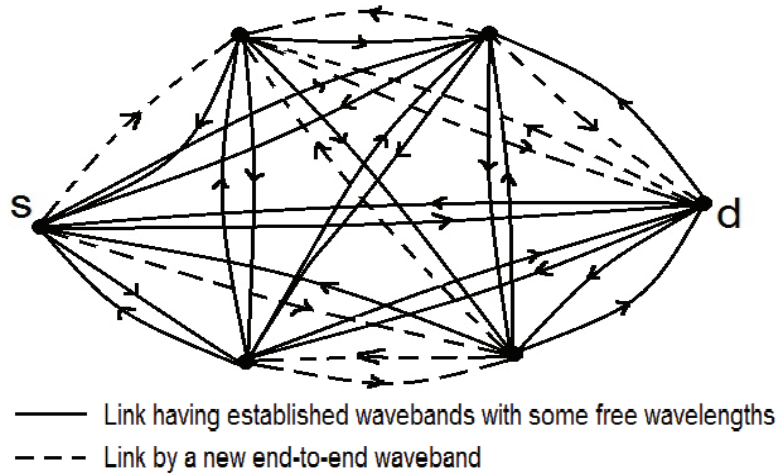


Figure 4-10. Full mesh virtual wavelength graph G^λ

- Routing each wavelength requested in the source edge part and the destination edge part from s_i to s ($s_i \neq s$) or from d to d_i ($d_i \neq d$) by using the shortest path algorithm Dijkstra on the full mesh virtual wavelength graph G^λ .
- Go back to Step 1-a.

Step 2- Grooming Sparse Remaining Wavelengths

- For remaining traffic demands in descending order of the hop count between source and destination nodes, find the shortest path based on the full mesh virtual wavelength graph (see Step 1-c) to route each remaining wavelength path.
- Update the graph and repeat this procedure until all the traffic demands are satisfied.

4.6.2 Numerical experiments

A. Parameter settings

In this section, we have adopted the following parameters for the simulations:

- Physical network topologies: $N \times N$ regular mesh networks ($N=3, 4, 5, 6, 7, 8$ and 9).
- Traffic demand: represented by number of wavelengths requested between node pairs in the network with a uniformly and randomly distribution.
- Capacity of fiber: $B \times W$ wavelengths per fiber; each fiber consists of B wavebands and each waveband includes W wavelengths.
- Parameter β : defined as the ratio of the cost of an electrical switched port to that of an optical switched port ($\beta = C_{EXC-NNI} / C_{BXC-NNI}$).

We applied the proposed algorithm with all possible thresholds $X_{wb} \in \{1/W, 2/W, \dots, W/W\}$; one of the thresholds that minimizes the total network cost is then selected. The obtained total network costs of the hierarchical optical path networks are normalized by those calculated using the corresponding single-layer optical path networks [4-18]. The algorithm was repeated 20 times for each traffic demand sample and each threshold X_{wb} ; then their ensemble averages were plotted. For comparison, we also evaluated the cost of the corresponding networks employing single-layer waveband cross-connects (non-grooming waveband switching nodes).

B. Network cost evaluation

We applied following values: the capacity of fiber is 8 wavebands ($B=8$) and each waveband consists of 8 wavelengths ($W=8$). Figure 4-11 shows the normalized network cost achieved by the proposed algorithm for the 5×5 regular mesh network with respects to the average traffic demand represented by number of wavelengths requested between node pairs. This result shows that the proposed algorithm can offer up to 70% less cost compared to the corresponding single layer optical path network and smaller cost than that given by the non-grooming waveband switching network. The cost reduction becomes greater as the traffic demand increases.

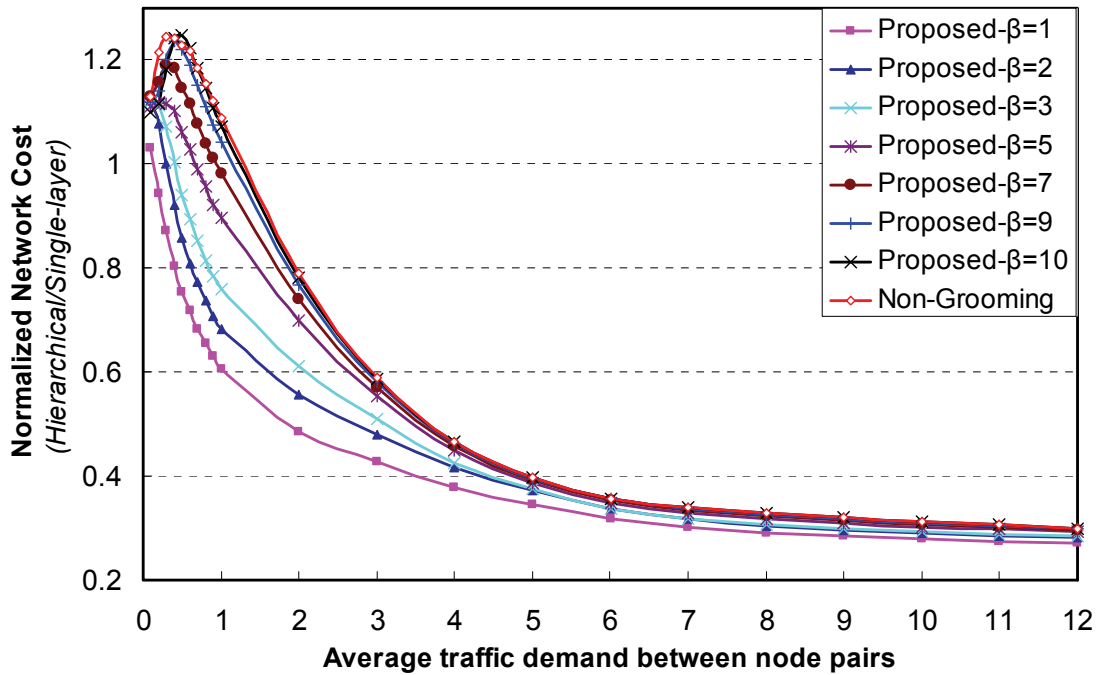


Figure 4-11. 5x5 regular mesh network cost versus traffic demand

Moreover, the obtained network cost depends on the parameter β , better network cost is achieved by smaller β . Figure 4-12 illustrates the effect of the parameter β on the network cost as the average traffic demand between node pairs was fixed at 2. When the value of β is enlarged, the network cost increases to that offered by the non-grooming waveband network. However, even though β is large ($\beta < 15$), the intermediate grooming of wavelength paths by proposed method still reduces the cost function.

