# Resource Management in Survivable MultiGranular Optical Networks 

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# RESOURCE MANAGEMENT IN SURVIVABLE MULTI-GRANULAR OPTICAL NETWORKS 

## by

## YANG WANG

Under the Direction of Dr. Xiaojun Cao


#### Abstract

The last decade witnessed a wild growth of the Internet traffic, promoted by bandwidthhungry applications such as Youtube, P2P, and VoIP. This explosive increase is expected to proceed with an annual rate of $34 \%$ in the near future, which leads to a huge challenge to the Internet infrastructure. One foremost solution to this problem is advancing the optical networking and switching, by which abundant bandwidth can be provided in an energyefficient manner. For instance, with Wavelength Division Multiplexing (WDM) technology,


each fiber can carry a mass of wavelengths with bandwidth up to 100 Gbits/s or higher. To keep up with the traffic explosion, however, simply scaling the number of fibers and/or wavelengths per fiber results in the scalability issue in WDM networks. One major motivation of this dissertation is to address this issue in WDM networks with the idea of waveband switching (WBS). This work includes the author's study on multiple aspects of waveband switching: how to address dynamic user demand, how to accommodate static user demand, and how to achieve a survivable WBS network. When combined together, the proposed approaches form a framework that enables an efficient WBS-based Internet in the near future or the middle term. As a long-term solution for the Internet backbone, the Spectrum Sliced Elastic Optical Path (SLICE) Networks recently attract significant interests. SLICE aims to provide abundant bandwidth by managing the spectrum resources as orthogonal subcarriers, a finer granular than wavelengths of WDM networks. Another important component of this dissertation is the author's timely study on this new frontier: particulary, how to efficiency accommodate the user demand in SLICE networks. We refer to the overall study as the resource management in multi-granular optical networks. In WBS networks, the multigranularity includes the fiber, waveband, and wavelength. While in SLICE networks, the traffic granularity refers to the fiber, and the variety of the demand size (in terms of number of sub-carriers).

INDEX WORDS: Waveband Switching, MG-OXC, Multi-granular Optical Switching, SLICE

# RESOURCE MANAGEMENT IN SURVIVABLE MULTI-GRANULAR OPTICAL NETWORKS 

by

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# RESOURCE MANAGEMENT IN SURVIVABLE MULTI-GRANULAR OPTICAL NETWORKS 

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## DEDICATION

To my Grandfathers.

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## LIST OF ABBREVIATIONS

- ABS - Active Band-segment
- AS - Autonomous System
- AWG - Arrayed Waveguide Gratings
- BBS - Backup Band-segment
- BLSA - Balanced Load Spectrum Allocation
- BPHT - Balanced Path Routing with Heavy-traffic First Waveband Assignment
- BS - Band-segment
- BTF - Band to Fiber Multiplexer
- BTW - Band to Wavelength Demultiplexer
- BV - Bandwidth-variable
- BXC - Band Cross-connect
- CS - Cut-set
- DBSP - Dedicated Band-segment Protection
- DEMUX - Demultiplexer
- DPP - Dedicated Path Protection
- EL - Even-load
- FFT - Fast Fourier Transform
- FTB - Fiber to Band Demultiplexer
- LB - Lower Bound
- HWA - Hierarchical Waveband Assignment
- HWAF - Hierarchical Waveband Algorithm with Full Separation
- IG - Interference Graph
- ILP - Integer Linear Programming
- MEMS - Micro-Electro-Mechanical-Systems
- MG-OXC - Multi-granular Optical Cross-connect
- MILB - Maximum Interference Length in Band
- MOR - Maximum Overlap Ratio
- MRSA - Maximum Reuse Spectrum Allocation
- MUX - Multiplexer
- NSF - National Science Foundation
- O-E-O - Optical-Electronic-Optical
- PAWR - Port-aware Wavelength Retuning
- RSA - Routing and Spectrum Allocation
- RWA - Routing and Wavelength Assignment
- SBSP - Shared Band-segment Protection Scheme
- SLICE - Spectrum-sliced Elastic Optical Path Networks
- SNWS - Simulated Non-uniform Waveband Assignment
- SPP - Shared Path Protection
- SPSR - Shortest Path with Maximum Spectrum Reuse
- SRLG - Shared Risk Link Group
- T-OXC - Traditional Optical Cross-connect
- UB - Upper Bound
- WBO-RWA - Oblivious Optimal Routing and Wavelength Assignment
- WBS - Waveband Switching
- WDM - Wavelength Division Multiplexing
- WGB - Weighted Graph-based Waveband Assignment
- WRN - Wavelength Routed Network
- WSS - Wavelength-Selective Switch
- WTB - Wavelength to Band Multiplexer


## PART 1

## INTRODUCTION

Since the last decade, the world has experienced a vast growth of Internet traffic. YouTube, P2P, VoIP are examples of emerging bandwidth-hungry Internet applications that promote this traffic explosion. In the near future, Global Internet traffic is expected to continue the increase at a compound annual rate of $34 \%$ [1]. This explosive traffic growth poses a huge challenge to the current Internet infrastructure.

Optical networking is a promising solution to resolve the challenge. With the state-of-the-art wavelength division multiplexing (WDM) technology, each fiber can carry a mass of wavelengths with bandwidth up to 100 Gbits/s or higher [2, 3]. To satisfy the user demands, wavelengths are assigned and routed to form lightpaths via the Routing and Wavelength (RWA) process, which result in the wavelength routed network (WRN). In WRNs, the lightpath is switched through intermediate nodes with the aid of the traditional optical cross-connects (T-OXCs) [2]. As shown in Fig. 1.1, the traffic carried in the incoming fiber is demultiplexed into individual wavelengths and switched to the outgoing fiber link after the multiplexing, with one port consumed per wavelength at the T-OXC.

To keep up with the lasting traffic climbing, it is unavoidable to scale the number of


Figure 1.1. Traditional optical cross-connect
fibers and/or number of wavelengths per fiber. Consequently, a major challenge faced by the WRN is the dramatic increase of the T-OXC node size as well as the associated cost and control complexity. To address such issues, waveband switching (WBS) in conjunction with multi-granular optical crossconnects (MG-OXCs) are introduced [4], [5], [6], [7]. The basic principle of waveband switching is to group and route multiple wavelengths together as a band or fiber and switch the whole group by using a single port whenever possible. To support the operation of the wavelengths at higher granularities (e.g., fiber or band), various designs of multi-granular optical crossconnects (MG-OXCs) architectures have been proposed in the literature [7], [8], [9], [10], [11], [12]. The deployment of MG-OXCs poses different challenges on critical issues such as routing and wavelength assignment (RWA), protection in WBS networks since the dominant goal in WBS networks is to minimize the port count of MG-OXCs [6], [13], [14]. The first half of this dissertation will deal with those critical issues of WBS networks with the proposed multi-granular optical switching framework.

Despite the popularity of wavelength division multiplexing (WDM) networks, the rigid spectrum management in WDM networks is considered to be in-efficient recently $[15,16]$. In specific, sub-wavelength traffic may have to be over-provisioned due to the coarse granularity of the wavelength. Also, when a traffic demand requires multiple wavelengths (i.e., super-wavelength traffic), guard-band frequencies between those wavelengths may lead to the under-utilization of the available spectrum resources. As a promising replacement (of WDM networks) in the long term, spectrum-sliced efficient elastic optical path (SLICE) networks currently attract significant interests. The basic idea of SLICE is to manage the optical spectrum at a finer granularity (i.e., sub-carriers) to efficiently satisfy sub-wavelength traffic, and rely on the OFDM modulation [17] to efficiently accommodate super-wavelength traffic. The second half of this dissertation will further clarify the advantage of SLICE networks and present our timely study on this new frontier.

Overall, the fundamental problem targeted in this dissertation is How to efficiently provision user demands via resource management in multi-granular optical networks. In


Figure 1.2. WDM granularity


Figure 1.3. SLICE granularity

WBS networks, the granularity consists of fiber, waveband, and wavelength, as shown in Fig. 1.2. While in SLICE networks, the traffic granularity refers to the fiber, and the variety of the demand size (in terms of number of sub-carriers) as shown in Fig. 1.3. Nevertheless the specific network type, addressing this fundamental problem relies on the provision process that allocates the optical spectrum resources (i.e., wavelengths in WDM networks, subcarriers in SLICE networks) to feed the user demand. This process in referred to Routing and Wavelength Assignment [3] in WDM networks and Routing and Spectrum Allocation in SLICE networks [18]. Most challenging issues in optical networks (e.g., protection) in fact contains an instance of the NP-Complete RWA (or RSA) problems [3]. Hence, this dissertation will devote significant efforts on resolving the RWA and RSA problem.