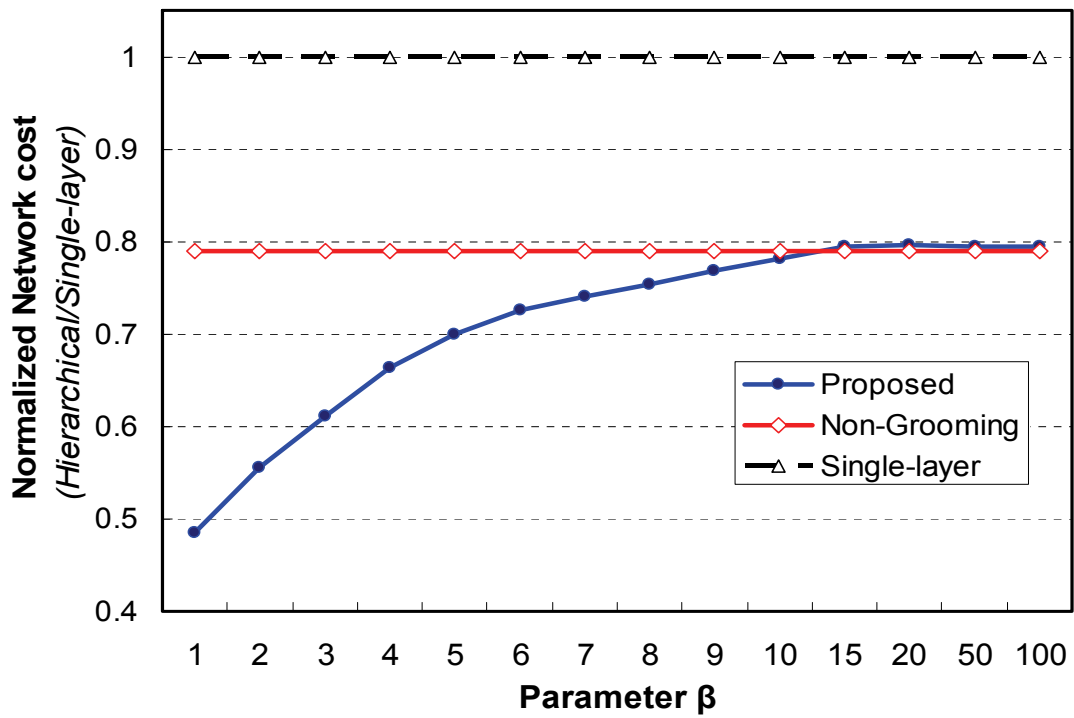


Figure 4-12. Network cost versus parameter β

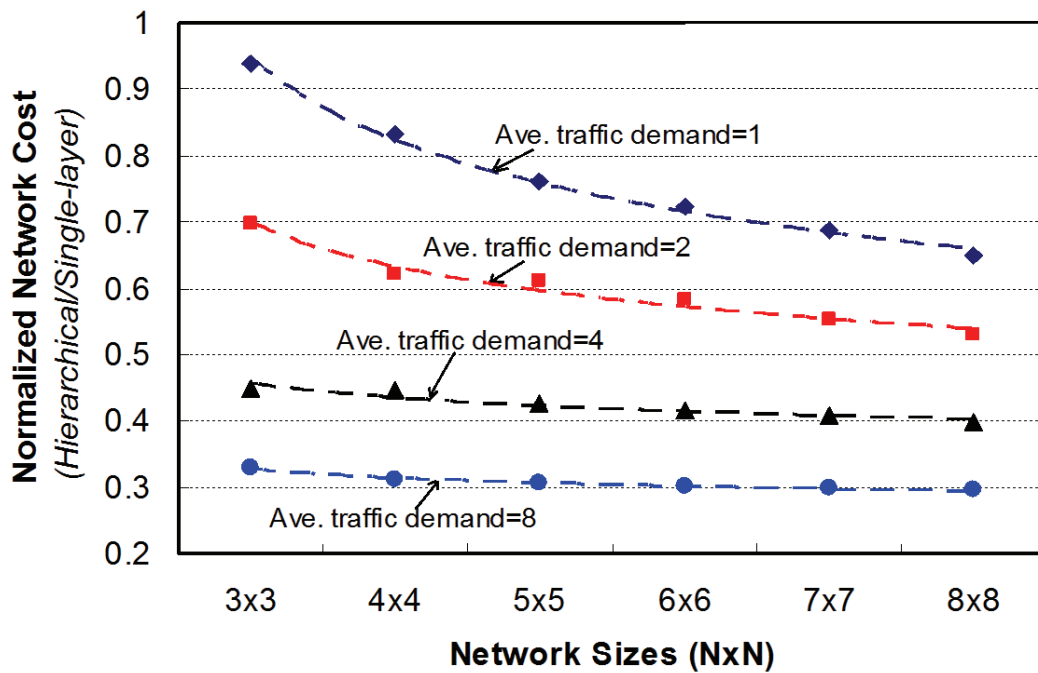


Figure 4-13. Network cost of different size of network topologies

C. Dependence of the network cost on network size

In this part, we studied the dependence of the network cost on network sizes with uniformly and randomly distributed traffic demands while each fiber consists of 8 wavebands ($B=8$) and the waveband capacity is 8 wavelengths ($W=8$), the value of β is set at 5. Figure 4-13 shows the normalized network costs of $N \times N$ regular mesh networks ($N=3, 4, 5, 6, 7$ and 8) when the average traffic demand between each node pair is 1, 2, 4 and 8 respectively. The normalized network cost reduction is improved as the size of networks or the traffic demand becomes large. Because the ratio of the EXC cut-through is strongly related to the average hop count that is determined by the network size while larger traffic demands help improve the utilization efficiency of waveband paths in the networks, both of them play important roles in reducing the total network cost.

D. Effect of selecting waveband capacity

Impacts of the waveband capacity W on the total port count mainly determining total network cost of a hierarchical optical path networks was theoretically and roughly analyzed in Chapter 2. It is shown that the hierarchical optical path networks offer larger cost reduction when W becomes large. In this part, we fixed the fiber capacity in terms of wavelength number as a constant ($B \times W=64$) and the waveband capacity, W , was variable and was set at 2, 4, 8, 16 and 32 respectively. The normalized network costs with $\beta=5$ and $W=2, 4, 8, 16$ and 32, where the average traffic demand between node pairs is changed, are shown in Figure 4-14.

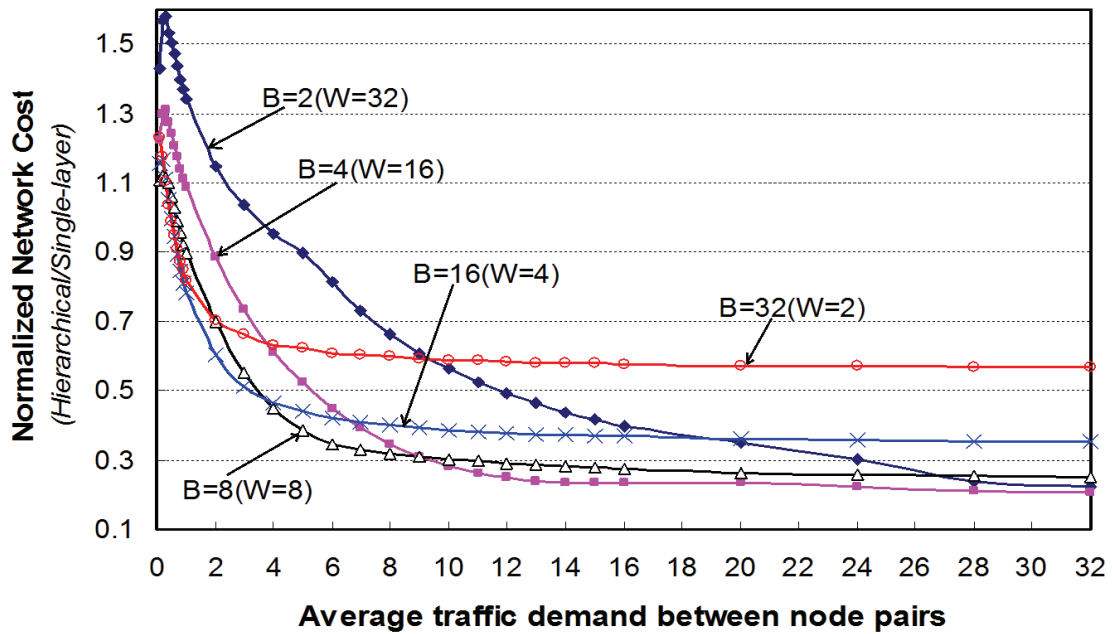


Figure 4-14. Effect of the waveband capacity on the 5x5 regular mesh network cost

Figure 4-14 describes that the smallest capacity $W=2$ only offers smaller network cost reduction for very small traffic region. Because with the fixed fiber capacity, selecting a smaller waveband capacity can help improve the waveband utilization efficiency but may cause increasing the number of waveband paths (waveband ports) necessary to carry the same given traffic demands, and as the result, the total network cost is increased. On the other hand, the largest waveband capacity ($W=32$) reduces the network cost less significantly where the traffic demands are not great enough, because such given traffic cannot fulfill such a huge waveband paths, and therefore reduces the waveband utilization efficiency. For intermediate waveband capacities, while $W=16$ provides the best network cost reduction with traffic demands less than 4, the most effective area of the traffic demands for $W=8$ is from 4 to 9. And the traffic demand is greater than 9, the best cost reduction is achieved by $W=4$. These results prove that the optimal waveband path granularities to gain better cost reduction depend on the given traffic demands in the network.

4.7 Summary

In order to realize HOXCs with current technologies by reducing the switch sizes and taking advantages of electrical switches while carefully restricting the usages of expensive electrical switch ports and power consumption of the node, we have proposed a new hybrid-hierarchical optical cross-connect architecture that consists of an optical waveband cross-connect for adding/dropping or routing large granular optical paths, waveband paths, and an electrical cross-connect only to intermediately groom wavelength paths. The proposed architecture exploits large throughput of optical waveband cross-connects and grooming wavelength paths accompanied with 3R and wavelength conversion capabilities of the electrical cross-connects. To tackle the design problems for optical WDM networks that utilize the proposed hybrid-hierarchical optical cross-connects. We first developed an integer linear programming model for hybrid-hierarchical optical path networks. Although it can offer the optimal solution, the ILP model can be applied only to very small networks due to the extremely high computational complexity requirement. In order to achieve better sub-optimal solutions for medium hybrid-hierarchical optical path networks, we have proposed a 2-stage ILP optimization based design algorithm that divides the network cost minimization problem into 2 sub-problems and uses ILP optimizations to solve. Furthermore, we have newly introduced a heuristic network design algorithm for larger hybrid hierarchical optical path networks employing the proposed hybrid-HOXCs by using a neighbor source and destination grouping method to groom wavelength paths that indirectly limits the use of EXC operations. The efficiency of the hybrid-hierarchical optical path networks applying the proposed design algorithms is evaluated by using numerical simulations with respects to different network parameters. The results revealed that, compared to the conventional algorithms, the hybrid-hierarchical optical path networks offer greater cost reductions from single layer optical path networks as well as single layer waveband switching networks, and the cost savings are enhanced by selecting the suitable

value of the waveband capacity or decreasing of the electrical switch port cost.

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Chapter 5

Impact of electrical grooming and regeneration of wavelength paths in creating hierarchical optical path networks

This chapter assesses the impact of utilizing electrical cross-connects in the proposed hybrid-hierarchical optical cross-connect architecture of Chapter 4 for intermediate grooming and 3R regeneration of wavelength paths in the hybrid hierarchical optical path networks. Simulation results prove that they offer a significant cost reduction. We also studied the dependencies of the network cost with an optical transparent reach restriction on important network parameters including electrical switch port cost, and waveband capacity. It is demonstrated that selecting the waveband capacity properly plays important role in minimizing the total network cost.

5.1 Introduction

Nowadays, optical network architectures are evolving from traditional opaque networks equipped with OEO interfaces toward all-optical (i.e. transparent) networks [5-1]. However, because optical signals in transparent optical networks traverse optical fiber links and node systems that consist of many passive and/or active optical components, the quality of the transmitted optical signals is affected by many factors such as dispersion, EDFA noise, non-linear effects, and crosstalk, etc, i.e. physical impairments. The physical impairments accumulate along the optical paths and may eventually degrade optical signals to be unrecognizable at the receiver if the signal is not relayed, therefore consequently limit the optical transparent transmission reach, the maximum distance (or hop count) that an optical signal can be transmitted [5-1]-[5-5].

In order to overcome the impairments, 3R regeneration is necessary to clean up the optical signals. 3R regeneration in which “3R” is the abbreviation for Re-amplification, Re-shaping, and Re-timing relays or regenerates optical signals in three domains including power, shape and time to provide an effective means of coping with the impairments, thereby enabling reliable transmission over long distances. In current technologies, Optical-Electronic-Optical (OEO) conversion is so far the most popular and mature technique for this purpose. The fundamental principle of OEO regeneration is to convert an optical signal into electronic format first so that the time and shape are restored, and then use the electronic signal to modulate an optical laser to

generate a new optical signal. Besides the OEO technique, it is also possible to carry out 3R regeneration in all-optical domain without converting optical signal into electronic signal. The advantage of all-optical 3R regeneration is its bit-rate transparency, without a bottleneck from electronic modulation. However, currently the all-optical 3R regeneration technique is not mature and very expensive. Therefore, translucent (or semi-transparent) optical networks, that are capable of partly providing OEO conversion, are emerging as a promising solution for bridging the gap between opaque and transparent networks [5-3].

In this chapter, we studied the performance of a translucent hierarchical optical path network that implements the hybrid-HOXC architecture proposed in Chapter 4 to overcome the optical impairments. The proposed hybrid-HOXC separates the wavelength adding/dropping and grooming functions at the WXC layer and employs a small scale EXC for intermediate grooming wavelength paths. Because of the necessity of OE/EO converters at the inputs and outputs of the electrical switching matrices, hybrid hierarchical optical path networks employing the proposed hybrid-HOXCs can perform 3R regeneration and wavelength conversion in combination with intermediate grooming of wavelength paths at EXCs. No separate expensive 3R regenerators need to be implemented. This idea will help to enhance the value of the hybrid-HOXCs, particularly when they are applied to large-scale (long reach) networks that require 3R regeneration. This chapter, therefore, highlights this point and clarifies the effectiveness of the hybrid-HOXCs for translucent optical WDM networks. To design large-scale translucent optical path networks and make full use of the advantages of hybrid-HOXCs, we have proposed a heuristic algorithm that considers the optical transparent reach limit and encourages the establishment of highly utilized waveband paths by grooming residual sparse wavelength paths while considering electrical port cost. Simulations prove that the hybrid-HOXC based networks designed by the proposed algorithm offer a substantial cost reduction compared to the corresponding single layer optical path network. With a consideration on the optically-transparent reach constraint, dependency of network cost on network parameters including electrical switch port cost, and waveband capacity are also investigated.

5.2 Impairment-aware design for hybrid hierarchical optical path networks

In optical path networks, because the signal quality needs to be acceptable for any situation such as protection/restoration operations, the maximum reach of the optical paths without regeneration must be considered by routing and wavelength assignment algorithms. As the results, the impairment-aware network design problem recently has received attention for the routing and wavelength assignment (RWA) of transparent optical networks [5-6]-[5-14]. The impairment-aware design problem including RWA and 3R placement problems is known to be NP-complete [5-1]. Thus these studies commonly establish optical paths one-by-one, i.e. they employ the sequential heuristic approaches, so as to satisfy the impairment constraints. In

hierarchical optical path networks, the difficulty of the design problem is greatly increased since the grooming issue of wavelength paths into waveband paths must be taken into account.