The rest of this dissertation is organized as follows. Chapter II and III mainly focus on the study of multi-granular waveband switching networks. In Chapter II, a classified overview of multi-granular optical switching is presented, which leads to the discussion on multiple unaddressed challenging problems. Targeting on resolving those challenges, the
multi-granular waveband switching framework is presented in Chapter III. In Chapter IV, we present our recent research in SLICE networks. Finally, we highlight the impact of the overall study and conclude the dissertation in Chapter V.

## PART 2

## MULTI-GRANULAR WAVEBAND SWITCHING: A CLASSIFIED OVERVIEW

In this chapter, we classify and comprehensively analyze the state-of-the-art studies in WBS networks. As the multi-granular optical cross-connect is the key component of WBS networks, we firstly present an overview of MG-OXC studies from the node-wise, network-wise, and implementation viewpoint. Clearly, the deployment of MG-OXCs poses new challenges on critical issues in WBS networks. Among those critical issues, we show a classified view of the WBS RWA problem since which is contained by all the others as an instance. Above overview reveals some open challenging issues in WBS networks, motivating the framework presented in the next chapter.

### 2.1 Three Views of Multi-granular Optical Cross-connects (MG-OXCs)

Three views of the MG-OXCs are presented in this section, including: node architecture, network architecture, and implementation technologies.

### 2.1.1 The Node-wise View: the Three-layer and Single-layer Architectures

In WBS networks, multiple wavelengths are grouped together as a band, and switched as a single entity (i.e., using a single port) whenever possible. This is achieved with the aid of the multi-granular optical cross-connects (MG-OXCs) for which traffic can be switched at multiple granularities (fiber, waveband, and wavelength). As a key component, reducing the size or the total port count has been a major goal in WBS networks. In the literature, two principle MG-OXC architectures: the three-layer architecture and single-layer architecture, have been proposed $[4,5,7,8,10-12,19-21]$.


Figure 2.1. The three-layer MG-OXC architecture


Figure 2.2. The single-layer MG-OXC architecture

Three-layer Architecture Figure 2.1 shows the architecture of a three-layer multigranular optical cross-connect [8]. It consists of three switches for wavelength, waveband and fiber switching. The WXC layer includes a wavelength cross-connect switch that is used to bypass/add/drop lightpaths at wavelength layer. The band-to-wavelength (BTW) demultiplexers are used to demultiplex bands into wavelengths, while the wavelength-toband (WTB) multiplexers are used to multiplex wavelengths into bands. At the BXC layer, the waveband cross-connect is used to switch wavebands. The BXC layer also includes the fiber-to-band (FTB) demultiplexers and band-to-fiber (BTF) multiplexers. Similarly, the fiber cross-connects (FXC) layer is used to switch fibers. Compared to the T-OXC, the three-layer MG-OXC can achieve a significant port saving. For example, assume that there are five fibers, each having 80 wavelengths, and one wavelength needs to be dropped and one to be added at a node. The total number of ports required at the node when using a T-OXC is 401: 400 for incoming wavelengths (i.e., 399 for bypass, and 1 for drop wavelength), and 1 for add wavelength. With the three-layer MG-OXC, if the 80 wavelengths in each fiber are grouped into 10 bands, only one fiber needs to be demultiplexed into 10 bands (using a 6 -port FXC). Only one of these 10 bands needs to be further demultiplexed into eight wavelengths (using a 11-port BXC). Finally, one wavelength is dropped and added (using a 9-port WXC). Accordingly, the three-layer MG-OXC requires only $6+11+9=26$ ports.

Single-layer Architecture Figure 2.2 shows a single-layer MG-OXC which includes three logical parts corresponding to FXC, BXC and WXC in the three-layer MG-OXC, respectively [8]. The major difference is the elimination of FTB/BTW demultiplexers and BTF/WTB multiplexers for cross-layer connection, which results in a simpler architecture to implement, configure and control. In the single-layer MG-OXC, some incoming fibers are pre-configured as designated fibers, only which may have some of their bands dropped. In contrast, all other non-designated incoming fibers can only bypass or drop all the bands within them entirely. Similarly, within these designated fiber(s), only designated band(s) can have some of the wavelengths dropped while the remaining bands bypass the node. We
note that if the lightpath to be dropped is assigned to an appropriate fiber (i.e., a designated fiber) and an appropriate (designated) band in the fiber, then even fewer ports are needed with the single-layer MG-OXC. Again, assume that there are five fibers, each having 80 wavelengths, and one wavelength needs to be dropped and one to be added at a node. With the single-layer MG-OXC, only one fiber needs to be demultiplexed into 10 bands, thus only 4 ports are needed for other non-designated fibers. In addition, only one of 10 bands demultiplexed from the designated fiber needs to be further demultiplexed into wavelengths, thus only 9 ports are needed for the non-designated bands in the fiber. Finally, 9 ports are needed for the 8 wavelengths demultiplexed from the designated band and for the add/drop wavelength. Hence, the total number of ports needed is only $4+9+9=22$, which is less than that of the three-layer MG-OXC.

Three-layer vs. Single-layer Architecture We compare the features of the threelayer and single-layer MG-OXC in Table 2.1. Specifically, the advantage of the three-layer architecture is its capability for dynamic selection of fibers (bands) for multiplexing/demultiplexing from the FXC (BXC) layer to the BXC (WXC) layer. In other words, as long as a free FTB (BTW) port presents, any fiber (band) can be demultiplexed into bands (wavelengths) at the fiber (band) layer. The similar flexibility is applicable to the multiplexing from WXC (BXC) to BXC (FXC) layer. Due to its flexibility, the proposed framework of next chapter will adopt the three-layer architecture by default. The single-layer MG-OXC, in contrast, is not as flexible as the three-layer MG-OXC since only the designated fibers and designated bands have the capability of multiplexing/demultiplexing. However, the singlelayer MG-OXC has a simpler and more compact design, which results in better signal quality [8].

Reconfigurable MG-OXC Architectures Instead of a fixed design, dynamic traffic provision prefers a reconfigurable architecture that can adaptively configure the MGOXC. This leads to the development of reconfigurable three-layer MG-OXC and single-layer MG-OXC as shown in Fig. 2.3 and Fig. 2.4. Reconfigurable MG-OXC only employs a pre-

Table 2.1. Comparison between the three-layer architecture and single-layer architecture

| Architecture | Three-layer | Single-layer |
| :---: | :---: | :---: |
| Advantages | Flexible in <br> demultiplexing <br> and multiplexing | Simple and <br> compact design, <br> better signal quality |
| Disadvantages | Employ more ports <br> for interconnection | Not <br> flexible |



Figure 2.3. Reconfigurable three-layer MG-OXC architecture


Figure 2.4. Reconfigurable single-layer MG-OXC architecture
determined limited port count. Specifically, in Fig. 2.3 and Fig. 2.4, $X$ denotes the number of incoming fibers, and $Y$ denotes the number of BXC ports from FTB demultiplexers. The parameter $\alpha(\leq 1)$ is the ratio of fibers (to the total number of fibers) that can be demultiplexed into bands using FTB ports, and the parameter $\beta(\leq 1)$ is the ratio of bands that can be demultiplexed to wavelengths using BTW ports. Therefore such MG-OXC architectures only allow $\lfloor\alpha X\rfloor$ fibers to be demultiplexed into bands and $\lfloor\beta Y\rfloor$ of these bands to be demulitiplexed into wavelengths simultaneously. In the literature, little work has been done on the analysis of the design parameters of reconfigurable MG-OXCs, which limits the deployment in reality. We will fill this gap in the next chapter, as well as propose novel RWA algorithms for dynamic WBS networks employing reconfigurable MG-OXCs.

### 2.1.2 The Network-wise View: Heterogeneous Waveband Switching or Non-heterogeneous Waveband Switching

With the introduction of MG-OXCs, the port required by the network can be dramatically reduced. However, the overall port reduction in WBS networks does not imply the port reduction at every single node. In other words, for some nodes in a WBS network, employing T-OXCs may be even more cost-effective in terms of the port number. Also, in reality, it takes time and capital for upgrading a WRN to a WBS network. As a result, it makes sense that a portion of the T-OXCs are replaced in the first phase of this evolution. Above ideas motive the consideration of a heterogeneous waveband switching network, where T-OXCs and various MG-OXCs are deployed in the same network.