In the translucent hybrid-hierarchical optical path networks employing the proposed hybrid hierarchical optical cross-connects, because the regeneration operation is processed simultaneously with waveband grooming operation at the EXCs of intermediate nodes, all grooming wavelength paths are processed by OEO conversion at the input/output interfaces of the EXC and the optical transparent reach of a waveband path is also exactly that of the wavelength paths accommodated within the waveband path (Figure 5-1). Hence, only the limitation of the optical transparent reach of waveband paths needs to be considered. This is an advantage over transparent hierarchical optical path networks that require impairment considerations not only for waveband paths but also for wavelength paths (wavelength paths may traverse multiple concatenated wavebands). Practically, the impairment constraint can be introduced in the form of a maximum number of physical hops that an optical signal can travel before requiring 3R regeneration for the worst impairment case. Moreover, in hybrid-hierarchical optical path networks, even though EXC layer operations can help to increase the network resource utilization efficiency and as a result reduce link cost, limiting the maximum optical transparent reach of waveband paths may depress the efficiency of waveband switching and substantially increase the required node cost. Hence, impairment-aware network design algorithms must consider the optical transparent reach limit of waveband paths while efficiently dealing with the tradeoff between link cost and node cost to minimize the total network cost.

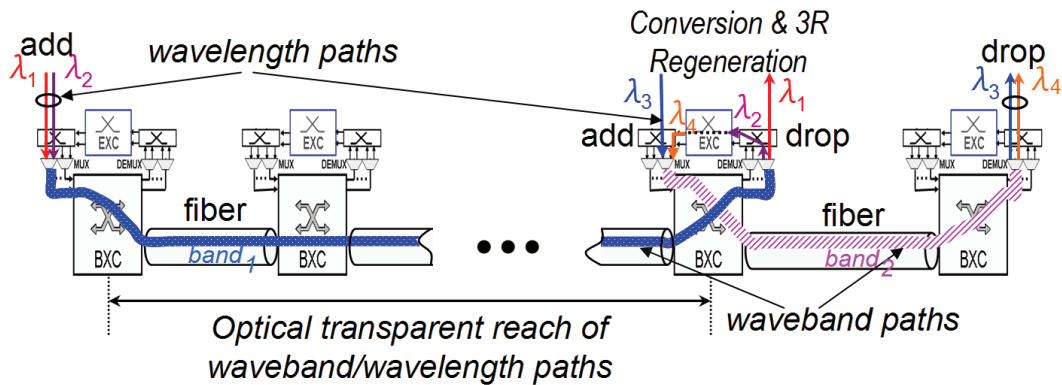


Figure 5-1. Optical wavelength/waveband transparent reach

5.3 Hybrid hierarchical optical path network design considering the optical transparent reach constraint

5.3.1 Problem statement

We assume that each fiber can carry up to B wavebands and each waveband consists of W

wavelengths. We denote the given physical topology by $G(V, A)$, where V is the set of all nodes and A is the set of all arcs. Matrix C is the set of all traffic demands, where each element, $C_{s,d}$, is the number of wavelength paths requested between node pair (s, d) . Hereafter, the optical transparent reach limit is represented by the hop count limitation, denoted by K ; it is set constant for all optical paths in the network for notational simplicity, however, if it is necessary, the generalization to the variable limit case is straightforward. The design goal is to minimize the total network cost required to accommodate all traffic demands subject to the given optical transparent reach limit.

5.3.2 Preliminary

In the hierarchical optical path network, the cost reduction can be attained by reducing EXC operation along with improving the waveband utilization efficiency by encouraging the use of free wavelengths within already established waveband paths. We need to evaluate the degree of the cost reduction obtained by EXC cut-through operations. Let $\text{cost}_\lambda(u, v) : V^2 \rightarrow R_+$, R_+ is the set of all nonnegative numbers, be the required port cost of implementing a wavelength path accommodated as a series of sequentially connected 1-hop waveband paths placed on the shortest route between u and v . Here, we assume that one of the shortest paths between source and destination will be assigned to the wavelength path. Similarly, we define $\text{cost}_{wb}(u, v; s, d) : V^2 \times V^2 \rightarrow R_+$ as the necessary port cost of routing the wavelength path between u and v as a part of the waveband path that directly connects nodes (s, d) . The cost functions of $\text{cost}_\lambda(u, v)$ and $\text{cost}_{wb}(u, v; s, d)$ are obtained as follows,

$$\text{cost}_\lambda(u, v) = 2C_{EXC}(\text{hop}(u, v) - 1) + \frac{2}{W}(C_{BXC_UNI} + C_{BXC_NNI})\text{hop}(u, v) \quad (5-1)$$

and

$$\begin{aligned} \text{cost}_{wb}(u, v; s, d) = & 2C_{EXC}(\text{hop}(u, s) + \text{hop}(d, v)) + \frac{2}{W}\{C_{BXC_UNI}(\text{hop}(u, s) + \text{hop}(d, v) + 1) \\ & + C_{BXC_NNI}(\text{hop}(u, s) + \text{hop}(s, d) + \text{hop}(d, v))\} \end{aligned} \quad (5-2)$$

, where $\text{hop}(u, v)$ is the minimum hop count between node pair (u, v) , C_{EXC} the EXC port cost, and C_{BXC_UNI} and C_{BXC_NNI} are, respectively, the add/drop waveband port cost and the by-pass waveband port cost of the BXC (see Section 4.2 of Chapter 4). Based on the port cost functions of $\text{cost}_\lambda(u, v)$ and $\text{cost}_{wb}(u, v; s, d)$, we then have the following relative cost reduction obtained by employing waveband switching in the network,

$$\text{gain}(s, d; u, v) = \frac{\text{cost}_\lambda(u, v) - \text{cost}_{wb}(u, v; s, d)}{\text{cost}_\lambda(u, v)} \quad (5-3)$$

5.3.3 Proposed network design algorithm

In order to minimize the total network cost while satisfying the optical reach restriction and fully utilizing the advantages of the hybrid-HOXC nodes, the direct establishment of highly utilized waveband paths that do not exceed K hops is encouraged, whereas grooming operations will be applied only to accommodate the sparse remaining wavelength paths that cannot be efficiently carried by any end-to-end waveband to improve the utilization of waveband paths, since electrical EXC ports are relatively expensive. Our proposed algorithm consists of 2 major steps. The first step is routing and assignment of waveband paths; it searches for and establishes waveband paths that are equal to or shorter than K hops and can be effectively filled up with wavelength paths. The second step is to accommodate all sparse remaining wavelength paths by applying an auxiliary full-mesh virtual wavelength path graph based on established waveband paths with spare capacities or new direct end-to-end unexceeded K hops waveband paths. In both steps, to find the route of waveband/wavelength paths, a proposed un-exceeded K -hops shortest path algorithm is applied (see Appendix). The developed design algorithm is briefly described as follows:

<Hybrid-Hierarchical Optical Path Network Design Considering the Optical Transparent Reach Limit>

Step 0- Selection of parameter values

Determine the following proper values:

- X_{wb} : waveband construction threshold, ($X_{wb} \in (0,1]$)
- h_{lim} : incremental hop count limit.

Step 1- Routing and Assignment of Waveband paths with the optical transparent reach limit

a) Searching for a highly utilized waveband path

- Search for node pair $(s, d) \in V \times V$ of a waveband path that satisfies:

$$(1) \quad \text{hop}(s, d) = \max \{ \text{hop}(u, v) \leq K \mid (u, v) \in V \times V \}.$$

- (2) maximize the total cost reduction that can be achieved by setting the waveband connecting s and d :

$$f(s, d) = \sum_{\substack{(u, v) \in N(s, d) \\ \text{gain}(s, d; u, v) > 0}} \text{gain}(s, d; u, v) \quad (5-4)$$

in which $N(s, d)$ is the set of candidate wavelength paths that can be groomed and carried by a waveband path connecting s and d ; $N(s, d)$ satisfies $W \geq \text{sum}(s, d) = \sum_{\substack{(u, v) \in N(s, d) \\ \text{gain}(s, d; u, v) > 0}} C_{u, v} \geq X_{wb} W$ and

$$\forall (u, v) \in N(s, d): \text{hop}(u, s) + \text{hop}(s, d) + \text{hop}(d, v) \leq \text{hop}(u, v) + h_{lim}.$$

- If such a node pair does not exist, go to Step 2. Otherwise, for all $(s_i, d_i) \in \{(u, v) \in N(s, d) \mid \text{gain}(s, d; u, v) > 0\}$, assign the traffic demand of node pair (s_i, d_i) on to concatenated node pairs (s_i, s) if $s_i \neq s$, (s, d) and (d, d_i) if $d_i \neq d$.

b) *Routing and waveband assignment*

- Define an auxiliary multi-layer waveband graph of the network as,

$$G^{Band} = \left\{ G_b^{Band} = (V, A_b) \mid 1 \leq b \leq B \right\} \quad (5-5)$$

in which each graph layer $G_b^{Band} = (V, A_b)$ is the corresponding network graph for the b^{th} waveband, $Band_b$ ($1 \leq b \leq B$). Arc set A_b of G_b^{Band} is derived from all edges in G with modified arc weight $w_b^{Band} : V^2 \rightarrow R_+$, where arc weight w_b^{Band} is based on the number of unoccupied wavebands in established fibers on the arc, denoted by f_b ($f_b \geq 0$). The weighting function for arc set A_b is defined by,

$$w_b^{Band}(v_i, v_j) = \begin{cases} (1 - f_b \varepsilon) \left\{ 2C_{BXC_NNI} + \frac{C_{fiber}(v_i, v_j)}{B} \right\} & \text{if } f_b > 0 \\ (1 + \Delta) \left\{ 2C_{BXC_NNI} + \frac{C_{fiber}(v_i, v_j)}{B} \right\} & \text{else if } f_b = 0 \end{cases} \quad (5-6)$$

, where $C_{fiber}(v_i, v_j)$ is the link cost connecting v_i and v_j including fibers and amplifiers; a constant $\Delta \leq (\max_{(v_i, v_j) \in V \times V} \{hop(v_i, v_j)\})^{-1}$ and another very small constant $\varepsilon < (\max\{\text{number of fibers at a node}\})^{-1}$ are introduced in order to encourage the use of existing fibers as much as possible while minimizing the hop count.

- Find the shortest waveband path that does not exceed K hops, r_b , on each layer of the auxiliary multi-layer waveband graph G_b^{Band} ($b=1, \dots, B$) and then select the shortest route r_{b_0} (b_0 is the waveband index) from among the found waveband routes:

$$r_{b_0} = \min \{ r_b \mid 1 \leq b \leq B \}.$$

- Establish the corresponding end-to-end waveband path from s to d on the route r_{b_0} and assign waveband index b_0 to carry the total traffic demand $sum(s, d)$ required in Step 1.a.

c) *Repeat Step 1 until no such waveband path remains.*

Step 2- Grooming Sparse Remaining Wavelength Paths

a) *Construct an auxiliary full-mesh virtual wavelength path graph $G^\lambda = (V, A^\lambda)$*

Auxiliary full-mesh virtual wavelength graph G^λ is based on established waveband paths with spare capacities or new direct end-to-end waveband paths that do not exceed K hops.

- Arc weight w^λ of G^λ , where $w^\lambda : V^2 \rightarrow R_+$, is given by

$$w^\lambda(v_i, v_j) = \min \{ C_{existed\ wb}(v_i, v_j), C_{e2e-wb}(v_i, v_j) \} \quad (5-7)$$

, where $C_{e2e-wb}(v_i, v_j)$ is the minimum cost of routing a wavelength by employing a new end-to-end un-exceeded- K -hop waveband path directly connecting v_i and v_j (if no end-to-end

un-exceeded- K -hop waveband path between v_i and v_j is available, $C_{e2e-wb}(v_i, v_j)$ is set to infinity), and $C_{existed\ wb}(v_i, v_j)$, the cost of using an established waveband path with free capacity between v_i and v_j , is given by

$$C_{existed\ wb}(v_i, v_j) = \begin{cases} 2C_{EXC} & \text{if there exists an established} \\ & \text{waveband with free wavelength(s)} \\ \infty & \text{otherwise} \end{cases} \quad (5-8)$$

, so as to encourage the use of existing waveband paths and fibers in order to improve the link utilization and attain cost reduction.

b) Routing and wavelength assignment of each remaining wavelength path

- For each remaining wavelength path request, in descending order of the hop count between its source and destination, apply Dijkstra's algorithm to find the shortest path based on the virtual wavelength path graph and then, assign the request to the shortest path thus found.
- Update graph G^λ and repeat Step 2.b until all requested traffic demands are satisfied.

5.4 Numerical experiments

We adopt the following parameters for the numerical simulations:

- Physical network topologies: 5x5 regular mesh network and pan-European network (COST266) consisting of 26 nodes and 51 links.
- Uniformly and randomly distributed traffic demand is represented as the average number of wavelength paths requested between each node pair.
- Capacity of fiber: $B \times W$ wavelengths per fiber; each fiber carries B wavebands and each waveband accommodates W wavelengths.
- No waveband conversion.
- Parameter β is defined as the ratio of the cost of an electrical switch port (including OE/EO) to that of an optical switch port ($\beta = C_{EXC}/C_{BXC_NNI}$).
- Parameter K stands for the optical transparent reach limit of waveband/wavelength paths.

We applied the proposed algorithm with all possible threshold values $X_{wb} \in \{1/W, 2/W, \dots, W/W\}$; the threshold value that minimizes the total network cost is then selected. The obtained network costs are normalized by that of the comparable single-layer optical path network utilizing OXCs with the same restriction on optical transparent reach. The network costs are evaluated with 10 different traffic patterns for every traffic demand and each threshold X_{wb} ; their ensemble averages were then plotted.

5.4.1 Network cost evaluation results

We evaluated the efficiency of the proposed algorithm for translucent hierarchical optical path networks employing hybrid-HOXCs with different network topologies including the

pan-European network with 26 nodes and 51 links (COST266) and 5x5 regular mesh networks. For comparison, we applied the conventional algorithm based on the traffic demand expression in a Cartesian product space (TDEC) [5-8], which is known to be one of the most efficient heuristic design algorithms for hierarchical optical path networks, and an end-to-end algorithm (End-to-End) [5-8][5-14], which establishes waveband paths that directly connect the source and the destination to accommodate the traffic demand between those source and destination nodes; i.e. wavelength paths are not groomed at intermediate nodes. Because both of the algorithms originally do not consider the optical reach limit, we assume that they apply the method of breaking down waveband paths longer than K hops and utilizing regeneration operations at every far-end node K hops along the waveband paths to satisfy the optical transparent reach constraint. The TDEC and End-to-End algorithms with this modification to satisfy the optical reach limit constraint are denoted as TDEC3R and End-to-End3R, respectively. We also assume that a fiber can carry up to 8 wavebands ($B=8$); the waveband capacity is also 8 ($W=8$).

Figure 5-2 shows the network cost comparison for the 5x5 regular mesh network with the optical transparent reach K of 3 and the EXC port cost ratio β of 3. The results indicate that the translucent hierarchical optical path network offers lower cost than the corresponding single-layer optical path network (normalized cost is less than 1). The cost reduction can reach 50% and strengthens as the traffic demand increases for all applied algorithms. Moreover, the graphs also show that our proposed algorithm outperforms other conventional algorithms (TDEC3R and End-to-End3R) and always offers the best cost reduction for all traffic demand values.