One of the first heterogeneous waveband switching frameworks was proposed in [22]. The authors of [22] proposed the HeteroWBS architecture by clustering the nodes in the network into multiple autonomous systems ( $A S s$ ). Within each $A S$, only one or a few MG-OXC nodes are deployed to provide the WBS functionality. To support practical wavebanding capabilities with limited number of MG-OXCs in each $A S$, multiple constraints are applied to construct the system. For instance, all the MG-OXC nodes should be connected for exchanging messages for available bands and wavelengths. Also, a T-OXC should com-


Figure 2.5. Some network topologies
municate with its attached MG-OXC (namely, group node) to form a waveband-level route, hence making the waveband switching transparent to T-OXCs. A more general and significant problem (that has not been studied in this work), however, is how to optimally select the nodes for MG-OXC upgrading to construct the HeteroWBS network.

The authors of [23] introduced the placement problem of MG-OXCs in WDM networks, and the resulted network is a heterogeneous network where both MG-OXCs and T-OXCs are employed. In their study, the authors referred to the phenomena that an MG-OXC requires more ports than a T-OXC as backfire. The reason for backfire is that MG-OXC which consists of fiber, band and wavelength cross-connects introduces overheads in terms of additional ports and demultiplexers/multiplexers for cross-layer interconnections. For example, in a network with the star topology shown in Fig. 2.5(a), assume that each node has one lightpath to other nodes and the wavelengths of all the lightpaths are within the same band, then all the bands have to be demultiplexed and switched through the WXC layer at the central node (that has the highest node-degree). In this case, a T-OXC might be a better choice at the central node since a T-OXC has no additional ports for fiber, band layers and interconnection. The authors hence proposed a WBS scheme in which the node-degree and bypass traffic at each node are considered when accommodating the traffic request. After
traffic demands are satisfied, the waveband switching efficiency can be calculated for each node, based on which the decision on whether to deploy an MG-OXC or not is made.

The authors of [24] proposed a hierarchical framework for waveband switching networks. Instead of treating the network as a flat entity for the traffic grooming, the authors designed a hierarchical model in which the network is separated into two levels. At the first level, the network is partitioned into clusters and one node (referred to as the hub) in each cluster is responsible for grooming intra-cluster lightpaths. The hub is similar to the group node, and the cluster is similar to the $A S$ in [22]. At the second level, each hub grooms lightpaths to a specific remote cluster into wavebands by routing the traffic to the hub of the remote cluster. Although not pointed out in [24], we note that it is a natural choice to use various optical cross-connects in this hierarchial model since hub and local nodes have different capacities.

In this dissertation, we target on a WBS-based solution for the Internet backbone in the middle term, where only MG-OXC nodes are employed.

### 2.1.3 O-E-O, O-O-O, and Hybrid: An Implementation Perspective

Optical-electronic-optical (O-E-O) and all-optical (O-O-O) are two leading technologies widely adopted by equipment vendors in cross-connects production. In O-E-O approach, the incoming optical signal is converted into electrical signal for electronic processing, and then converted back to outgoing optical signal. In the O-O-O approach (enabled by technologies such as 2-D and 3-D Micro-Electro-Mechanical-Systems (MEMS), or Arrayed Waveguide Gratings (AWG)), the optical signal stays in the optical domain and is switched from the incoming ports to the outgoing ports via the all-optical switching fabric. Table 2.2 shows a brief comparison between the O-E-O and O-O-O solution. The major advantage of O-E-O solution is the signal processing capabilities including typical regeneration, reshaping, and retiming (3-R) processing, while the O-O-O solution leads to less cost and bear the merits of transparency to protocol and bit-rate [3].

Instead of adopting a sole technology, the traffic hierarchy in WBS networks implies the preference of a hybrid technology using both O-E-O and O-O-O [19, 20, 25]. In specific,

Table 2.2. Comparison between O-E-O and O-O-O Cross-connects

| Solution | O-E-O | O-O-O |
| :---: | :---: | :---: |
| Hardware | Expensive | Less expensive |
| Footprint | Large | Small |
| Signal Processing | 3-R | Hard to achieve |
| Wavelength Conversion | Support | Not mature |
| Protocol Independent | No | Yes |
| Bit-rate Independent | No | Yes |
| Scalability | Hard to scale | Highly scalable |

waveband level traffic can be handled by the O-O-O switching fabric while wavelength level traffic are handled by the O-E-O switching fabric. This strategy brings advantages for both levels: the waveband level only requires a transparent all optical forwarding; the wavelength level traffic can go through wavelength conversion and other electronic processing.

### 2.2 Routing and Wavelength Assignment in WBS networks

In WDM networks, the fundamental problem is the routing and wavelength assignment (RWA) [26-29]. In WRNs, one major goal of the RWA process is to minimize the total number of wavelengths allocated. Figure 2.6(a) illustrates the routing and wavelength assignment in a wavelength routed network with static traffic. In Fig. 2.6(a), the RWA process selects $A-D-E$ as the routing path and $\lambda_{1}$ as the wavelength of the lightpath between the traditional wavelength OXC $A$ and $E$. Note that the chosen wavelength $\left(\lambda_{1}\right)$ has to be continuously available at all the links that the routing path spans. Similarly, the data transmission between $A$ and $B(E$ and $C)$ can be established along path $A-B(E-C)$ as another lightpath using the same wavelength $\lambda_{1}$ since these two lightpaths are disjoint. For the data transmission between $A$ and $C$, a lightpath along the shortest path $A-B-C$ can be further established. Note that the lightpath between $A$ and $C$ has to use a different wavelength (i.e., $\lambda_{2}$ ) since $\lambda_{1}$ is occupied at link $A-B$. Due to the traffic grouping, the WBS RWA owns more constraints than that of WRNs while employing the goal of minimizing the port number. Figure 2.6(b) illustrates the routing and wavelength assignment in a WBS network where

MG-OXCs are deployed at each node and each band has two wavelengths. In Fig. 2.6(b), the disjoint lightpaths from $A$ to $E$, from $A$ to $B$, and from $E$ to $C$ again use the continuous wavelength $\lambda_{1}$ along their respective routing paths. However, the WBS RWA process may prefer to allocate $\lambda_{2}$ along path $A-D-E-C$ to form the lightpath between $A$ and $C$ rather than the shortest path $A-B-C$. This is because the resulted lightpath can form a waveband along $A-D-E$ by combining the wavelength $\lambda_{1}$ of the lightpath between $A$ and $E$. Consequently, the port saving can be achieved (e.g., at MG-OXC $D$ ) since all the wavelengths within the band can share the same port. In contrast, allocating the wavelength $\lambda_{2}$ along $A-B-C$ for the lightpath from $A$ to $C$ cannot save ports ${ }^{1}$. In the above example, the grouped lightpaths share the same source node $A$. Various other grouping policies, however, can exist based on where to aggregate/disaggregate wavelengths. The above example assumes a static traffic demand pattern and a fixed uniform band size. In reality, the traffic pattern can also be dynamic, and the band size can vary from band to band. In the following subsections, we thus classify WBS schemes based on the traffic pattern, grouping policies and the band configurations. We further note that the optimal WBS RWA problem was shown to be NP-Hard [6, 27]. In the literature, Integer Linear Programming (ILP) models and heuristic algorithms are proposed to resolve the WBS RWA problem, which will also be reviewed.

### 2.2.1 Classification based on the Traffic Pattern

We first classify WBS schemes based on the traffic pattern as shown in Fig. 2.7. For the case with static or off-line traffic, the set of lightpath requests is known a priori and remains unchanged (e.g., a green-field WBS network design). In contrast, the case with online traffic assumes that all the lightpath requests are unknown and arrive dynamically. The on-line traffic can be further classified as fully dynamic traffic and incremental traffic. With fully dynamic traffic, the request arrives and departs after a random amount of time (i.e., a finite holding time). In the case with incremental traffic, new lightpath requests need to be

[^0]
(b)

Figure 2.6. Routing and wavelength assignment


Figure 2.7. Classification according to the traffic pattern
processed one at a time without knowledge of any future requests while existing connections stay indefinitely and are non-rearrangeable (i.e., infinite holding time). The features of on-line and off-line WBS are summarized and compared in Table 2.3. To accommodate online traffic in WBS networks, a reconfigurable MG-OXC architecture (e.g., the MG-OXC in Fig. 2.1) is generally adopted. As discussed above, reconfigurable MG-OXCs deploy limited number of demultiplexers/multiplexers, which may cause the blocking of lightpath requests due to the exhaustion of the demultiplexers/multiplexers. In on-line WBS, both the blocking probability and the port reduction hence should be considered. We note that, although both three-layer and single-layer reconfigurable MG-OXCs can be used for the on-line WBS, the study in [12] showed that the single-layer MG-OXC outperforms three-layer MG-OXC in terms of port savings due to the elimination of cross-layer connection, while the three-layer MG-OXC outperforms the single-layer MG-OXC in the blocking probability. Since the offline WBS has a full knowledge of all the traffic demands to be satisfied, an optimal solution can be obtained using ILP techniques. For on-line WBS, it is generally impossible to achieve the optimal routing and wavelength assignment due to the unknown traffic.