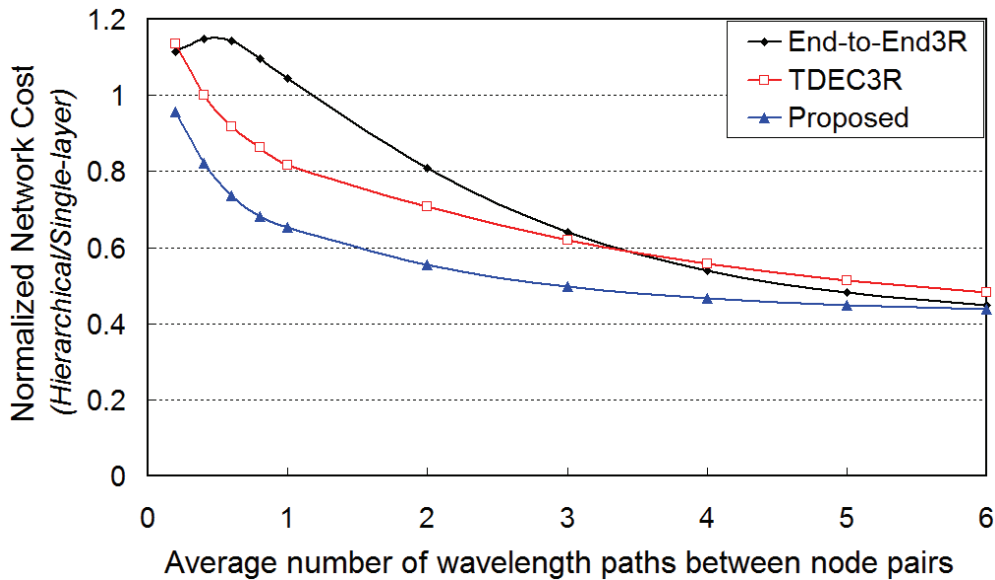


Figure 5-2. Network cost evaluation for 5x5 regular mesh network

Figure 5-3 illustrates the normalized network costs yielded by the proposed algorithm, TDEC3R and OBXC3R algorithms for the COST266 network with following parameter values; $B=W=8$; the optical transparent reach $K=2$ and $\beta=1$. The graphs also show that the cost reduction of the translucent hierarchical optical path network increases as the traffic demand increases, and can reach 60%. In this network topology, except for the very small traffic area (i.e. less than 0.4), the proposed algorithm offers the lowest cost.

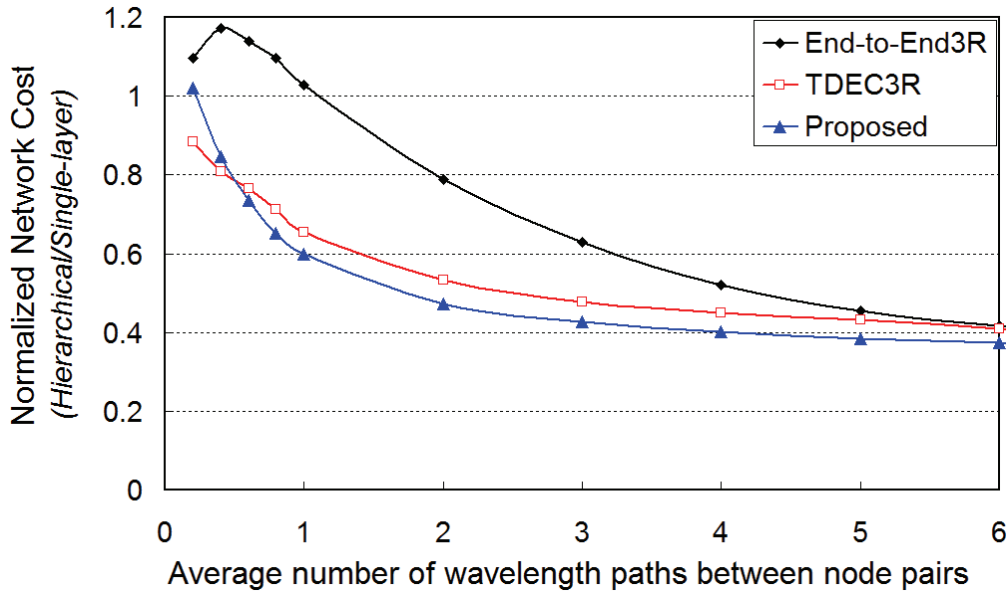


Figure 5-3. Network cost comparison for COST266 network

5.4.2 Impact of network parameters

In this part, we investigate the dependencies of the total network cost on important network parameters such as optical transparent reach, EXC port cost and waveband capacity for the COST266 network. Fiber capacity is 8 wavebands ($B=8$) and each waveband consists of 8 wavelengths ($W=8$).

A. Optical transparent reach

The normalized network cost with different optical transparent reaches ($K=2$ and 5) and EXC port cost ratios ($\beta=1$ and 5) with respect to the traffic demand, is shown in Figure 5-4. The results demonstrate that, in the small traffic demand area, less than 3 for $\beta=5$ and less than 6 for $\beta=1$, the obtained cost reduction of the translucent hierarchical optical path network (compared to the corresponding single-layer optical path network with the same restriction on optical reach) increases with the optical reach (larger K). This traffic area is limited and strongly depends on the EXC port cost ratio because in the translucent hierarchical optical path network, as the required grooming cost, which is mainly determined by β , is reasonable, establishing short waveband paths (smaller K) encourages grooming at the EXCs, and as a result, it offers

higher link utilization, which can help reduce the total cost. However, when the grooming cost is high and the traffic demand is large, longer optical transparent reach permits further exploitation of waveband switching to decrease the number of necessary switch ports, and consequently offers greater cost reduction.