Table 2.3. Comparison between the off-line and on-line WBS

| Classification | Off-line WBS | On-line WBS |
| :---: | :---: | :---: |
| Traffic Pattern | Given static traffic <br> demand matrix | Fully dynamic or <br> incremental requests |
| Architecture | Normal MG-OXC, <br> prefer single-layer | Reconfigurable MG-OXC, <br> prefer three-layer |
| Goals | Minimize the <br> port number | Minimize the blocking <br> and port number |

### 2.2.2 Classification based on Grouping Policies

Depending on where to aggregate the wavelengths into wavebands and disaggregate the waveband into wavelengths, there are various grouping policies as shown in Fig. 2.8. The same-ends grouping is the most straightforward form of wavebanding where the lightpaths between the same source and destination nodes are grouped as waveband(s). The remaining


Figure 2.8. Classification according to the grouping policy
group policy can be referred to as intermediate grouping since the aggregation or disaggregation can happen at the intermediate node. In specific, the same-destination policy groups the lightpaths with the same destination node (but different source nodes) into waveband(s). As a result, the aggregation of lightpaths occurs at an intermediate node where the common segment of those lightpaths starts. Similarly, the same-source grouping occurs among the lightpaths sharing the same source node but various destination nodes. The most flexible grouping policy is known as the intermediate-to-intermediate grouping, in which both the aggregation and disaggregation are allowed to happen at intermediate nodes. In a specific WBS network, one may choose to deploy a combination of several grouping policies. For example, we can employ both the same-source and same-destination grouping, which is known as either-end grouping.

In general, any waveband switching algorithm should adopt a grouping policy. For example, the study in [30] adopted the either-end grouping, and the work in [6] used the combination of the intermediate grouping and the same-ends grouping. In [31], the authors proposed algorithms based on multiple grouping policies including the same-destination and either-end grouping. In the literature, the authors of [32] firstly studied the impact of different grouping policy including same-ends and same-destination on the blocking probabilities and port savings in on-line WBS. One important conclusion reached in their work is that the same-ends grouping can achieve lower blocking probability than same-destination while


Figure 2.9. Classification according to the band configurations
the same-destination grouping outperforms same-ends in terms of port savings.

### 2.2.3 Classification based on the Band Configurations

Figure 2.9 gives a band-configuration classification of WBS schemes based on whether the number of bands per fiber $(P)$, the number of wavelengths per band $(W)$, and the set of wavelengths $(\lambda s)$ are fixed or not. Existing studies all assume that $P, W$, and $\lambda s$ are fixed. With the fixed $P, W$ and predefined wavelength set, however, variations exist based on whether the number of wavelengths per band is the same or uniform for all the bands or not. In specific, waveband granularity refers to the number of wavelengths that are grouped into a waveband. When the waveband granularity is the same for all the bands, the corresponding WBS scheme is known as the uniform WBS. In contrast, if the granularity for the different band can vary, the resulted WBS scheme is referred to as non-uniform WBS. It is worth noting that the non-uniform waveband switching requires the hardware support from MG-OXCs, which was shown to be feasible by appropriately configuring the waveband filtering [20].

It has been confirmed that uniform WBS has features such as small nodal size, low cost and complexity in the literature. However, it can be shown that non-uniform WBS may further increase the port savings. Figure 2.10 shows an example where the non-uniform WBS


Figure 2.10. An example for the comparison between non-uniform WBS and uniform WBS
and uniform WBS are compared. In the star network, Node $A$ has 2, 3, and 1 lightpath(s) to Node $B, C, D$, respectively, all of which bypass Node $N$. With the uniform WBS at Node $N$, one choice is to configure $W=2, P=3$. Consequently, the third band which contains the lightpath for both $C$ and $D$ has to be demultiplexed. For the uniform WBS, another choice is to configure $W=2, P=4$, then no bands need to be demultiplexed at Node $N$. However, in this case, the last two bands cannot be saturated thus degrading the wavelength utilization. Finally, we note that using the non-uniform configuration of 3 bands with size 2,3 , and 1 , respectively, we can fulfill all the bands without demultiplexing.

The study in [20] is the first work on non-uniform WBS under the on-line traffic. For arbitrary incoming traffic, their study attempted to decompose the traffic demands at the waveband level without demultiplexing. To achieve this goal, the authors divided the nonuniform WBS into two sub-problems: waveband selection and waveband assignment. In the waveband selection sub-problem, a model similar to $k$-payment problem is formulated to preconfigure a minimum set of wavebands that can represent an arbitrary breakdown of input wavelengths to output fibers, and then wavelengths are assigned to the preconfigured wavebands in the waveband assignment sub-problem. The authors of [33] studied nonuniform WBS by identifying two different problems: minimum-wavelength problem which uses minimum possible wavelengths for banding; and minimum-waveband problem, in which


Figure 2.11. Achievable performance in WBS
minimum number of wavebands is used. The rational beneath these two problems can be illustrated by Fig. 2.11 from [33]. Conceptually, every WBS algorithm can be represented by a point in a two dimensional performance space in Fig. 2.11, the $x$-axis and $y$-axis indicate the number of wavelengths and wavebands required by the algorithm, respectively, while the shaded area represents the achievable region of performance. The optimal solution will be a tradeoff between the number of used wavelengths and used wavebands. The authors claimed that, therefore, the optimal performance can be achieved by obtaining a tradeoff between the two problems using hybridization. Different from above work, we will address the non-uniform waveband switching in the WBS network with off-line traffic in the next chapter.

### 2.2.4 Integer Linear Programming formulations for Optimal RWA

Integer Linear Programming (ILP) models are widely used in WRNs to solve the routing and wavelength assignment problem [34], and are introduced in WBS networks in the studies of $[4,6]$. There are several major differences in the ILP formulation to model WRNs and WBS, which are summarized in Table 2.4. First of all, optimization goals and the deployed architecture are different, which should be reflected in the ILP formulations. Moreover, the incorporated constraints in WBS ILP are more than that of WRNs. In specific,

Table 2.4. Comparison between the WRN ILP and WBS ILP

| ILP | WRN | WBS |
| :---: | :---: | :---: |
| Objective | Minimize used wavelengths | Minimize the port number |
| Arch. | T-OXCs | MG-OXCs |
| Constraints | 1.Wavelength continuity | 1.Wavelength continuity |
|  | 2.Wavelength capacity | 2.Wavelength capacity |
|  | 3.Traffic flow | 3.Traffic flow |
|  |  | 4.Wavelength grouping |
|  |  | 5.Demultiplexing |
|  |  | \&multiplexing |

the wavelength continuity constraint requires that one lightpath has to employ a continuous available wavelength along its path. The wavelength capacity constraint prohibits the usage of one wavelength within one fiber by more than one lightpaths. The traffic flow constraint ensures that all the traffic demands are added/dropped at the respective source and sink node, and the number of flow-in lightpaths equals to the number of flow-out lightpaths at any intermediate nodes. Above three constraints have to be satisfied in both WRNs and WBS networks. The WBS ILP formulations incorporate additional constraints for wavelength grouping and demultiplexing and multiplexing. The wavelength grouping constraint requires that one lightpath is switched at one of the three layers (FXC, BXC, and WXC). The demultiplexing and multiplexing constraint guarantees that the fibers, and bands are appropriately demultiplexed and bands, wavelengths are multiplexed whenever necessary.

In general, the WBS ILP model should be aware of the grouping policy, the specific MG-OXC architecture and the band configurations. For example, the authors in [6] formulated an ILP model based on intermediate grouping policy for wavebanding. While for the ILP model in [4], the grouping was restricted between the lightpaths with the same destination. Similarly, all the ILP models are associated with specific MG-OXC architectures. For example, the study in [12] presented different ILP models corresponding to the three-layer and single-layer MG-OXC architectures. We further note that ILP models are used in the protection of WBS networks as well by incorporating the constraints regarding the backup traffic [14, 35].

Although ILP models can provide an optimal solution for the RWA problem, the performance becomes intractable when the size of the problem grows large. Hence, heuristics are proposed to provide a practical solution for large-scale problems, which will be discussed in the next subsection.

### 2.2.5 Heuristic RWA Algorithms for WBS Networks

In this subsection, we review heuristic WBS algorithms with a focus on a few representative studies. We then summarize the major principles adopted in the WBS algorithm design.