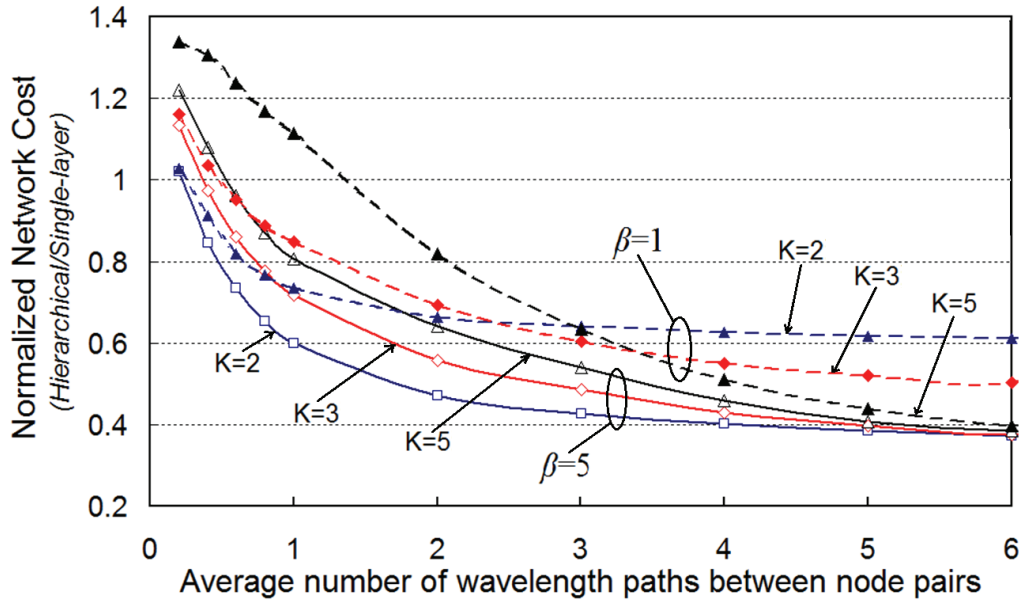


Figure 5-4. Impact of the optical transparent reach on the network cost

B. EXC port cost

In translucent hierarchical optical path networks, EXC port cost is the main factor determining the efficiency of grooming operations. Grooming wavelength paths can strengthen waveband utilization and as a result, reduce link cost, however, the cost of EXC ports can increase node cost. Figure 5-5 illustrates the dependence of the hybrid hierarchical optical path network cost on the EXC port cost (represented as the EXC port cost ratio, β) at the traffic demand of 4 with different values of the optical transparent reach ($K=2, 3, 4$ and 5) for the COST266 network. The total network cost increases as β becomes large, but its growth rate drops more rapidly with longer optical transparent reach. The reason is that using short waveband paths encourages grooming and helps to improve the link utilization and consequently reduces the total cost if the cost of grooming (EXC port cost) is not high. However, permitting longer waveband paths allows the waveband switching advantages to be better exploited to reduce the total number of switch ports in the network needed. This is especially important when EXC ports are expensive.

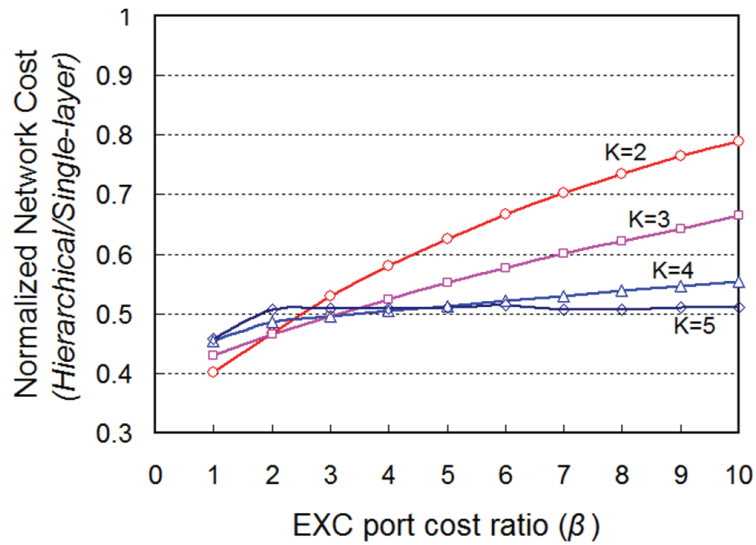


Figure 5-5. Dependence of network cost on β

C. Waveband capacity

The theoretical analysis in [5-8] of the impact of waveband capacity W on the total port count, which mainly determines the total network cost of a hierarchical optical path network, proved that the hierarchical optical path network offers greater cost reduction with larger W when traffic demands are not small. In this part, we fix the fiber capacity in terms of wavelength number as a constant ($B \times W = 64$) and the waveband capacity, W , was varied (2, 4, 8, 16 and 32). The normalized COST 266 network costs with $\beta=2$ and $K=3$ with respect to different waveband capacity values ($W=2, 4, 8, 16$ and 32), where the average traffic demand between node pairs is changed, are shown in Figure 5-6.

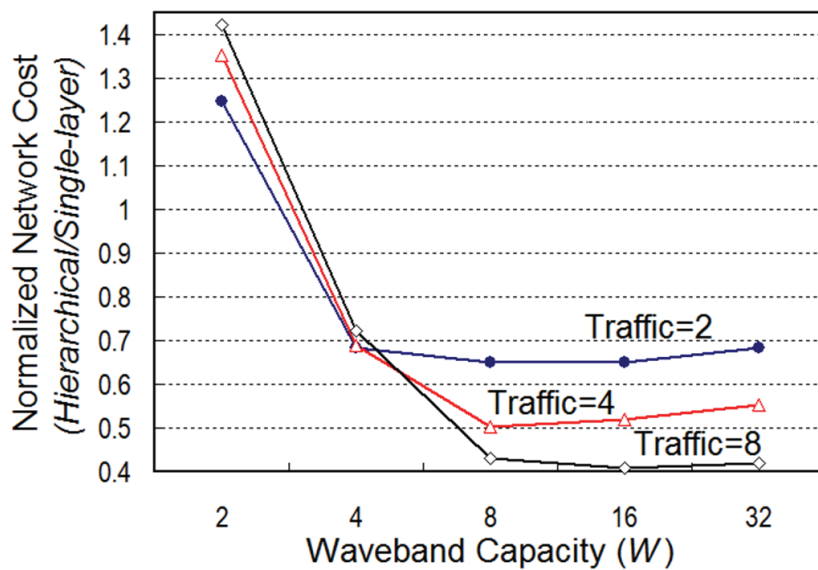


Figure 5-6. Impact of waveband capacity

It is shown that, depending on the traffic demand, the proper waveband capacity must be selected to minimize network cost. For the traffic demands of 2 and 4, the optimal waveband capacity value is 8 while the waveband capacity of 16 is the best for larger traffic demand (traffic demand of 8). Because of the fixed fiber capacity, selecting a smaller waveband capacity can help improve the waveband utilization efficiency but at the cost of increasing the number of waveband paths (and hence waveband ports) necessary as well as the number of expensive EXC ports required for grooming operations to carry the same given traffic demand, and as a result, the total network cost is increased. On the other hand, large waveband capacity such as 32 reduces the network cost less significantly. Even though the waveband utilization efficiency is weakened, since the given traffic demands are not great enough to occupy the huge waveband paths.

5.5 Summary

The value of the proposed hybrid-hierarchical optical cross-connect can be significant when it is applied to large-scale optical WDM networks that require 3R regeneration. Translucent hierarchical optical path networks implementing the hybrid-hierarchical optical cross-connects can incorporate 3R regeneration in waveband grooming operations; it is processed simultaneously at the electrical cross-connects of intermediate nodes. To design the large-scale translucent optical path networks and make full use of the advantages of hybrid-hierarchical optical cross-connects, we have proposed a heuristic network design algorithm that considers the optical transparent reach constraint and encourages the establishment of highly utilized waveband paths by grooming residual sparse wavelength paths while considering electrical port cost. Simulation results prove that the hybrid-hierarchical optical cross-connects based optical WDM networks designed by our proposed algorithm offer a substantial cost reduction compared to the corresponding single layer optical path networks. Under the consideration on optical transparent reach constraint, we also investigated the dependence of the network cost on the optical transparent reach, the electrical cross-connect port cost and the selection of waveband capacity. It was demonstrated that it is critical to choose the waveband capacity properly to minimize total network cost.