One of the first study on on-line WBS appeared in [36], where the authors proposed a heuristic algorithm, namely Maximum Interference Length in Band (MILB), for WBS networks with incremental traffic. The interference length (say $L$ ) of a given band $b$ refers to the overlap length (i.e., the number of common links) for a candidate path of the current request with all the existing lightpaths within band $b$. MILB prefers to select a band along a candidate path that is mostly used by existing overlapping lightpaths (i.e., maximize $L$ ) since it potentially consumes less extra ports and causes less blocking. The MILB algorithm was extended in [37] by considering the length (say $H$ ) of the candidate path as well (i.e., maximize $\frac{L}{H}$ ), and the extended algorithm, namely Maximum Overlap Ratio (MOR), was shown to be better than MILB. The study in [37] also presented a Waveband Assignment with Path-Graph (WAPG) algorithm to carry fully dynamic traffic in WBS networks with wavelength conversion. More studies on the on-line WBS can be found in [20, 32, 33, 37, 38].

In the case with the off-line traffic, one well-known algorithm is the balanced path routing with heavy-traffic first waveband assignment (BPHT) heuristic algorithm [6]. BPHT is a three-stage scheme deploying the same-source or same-destination grouping policies. BPHT algorithm selects the paths for node-pairs with non-zero traffic by balancing the load over all the links, then the node-pair with higher traffic demand is accommodated along with the node-pairs having the same end (i.e., the same source or destination) first, and proceeds until all traffic demands are satisfied. The comparison between BPHT and the ILP model
proposed in the same work shows that BPHT provides a near-optimal performance. Other studies on the heuristic off-line WBS algorithms can be found in [19, 39, 40].

One basic methodology adopted in the WBS algorithm design is to divide the routing and wavelength assignment into two sub-problems: the routing, and the wavelength assignment. The routing sub-problem in most WBS algorithms falls into two categories: (i). fixed routing (e.g., the shortest path routing); (ii). alternative routing (e.g., the $k$-shortest path routing [41]). This divide-and-conquer strategy can simplify the RWA problem since the routing and wavelength/waveband assignment can be completed in different stages (e.g., [6]). However, this strategy may fail to produce a jointly optimum solution due to the same reason. A joint optimum solution can be obtained in graph-based WBS heuristics [36, 38-40]. In graph-based schemes, the network topology is transformed into the auxiliary graph(s). The edges in the auxiliary graph generally include both the physical fiber link connection (i.e., the routing is self-contained in the auxiliary graph) and artificial edges to reflect the port consumption. By varying the weight of edges (to reflect the cost in port count or probability for wavebanding), the routing and wavelength/waveband assignment can be done in an integrated manner. For example, in [40], a separate auxiliary graph for every waveband in the network was constructed by transforming the network topology, and different edges were defined on the auxiliary graph to aid in the selection of route and waveband with the goal of saving ports. The authors of [39] proposed another graph-based scheme where an auxiliary graph (AUG) according to the given network configuration was constructed to assist in making routing decision and wavelength assignment under the on-line traffic.

We further note that WBS schemes are node-architecture-dependent and network-architecture-dependent. Most of existing work adopted the three-layer MG-OXC while few work has been done based on the single-layer MG-OXC (due to its inflexibility). Moreover, the WBS schemes can vary due to the network framework. For example, in heterogeneous WBS networks, the routing and wavelength assignment are mostly done in a hierarchial way as discussed above.

### 2.3 Unaddressed Challenges in WBS Networks

Upon the above overview, we highlight critical issues that have not been well addressed in the literature for static waveband switching, dynamic waveband switching, and protection in WBS networks, respectively, which motivate the proposed framework in the next chapter.

### 2.3.1 Static Waveband Switching

As the major goal in WBS networks is to reduce the port number of the optical crossconnects, waveband switching efficiency is defined as the ratio between the ports reduced by MG-OXCs and that required by the T-OXCs of WRNs [13]. Among existing work, none has clarified possible governing factors that impacts the waveband switching efficiency, which can benefit any WBS protocol/agrithm design in general. In the next chapter, we will introduce and analyze multiple impacting factors, and propose an efficient algorithm making use of those factors.

Existing studies on the non-uniform waveband switching only tackled the dynamic case [20,33] with simplified assumption that the routing is given or pre-configured. Compared to dynamic waveband switching, we note that static waveband switching may gain more port savings with non-uniform wavebands. This is because that the known traffic pattern can be fully utilized to configure the band assignment (instead of predicting any possible patterns as in the dynamic case). Different from dynamic WBS, however, simple fixed or pre-configured routing is unlikely to be adopted in the static WBS, and the routing unavoidably affects the traffic mapping, grouping as well as the band selection. In the next chapter, we address the static non-uniform waveband switching with an optimal model.

### 2.3.2 Dynamic Waveband Switching

In a dynamic WBS network, a reconfigurable MG-OXC with limited number of ports (reflected through the number of demultiplexers/multiplexers) is normally deployed. Consequently, besides the blocking caused by the wavelength shortage, the blocking of lightpath requests can be resulted from the limited number of demultiplexers and multiplexers. Ex-
isting studies in dynamic WBS networks, on one hand, have not integrally taken both the wavelength assignment and the usage of demultiplexers and multiplexers into consideration. On the other hand, how the design parameters of the reconfigurable MG-OXCs can be selected in reality is not addressed, thus leaving the reconfigurable MG-OXC not practically adoptable.

Moreover, given the local view of dynamic traffic accommodation, it is prone to make short-sighted assignment decision and cause future blocking in dynamic WBS networks. Given the unavailability of a precise forecast, a promising alternative is to actively and adaptively adjust the existing resource allocation (without causing severe performance degradation), which will be explored in the next chapter.

### 2.3.3 Waveband Protection

Due to the high bit rate of one wavelength and the large number of wavelengths per fiber, network survivability is drawing much attention in optical networking design and modeling [42-46]. Protection can be broadly classified into path-protection, link-protection, and segment-protection. In path or link protection, one backup path is established for each working path or link, respectively, while in segment-protection each working path is divided into several segments and backup path is assigned per working segment. These protection schemes can be shared or dedicated protection depending on whether resources are allocated exclusively for each backup path or shared among several backup paths. In general, link or segment protection could have longer backup paths thus consuming more network resources than path protection, but they may provide faster restoration [14].

One of the first work in the survivable WBS networks appears in [14], where the authors formulated the shared-path protection in WBS networks with an integer linear programming (ILP) model, and presented a spanning tree based heuristic scheme. The routing sub-problem, however, was not considered in their work. In [35], the authors considered routing multi-granular traffic under dedicated path protection with shared risk link group (SRLG) constraint. A shared-risk link group (SRLG) is a group of links with a shared vul-
nerability (e.g., a shared fiber cable) [35]. Therefore, the backup path can not be in the same SRLG as the working path. In [40], the authors studied a graph-based shared-path protection scheme in WBS networks. One interesting observation shown in this paper is that the wavelength sharing for backup traffic undesirably impedes wavebanding and degrades the performance of port reduction (port saving drops up to $15 \%$ compared to dedicated protection). As a matter of fact, none of existing waveband protection schemes have successfully resolved one fundamental problem: how to achieve the joint goal of port reduction, network survivability and resource sharing. Our study in the next chapter will attempt to resolve this.

## PART 3

## MULTI-GRANULAR WAVEBAND SWITCHING FRAMEWORK FOR WDM NETWORKS

In this chapter, we present the multi-granular waveband switching framework, which aims at enabling a WBS-based future Internet backbone for user demand provision. Following the overview of the framework, we present our detailed study on the major components of the framework.

### 3.1 The Framework Overview

Figure 3.1 presents an overview of the multi-granular waveband switching framework. At the top level, according to the traffic pattern, we classify the waveband switching as static and dynamic one, respectively, both of which has the components of the uniform/nonuniform WBS switching, protection, and MG-OXC architecture design at the bottom level. Note that for the dynamic case, since optimal decision is impossible to be made on-line, we rely on the Re-optimization process to adaptively adjust the resource management. As to be discussed below, we employ the technique of wavelength retuning for the re-optimization in this dissertation. In the following part of this chapter, we present our studies in four important components of the framework: uniform and non-uniform static waveband switching, dynamic WBS switching and analysis on the associated reconfigurable MG-OXC architecture, wavelength retuning in WBS networks for dynamic re-optimization, and waveband protection ${ }^{1}$. For each major component, we explain our major goals as follows, and present the detailed study in the following sections.

Static (Uniform) Waveband Switching RWA Algorithm: For the first time,

[^1]

Figure 3.1. Framework overview
we analyze possible impacting factors that affects the waveband switching efficiency, which can benefit any other WBS protocol/agrithm design in general. Based on these factors, we propose an novel algorithm.

Static Non-uniform Waveband Switching: Static WBS networks potentially can fully utilized the given traffic pattern and flexility of band selection to achieve more port savings. In the framework, we present an optimal model that takes routing, wavelength grouping, traffic demands and non-uniform band settings all into consideration. For largescale problems, we will also incorporate a fast heuristic algorithm.

Dynamic (Uniform) Waveband Switching: In a dynamic WBS network, the blocking probability of lightpath requests can result from both the wavelength shortage and the limited number of demultiplexers and multiplexers. We will analyze the usage pattern of the demultiplexers and multiplexers, based on which a novel dynamic RWA algorithm is proposed to integrally consider both the wavelength assignment and the usage of demultiplexers/multiplexers. We will also fill the gap in the analysis of design parameters of the reconfigurable MG-OXC.

Wavelength Retuning in Dynamic WBS Networks: We resolve the shortsightness problem of dynamic WBS networks with the idea of actively adapting the existing assignment. Note that this adjustment should not disrupt the existing service's quality significantly nor hurting the port saving performance. The approach presented in this dissertation, namely wavelength retuning will achieve this purpose.

Static Waveband Protection: We target on a protection scheme in WBS networks that can achieve the goal of port reduction, network survivability, and resource sharing altogether. This will be realized with the novel concept of band-segment. Traditionally, the protection is either realized at the path level or the link level. With the concept of band-segment, we will enable a band-level protection.

### 3.2 Wavebanding Factors and A Hierarchical Waveband Algorithm for the Static Traffic

In this section, we analyze factors that impact the waveband switching efficiency in WBS networks, based on which a hierarchical waveband assignment algorithm is presented and evaluated.

### 3.2.1 Wavebanding Factors

Overlapping Hops Between Grouped Lightpaths: To be grouped together, the lightpaths under consideration should have common segment(s). We note that the hop number of the common segments, should be at least 2 hops to be cost efficient. For example, in Fig. $2.5(\mathrm{~b})$, assume that there are two lightpaths, $p_{1}$ (along the path 3-1-2-4) and $p_{2}$ (along the path 5-1-2-6), which only share a single hop (i.e., link 1-2). If the band size is 2 , it seems that one can group those two traffic demands through assigning $\lambda_{0}$ and $\lambda_{1}$ to $p_{1}$ and $p_{2}$, respectively. However, with this configuration, both $p_{1}$ and $p_{2}$ have to be multiplexed through WXC layer at Node 1 (since with different incoming links) and demultiplexed through WXC layer at Node 2 (due to different outgoing links). Hence, 2-hop overlapping should be the lower bound for grouped lightpaths.

Bypass Traffic: We define the bypass fiber as the fiber only consisting of bypass traffic, and the bypass band as the band within which is all bypass traffic. Bypass fiber and bypass band keep the traffic at the FXC or BXC layer thus can facilitate port reduction. In contrast, the bypass wavelength, which is defined as the traffic (within one non-bypass band), has to be demultiplexed/multiplexed into the WXC layer (even though such bypass wavelength can significantly reduce electrical process at the node [2]). In the worst case, if all the traffic demands at a node go through the WXC layer, the WXC layer has exactly the same number of ports as that of a T-OXC. Clearly, the additional BXC layer and FXC layer as well as the ports for interconnection between different layers result in more ports in MG-OXC than T-OXC. In general, more bypass traffic implies more opportunities that we can group the traffic into bypass fibers and bypass bands, and hence more port savings. At the same time, node-degree may offset the benefits of high bypass traffic since higher node-degree implies that the bypass traffic traveling through this node is more inclined to bifurcate. As a result, the bypass-traffic node-degree ratio $(P / D)$ may be considered together on the impacts to waveband efficiency.

Traffic Hierarchy: The introduction of the wavebanding and MG-OXCs adds new hierarchies to the traffic demands in WBS networks, which can be classified into three tiers: (i). Fiber-tier traffic. (ii). Band-tier traffic. (iii). Wavelength-tier traffic. If $F$ is the number of wavelengths per fiber and $W$ is the band size, then one unit of Wavelength-tier traffic is one lightpath demand; one unit of Band-tier traffic includes $W$ lightpath demands; and one unit of Fiber-tier traffic consists of $F$ lightpath demands. Taking the traffic hierarchy into consideration in the process of RWA can benefit the port savings. For example, in a network with $X=4$ fibers per link, $F=100, W=10$ as shown in Fig. 2.5(c), the traffic demand from node 1 to node 6 is 125 lightpaths, which consists of 1 Fiber-tier, 2 Band-tier and 5 Wavelength-tier traffic demands. We assume that the traffic demands are 120 lightpaths and 110 lightpaths for node-pair $(7,8)$ and $(9,10)$, respectively. With WBS algorithms like BPHT or First-fit algorithm which do not consider the traffic hierarchy, the waveband assignment
process first assigns fiber 0 and part of fiber 1 (i.e., $\lambda_{0}, \lambda_{1} \ldots \lambda_{24}$ ) to node-pair 1-6 along route $1-2-3-4-5-6$. Then these schemes will further assign fiber 2 and part of fiber 3 (i.e., $\lambda_{0}$, $\left.\lambda_{1} \ldots \lambda_{19}\right)$ to node-pair $(7,8)$ along path 7-2-3-4-5-8. As a result, the fibers (i.e., fiber 1 and 3 ) along 2-3-4-5 have been partially used, and one cannot accommodate the Fiber-tier traffic between node-pair $(9,10)$ as bypass-fiber. In contrast, by giving priority to the Fiber-tier traffic and accommodating them first, we can assign bypass fibers (i.e., fiber 0,1 and 2 ) to all the Fiber-tier traffic in the above scenario thus saving more ports.

### 3.2.2 A Hierarchical Waveband Switching Algorithm

We combine above three factors and propose a hierarchical waveband switching (HWA) algorithm. HWA divides the RWA problem into the routing and the wavelength/waveband assignment subproblems. The routing subproblem is resolved by choosing the path among $k$-shortest paths while balancing the load over all the links. The wavelength/waveband assignment process gives higher priorities to Fiber-tier and Band-tier traffic while grouping the lightpaths with higher overlapping and bypass traffic. The following notations are used for describing the HWA algorithm.
$X: \quad$ The number of fibers per link;
$F: \quad$ The number of wavelengths per fiber;
$B: \quad$ The number of wavelengths per band;
$W: \quad$ The minimum overlapping hops among routing paths of any grouped traffic demands;

Path $_{s, d}$ : The routing path of the node-pair $(s, d)$;
$D[i]: \quad$ The degree of node $i$;
$T[s][d]: \quad$ The traffic demand between the node-pair $(s, d)$;
$F T[s][d]$ : The Fiber-tier traffic between the node-pair $(s, d)$;
$N F T[s][d]$ : The Non-Fiber-tier traffic between the node-pair $(s, d)$.

We assume that for each node-pair $(s, d)$, the amount of traffic demands are $T[s][d]$ lightpath(s). The amount of the Non-Fiber-tier and the Fiber-tier traffic is specified in Eq.
(3.1) and Eq. (3.2), respectively. In the proposed two-stage algorithm, we accommodate as much the Fiber-tier traffic as possible in Stage 1. Then the Non-Fiber-tier traffic (i.e., including the Band-tier and the Wavelength-tier traffic) is satisfied in Stage 2.

$$
\begin{gather*}
N F T[s][d]=T[s][d] \% F  \tag{3.1}\\
F T[s][d]=(T[s][d]-N F T[s][d]) / F \tag{3.2}
\end{gather*}
$$

Stage 1: The Fiber-tier traffic assignment. Since the number of fibers and wavelengths per link is limited and large node size is generally not encouraged, we select the routes while balancing the load on all the links in the network.

1. Path generation. Use the $k$-shortest path algorithm [41] to generate the $k(k>=1)$ path(s), namely $P_{s, d}^{h}$, where $h=1,2, \ldots, k$, for each node-pair $(s, d)$.
2. Path selection. The link load is defined as the sum of all the traffic on the link, and the maximum load $M$ is defined as the largest link load among all the links in the network. Starting from the node-pair with the largest traffic demands, assign one of the $k$ paths to the node pair while minimizing $M$, until all the node-pairs with traffic demands are considered. We denote the selected path for the node-pair $(s, d)$ as Path $_{s, d}$.
3. Fiber-tier traffic accommodation. Following the same sequence as in the previous step, assign bypass fiber(s) along the selected routing path to satisfy all the Fiber-tier traffic. For the node-pair ( $s, d$ ), if only part of the Fiber-tier traffic can be accommodate along Path ${ }_{s, d}$, we accommodate the remaining part of the Fiber-tier traffic along another candidate path in $P_{s, d}^{h}$.