APPENDIX

We propose a dynamic programming algorithm that can find the shortest path whose hop count does not exceed a given threshold, K , in a non-negative graph. The algorithm is briefly described as follows:

Input:

- Given non-negative graph $G(V, A)$ where $V = \{v_1, \dots, v_N\}$ is the set of vertices and $A = \{(v_i, v_j) \mid a(v_i, v_j) \geq 0\}$ is the set of arcs in which $a(v_i, v_j)$ is the weight of the arc between node v_i and node v_j ; $a(v_i, v_j) = \infty$ if there is no physical connection between node v_i and node v_j .
- Source and destination node pair: $(s, d) \in V \times V$
- Hop count limit: K

Output:

- $r(s, d)$ = the shortest route from s to d that is less than K hops
- $D_K(s, d)$ = Minimum value of the shortest path from s to d

Variables:

- $d[k][v]$ = minimum cost of the k -hop shortest path connecting node pair (s, v) in which $v \in V$; and k is the hop count of the route ($k \in \{1, \dots, K\}$).
- $\text{prev}[k][v]$ = the preceding node of v on the shortest route from the source s to v that has exactly k hops.
- $\text{Selected}[v]$ = Selection status of node v (=1 iff v was selected; =0 if not)

The proposed algorithm:

1. Initialization ($k=1$)

$$\begin{aligned} d[1][v] &:= a(s, v) \quad \forall v \neq s \\ \text{prev}[1][v] &:= s \quad \forall v \neq s \\ d[i][v] &:= \infty \quad \forall v; \quad \forall i=2, \dots, K \end{aligned}$$

2. While ($k < K$) do

a) Clear the selection status of all nodes

$$\text{Selected}[t] := 0 \quad \forall t \in V; t \neq s$$

$$\text{Selected}[s] := 1$$

b) Find node i that satisfies:

$$d[k][i] = \min \{d[k][t] \mid t \in V; \text{Selected}[t]=0\}$$

c) If found i

(1) Relabeling all nodes

For $\forall t \in V$

If ($d[k+1][t] > d[k][i] + a[i, t]$)

Begin

$$d[k+1][t] := d[k][i] + a[i, t]$$

$$\text{prev}[k+1][t] := i$$

End

(2) $\text{Selected}[i] := 1$ and Go back to b).

d) $k := k+1$;

End while

3. The minimum cost and the route

- $D_K(s, d) = \min \{ d[k][d] \mid 1 \leq k \leq K \}$
- If the un-exceeded- K -hop shortest route is available ($D_K(s, d) < \infty$), route $r(s, d)$ can be obtained from $\text{prev}[k][v]$.

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Chapter 6

Conclusions

Recent advances in WDM technologies and related optical technologies have significantly increased the capacity of transport networks. To cope with the traffic explosion driven by video-centric new broadband services including High-/Ultrahigh-Definition TV or 3D-TV, fast optical circuit/path switching will play a key role in creating cost-effective and bandwidth abundant video-centric future networks. Hierarchical optical path network and node technologies and network architectures that fully harness the power of optical transmissions to enhance network throughput and reduce energy consumption are of great importance. Our research work aims to resolve the recent challenges to realizing hierarchical optical cross-connect and make it possible with mature optical technologies and creating a cost-effective and bandwidth-abundant optical path network.

This thesis presents the research results of our work with the proposals and the developments of the effective network design solutions and node architecture for realizing future hierarchical optical path networks. The main contributions of the work are summarized as following:

- (1) Development of two effective network design solutions that are capable of incorporating the node size optimization into network cost minimization for both two types of HOXCs in terms of waveband adding/dropping capability (Chapter 3).
- (2) Proposal of a hybrid-HOXC architecture which can overcome current technical challenges to be efficiently realized by utilizing current technologies (Chapter 4).
- (3) Effective network design algorithms for hybrid hierarchical optical path networks employing the proposed hybrid-HOXC (Chapter 4).
- (4) An efficient heuristic impairment-aware algorithm to design large-scale translucent hierarchical optical path networks and make full use of the advantages of the proposed hybrid-HOXC (Chapter 5).

Firstly, in Chapter 3, we clarify the effect of waveband add/drop ratio, an important parameter for designing HOXCs, on switch size reduction of HOXC nodes. Detailed analyses of HOXC switch sizes show that the HOXC switch size strongly depends on waveband add/drop ratio, which is the ratio of number of added/dropped wavebands to the number of incoming/outgoing wavebands. Switch scale of HOXC can be decreased by limiting the waveband add/drop ratio. Bounding the waveband add/drop ratio is, therefore, the direct way of effectively reducing the WXC portion. In order to deal simultaneously with both minimizing the total network cost and reducing the HOXC node sizes in the hierarchical optical path network, we have proposed two new network design algorithms which incorporate a restrictions on waveband add/drop ratios according to two types of HOXC architectures regarding

adding/dropping capability of waveband paths. Their effectiveness is verified by conducting extensive numerical experiments. The effects of the network parameters, which include network size, link distance and network topology, on total network cost are also elucidated. Furthermore, impact of selecting waveband capacity to minimize the hierarchical optical path network cost is evaluated. It is shown that the developed algorithms will play a key role in maximizing node-scale reduction and realizing the resultant network cost reductions when the waveband switching is to be fully utilized.

Then, proposal of a hybrid-hierarchical optical cross-connect that employs a waveband cross-connect for routing waveband paths and an electrical cross-connect for grooming wavelength paths in order to make HOXCs possible with current technologies is presented in Chapter 4. The key idea to exploiting the mature commercial technologies that underlie SDH/SONET and OTN cross-connects to realize HOXCs is implementing electrical cross-connects for handling wavelength paths. And also in this chapter, we have developed network design algorithms for the corresponding hierarchical optical path networks utilizing the proposed hybrid-hierarchical optical cross-connects. At first, an integer linear programming model to solve the network design problem is introduced. Then a 2-stage ILP optimization based design algorithm for medium size networks and a heuristic algorithm being capable of design large networks have been developed. Performances of the proposed algorithms and hybrid-hierarchical optical path network efficiency are evaluated through numerical experiments. Finally, impact of the critical network parameters on total network cost is investigated.

Moreover, the EXCs in our proposed hybrid-HOXC architecture can easily provide wavelength conversion and 3R regeneration due to the necessity of OE/EO converters at the input/output interfaces of electrical switching matrices. Hence, hybrid-hierarchical optical path networks utilizing the proposed hybrid-HOXC architecture can perform 3R regeneration and wavelength conversion in combination with intermediate grooming of wavelength paths at EXCs. This idea can help to enhance the value of the hybrid-HOXC, particularly when they are applied to large-scale networks with 3R regeneration requirement.

Therefore, in Chapter 5, we assess the impact of utilizing electrical cross-connects in the proposed hybrid-HOXC architecture for intermediate grooming and 3R regeneration of wavelength paths in the hierarchical optical path networks. To design the translucent hierarchical optical path networks and make full use of the advantages of the proposed hybrid-HOXC architecture, a heuristic network design algorithm considering the optical transparent reach constraint has been proposed. Its effectiveness is verified by simulation results. In addition, dependencies of the network cost with an optical transparent reach restriction on important network parameters including electrical switch port cost, and waveband capacity are also investigated. It is demonstrated that selecting the waveband capacity properly plays an important role in minimizing the total network cost.

Finally, transport network paradigm is moving toward NGN (Next Generation Networks) which aims at IP convergence, while architectures and technologies are diversifying. The

inefficiencies of current IP technologies, in particular the energy consumption and throughput limitation of IP routers, will become pressing problems. Harnessing the full power of light will resolve these issues and spur the creation of future video-centric networks. The enhancement of optical layer technologies and the introduction of new transport protocols will be critical; hierarchical optical path technologies and optical circuit/flow switching will play key roles. Hence, we believe the developments in this work will contribute a lot to creating the cost-effective, bandwidth-abundant and low-power-consumption networks.

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List of Publications

A. Journal Papers

- [1] Hai-Chau Le, Hiroshi Hasegawa and Ken-ichi Sato, “**Hierarchical Optical Path Network Design Algorithm Considering Waveband Add/Drop Ratio Constraint**,” *IEEE/OSA Journal of Optical Communications and Networking (JOCN)*, vol. 2, No.10, pp.872-882, October 2010.
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