Stage 2: The Non-Fiber-tier traffic assignment. In this step, we accommodate the Non-Fiber-tier traffic by using the routing path selected in Stage 1. Assume that the set of the nodes along Path $_{s, d}$ for the node-pair $(s, d)$ is $s, s_{1}, s_{2}, \ldots, s_{i}, d$, we use $N_{\text {odeSet }}^{s, d}$ to denote this set. To take advantage of the bypass traffic in wavebanding, we calculate the sum of the bypass traffic at each node $i$ using Eq. (3.3). Then we calculate the sum of the bypass-traffic
node-degree ratio along the path, say $B D S u m_{s, d}$, for each selected routing path Path $_{s, d}$ as shown in Eq. (3.4).

$$
\begin{gather*}
\text { bypassT}[i]=\sum_{i \in \text { NodeSet }_{s, d}}^{s!=d, s!=i, d!=i} N F T[s][d]  \tag{3.3}\\
\text { BDSum }_{s, d}=\sum_{i \epsilon \text { NodeSete } s, d} \text { bypassT }^{s}[i] / D[i] \tag{3.4}
\end{gather*}
$$

For the Non-Fiber-tier traffic, Algorithm 1 is adopted for routing and wavelength assignment. Specifically, the lines 2-11 are to accommodate the traffic demands as bypass bands and the lines $13-22$ are to accommodate the traffic demands one by one while considering wavelength grouping. The lines $24-29$ are to handle the exception when the traffic cannot be accommodated using the current selected path. The variables $w$ and $b$ (both are initialized to be 0 ) in this algorithm are the index of the respective wavelength and waveband from which to start the search for an available wavelength and waveband.

In this scheme, we adopt the intermediate wavelength grouping policy. Since one-hop overlapping does not help in wavebanding, we require that traffic demands which are to be grouped with the current traffic demand should have at least $W$-hop ( $W \geq 2$ ) overlapping with the current traffic demand along their routing paths. There are four steps in this stage.

1. Starting with the node-pair $(s, d)$ that has the largest $B D S u m_{s, d}$, use Algorithm 1 to accommodate the traffic demand for the node-pair $(s, d)$.
2. Use Algorithm 1 to accommodate the traffic for every node-pair along Path $_{s, d}$ that has the source $s$, and at least $W$ overlapping hops with Path $_{s, d}$, starting with the node-pair $\left(s, s_{i}\right)$, node-pair $\left(s, s_{i-1}\right), \ldots$, until the node-pair $\left(s, s_{2}\right)$.
3. Use Algorithm 1 to accommodate the traffic for every node-pair along Path $_{s, d}$ that has the destination $d$, and at least $W$ overlapping hops with $P a t h_{s, d}$, starting with the node-pair $\left(s_{1}, d\right)$, node-pair $\left(s_{2}, d\right), \ldots$, until the node-pair $\left(s_{i-1}, d\right)$.
4. Use Algorithm 1 to accommodate the traffic demands of the remaining node-pairs
```
Algorithm 1 Wavelength Assignment for the Traffic Demands Between Node Pair \((s, d)\)
    Begin:
    while \(N F T[s][d]>=B\) do
        Find a free band \(m\) starting with \(b\) along Path \(_{s, d}\);
        if the band \(m\) exists then
            \(b \leftarrow(m+1) \% B\)
        else
            Break
        end if
        Assign the band \(m\) to this traffic;
        \(N F T[s][d] \leftarrow N F T[s][d]-B\)
    end while
    while \(N F T[s][d]>0\) do
        Find a free wavelength \(n\) starting with \(w\) along Path \(_{s, d}\);
        if the wavelength \(n\) exists then
            \(w \leftarrow(n+1) \% F\)
        else
            goto Exception
        end if
        Assign the wavelength \(n\) to this traffic;
        \(N F T[s][d] \leftarrow N F T[s][d]-1\)
    end while
    Exception:
    if all the \(k\) paths for \((s, d)\) has been tried then
        Block and Exit
    else
        Select an alternative path for the node-pair \((s, d)\) from \(P_{s, d}^{h}\) as \(P a t h_{s, d}\) and goto Begin
    end if
    End:
```

whose routing paths overlap with Path $_{s, d}$ by at least $W$ hops. Update $B D S u m_{s, d}$ and goto Step 1, until all traffic demands are satisfied.

It is worth noting that HWA does not separate the Non-Fiber-tier traffic further into the Band-tier and Wavelength-tier traffic to accommodate them in different stages. For the purpose of comparison, we consider another scheme, namely, Hierarchical Waveband Algorithm with Full Separation (HWAF), which accommodates the Band-tier traffic (using steps similar to lines 2-11 of Algorithm 1) and the Wavelength-tier traffic (using steps similar to lines 13-22 of Algorithm 1) of a node-pair $(s, d)$ separately. Figure 3.2 shows the comparison of port count for HWA and HWAF based on simulations on a random 6-node network with $X=2, F=100, B=5$. The X-axis is the size of the uniform traffic $(t)$ for each node-pair, and the Y-axis is the port count for both algorithms. As shown in Fig. 3.2, when the traffic size is less than the band size 5 , there is no difference between HWA and HWAF since the Band-tier traffic is 0 for both algorithms. When the traffic size is a multiple of the band size (e.g., 5,10 ), the difference is small since only the Band-tier traffic exists in both HWA and HWAF. As a result, one can observe a steep drop when the size of the traffic demand is a multiple of the band size. For all the remaining traffic requests, we can see that HWA outperforms HWAF. The advantage of HWA over HWAF can be explained as follows: (i). The probability that we fail to find free bands to accommodate the Band-tier traffic in Algorithm 1 is very small compared to the probability of failing to find free fibers to accommodate the Fiber-tier traffic. (ii). The coupling of the Band-tier and Wavelength-tier traffic can facilitate the formation of bypass fibers.

### 3.2.3 Performance Evaluation of HWA

In this section, we compare the performance of HWA with the optimal waveband assignment for small size problems. For large scale problems, we compare the performance of HWA with that of BPHT, which is proven to be near-optimal [6]. For various combinations of $X, F, B$, we omit the results here if the same patterns can be observed.

For a random 6-node network with $X=2, F=4, B=2$, a traffic matrix is randomly


Figure 3.2. A port count comparison between HWA and HWAF


Figure 3.3. Port count under uniform traffic
generated for all the node-pairs, and the traffic size is randomly generated in the range of $[0,5]$. Two different representative random traffic patterns, where the total lightpath requests among all node-pairs are 16 and 25 , are simulated using the ILOG CPLEX [47]. As shown in Table 3.1, we collect the port count from the Waveband Oblivious optimal Routing and Wavelength Assignment (WBO-RWA) [6], the Optimal WBS [6], BPHT, and HWA. Note that the results from WBO-RWA are from the optimal RWA without considering wavebanding, while the results from the Optimal WBS are the optimal results with wavebanding consideration. From the table, we see that the performance of HWA is close to that of the ILP model (i.e., the optimal WBS) and better than that of BPHT and WBO-RWA.

Table 3.1. Results for the six-node network

|  | WBO-RWA |  | Optimal WBS |  | BPHT |  | HWA |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\sum T[s][d]$ | 16 | 25 | 16 | 25 | 16 | 25 | 16 | 25 |
| Port count | 64 | 106 | 48 | 74 | 56 | 81 | 51 | 79 |

In the case with uniform traffic where each node-pair has $t$ lightpath demands, simulations are conducted on a random 6 -node network with $X=8, F=100, B=5$. The performance comparison is shown in Fig. 3.3, where the vertical axis stands for the total port count of the whole network, and the horizontal axis corresponds to traffic requests for each node-pair. When traffic demands from each node-pair are all the Fiber-tier traffic (i.e., $t=100$, or $t=200$ ), no differences exist between HWA and BPHT since all traffic demands are accommodated at the FXC layer. When $t$ is equal to $110,115,120$, or 210 (i.e., a multiple of the band size 5), the results show that the performance of the two schemes is relatively close since both schemes are operating at the fiber and band layers only. However, for other cases in which we have to accommodate the traffic at all the three tiers, HWA outperforms BPHT by as much as $18 \%$ in terms of port count. The results for other deployments (e.g., $t>210)$ also show the same pattern and hence it is not shown here.

We also simulate HWA and BPHT in the 24-node USA backbone network (see Fig. 3.4) with $X=4, F=100, B=10$. The traffic demands are randomly generated within $[0, r]$ for each node-pair, and the factor $W$ (in Stage 2 of the proposed scheme) is set


Figure 3.4. 24-node topology
to 4. The simulation results from HWA and BPHT under random traffic demands are shown in Fig. 3.5, where the vertical axis stands for the port count, and the horizontal axis represents the maximum generated traffic demand (i.e., $r$ ). The simulation results show that HWA again outperforms BPHT by a noticeable margin. Since there is no Fibertier traffic (because of $t<F$ ), the overlapping path consideration and the highlight of bypass traffic primarily account for the improvement over BPHT in this case. Specifically, instead of considering the whole traffic as the weight to order the waveband assignment sequence in BPHT, the bypass-traffic node-degree ratio in HWA can more accurately reflect the probability of wavelength banding thus reducing ports. At the same time, the factor $W$ also contributes to the performance improvement. Our simulation indicates that the best performance can be achieved when $W$ is set to $4-6$ for the USA backbone network under random traffic demands. Interestingly, our study also shows that neither overlarge $W$ nor over-small $W$ will facilitate wavelength grouping. In other words, a medium size $W$ may be preferable in practice. This is because overlarge $W$ may reduce the chance of grouping and port savings, while over-small $W$ does not help much in port savings.

The relationship among the bypass traffic, node degree and the port count, is illustrated in Fig. 3.6, where $P / D$ is the bypass-traffic node-degree ratio as discussed above. The results are obtained from the USA backbone network with $X=4, F=100, B=10$ and a uniform


Figure 3.5. Port count under random traffic


Figure 3.6. P/D, port count and port reduction
traffic demand $t=4$ between each node-pair ${ }^{2}$. In Fig. 3.6, the horizontal axis represents the node identification number, and the vertical axis stands for port count or $P / D$ value. The port reduction is the port count using MG-OXCs subtracted by the port count using T-OXCs. As shown in the figure, the curve of $P / D$ follows the curve of port count or the trend of port reduction. This suggests that the nodes with higher bypass-traffic node-degree ratio have a higher probability of wavebanding, and hence facilitating the port reduction in WBS networks.

### 3.3 Non-uniform Waveband Switching in Static WBS Networks

In this section, we present the optimal Integer Linear Programming (ILP) model for non-uniform waveband switching in multi-granular optical networks. We then present a heuristic algorithm for large scale problems when solving the ILP becomes time in-efficient.

### 3.3.1 Optimal Integer Linear Programming Model for Non-uniform WBS

Following notations are used in the model.
$F$ : $\quad$ Number of fibers per physical link in each direction;
$W: \quad$ Number of wavelengths per fiber;
$B$ : Number of wavebands per fiber;
$I_{n}$ : Set of incoming fibers at node $n$ (from other nodes);
$I_{n, m}$ : Set of fibers coming from node $m$ to node $n$;

[^2]$O_{n}$ : Set of outgoing fibers at node $n$ (to other nodes);
$O_{n, m}$ : Set of fibers going out of node $n$ to node $m$;
$A_{n}$ : Set of add fibers at node $n$ (from local), including those used at the WXC, BXC, and FXC layer;
$D_{n}$ : $\quad$ Set of drop fibers at node $n$ (to local), including those used at the WXC, BXC, and FXC layer;
$\Xi_{n, m}$ : Traffic demands matrix. The element $T_{n, m}$ represents the traffic demands between node $n$ and node $m$ in terms of number of lightpaths.
$V_{i, o, s, d}^{n, w}: 1$, if at node $n$, there is a lightpath using wavelength $w$ to satisfy the traffic demands between node-pair $(s, d)$ going from fiber $i$ to fiber $o$ and 0 otherwise;

ILP Variables We define bypass fiber (band) as the fiber (band) within which all wavelengths are carrying bypass traffic. Bypass fiber/band can result in ports saving since the traffic within bypass fiber/band can be switched as a single entity through the FXC/BXC layer. Similarly, the bypass wavelength is defined as the wavelength within one non-bypass band which has to be demultiplexed to the WXC layer. According to above definitions, following variables are used to model the bypass traffic that is accommodated at different layers.
$A W_{i, o}^{n, w}: 1$, if at node $n$, there is a wavelength $w$ going from fiber $i$ to fiber $o$ at the WXC layer and 0 otherwise;
$A B_{i, o}^{n, b}: \quad 1$, if at node $n$, there is a bypass band $b$ going from fiber $i$ to fiber $o$ at the BXC layer (without going through the WXC layer) and 0 otherwise;
$A F_{i, o}^{n}: \quad 1$, if at node $n$, there is a bypass fiber from fiber $i$ to fiber $o$ at the FXC layer (without going through the BXC and WXC layers) and 0 otherwise;

FTB $B_{i}^{n}: \quad 1$, if the fiber $i\left(i \in I_{n}\right)$ is demultiplexed into the BXC layer at node $n$ and 0 otherwise;
$B T W_{i}^{n, b}: 1$, if the band $b$ within fiber $i\left(i \in I_{n}\right)$ is demultiplexed into the WXC layer at node $n$ and 0 otherwise;
$B T F_{o}^{n}$ : 1, if a band from the BXC layer is multiplexed to fiber $o\left(o \in O_{n}\right)$ at node $n$ and 0 otherwise;
$W T B_{o}^{n, b}: \quad 1$, if a wavelength from the WXC layer is multiplexed to band $b$ of fiber $o\left(o \in O_{n}\right)$ at node $n$ and 0 otherwise;
$W X C$ : Port count at WXC layer for all MG-OXCs;
$B X C$ : Port count at BXC layer for all MG-OXCs;
$F X C$ : Port count at FXC layer for all MG-OXCs;
The following variables are defined to allocate set of wavelengths for each waveband, which also identify the waveband granularity of each band. Note that the optimal solution may need less than $B$ wavebands.
$B W_{b, w}$ : 1, if wavelength $w$ belongs to waveband $b$ and 0 otherwise;

Objective Function The objective is to minimize the total port count in the network as specified by Equation (3.5).

$$
\begin{equation*}
\text { Minimize }[W X C+B X C+F X C] \tag{3.5}
\end{equation*}
$$

Constraints Routing and Wavelength Assignment: Equations (3.6-3.8) specify that the traffic for node-pair $(s, d)$ should be exactly added at node $s$ and dropped at node $d$ instead of other nodes.

$$
\begin{gather*}
\sum_{w, n=d, i \in A_{n}, o \in O_{n}} V_{i, o s, d}^{n, w}=T_{s, d} \forall n ;  \tag{3.6}\\
\sum_{w, n=s, i \in I_{n}, o \in D_{n}} V_{i, o, s, d}^{n, w}=T_{s, d} \forall n ;  \tag{3.7}\\
\sum_{w, n \neq s, i \in A_{n}, o \in O_{n}} V_{i, o, s, d}^{n, w}=\sum_{w, n \neq d, i \in I_{n}, o \in D_{n}} V_{i, o, s, d}^{n, w}=0 \quad \forall n ; \tag{3.8}
\end{gather*}
$$

Equation (3.9) ensures that no traffic is added and dropped at the same node. Equation (3.10) is the wavelength continuity constraint. Equation (3.11) guarantees that one wavelength can be used for satisfying at most one lightpath.

$$
\begin{gather*}
\sum_{i \in A_{n}, o \in D_{n}} V_{i, o, s, d}^{n, w}=0 \quad \forall w, s, d, n ;  \tag{3.9}\\
\sum_{i \in I_{m} \cup A_{m}, o \in O_{m, n}} V_{i, o, s, d}^{m, w}=\sum_{i \in I_{n, m}, o \in O_{n} \cup D_{n}} V_{i, o, s, d}^{n, w} \forall m, n, s, d, w ;  \tag{3.10}\\
\sum_{s, d, i \in A_{n} \cup I_{n}, o \in O_{n} \cup D_{n}} V_{i, o, s, d}^{n, w} \leq 1 \quad \forall w, n ; \tag{3.11}
\end{gather*}
$$

Non-uniform Waveband Switching: Equation (3.12) and (3.13) achieves the band assignment. Equation (3.12) specifies that one wavelength can exclusively belong to one
band and Equation (3.13) ensures that the total capacity for all bands equals the number of wavelengths per fiber.

$$
\begin{gather*}
\sum_{b \in[0, B-1]} B W_{b, w} \leq 1 \quad \forall w ;  \tag{3.12}\\
\sum_{b \in[0, B-1], w \in[0, W-1]} B W_{b, w}=W \tag{3.13}
\end{gather*}
$$

In non-uniform WBS networks, a lightpath going through MG-OXC node $n$ (i.e., $\sum_{s, d} V_{i, o, s, d}^{n, w}=1$ ) can only be processed by using $A W_{i, o}^{n, w}, A B_{i, o}^{n, b}$ or $A F_{i, o}^{n}$ when wavelength $w$ belongs to band $b$. In other words, if $B W_{b, w}=1$, then we can apply following two equations to ensure that a lightpath is properly switched through the MG-OXC node.

$$
\begin{gathered}
A F_{i, o}^{n}+A B_{i, o}^{n, b}+A W_{i, o}^{n, w} \leq 1 \quad \forall i \in I_{n} \cup A_{n}, o \in O_{n} \cup D_{n} ; \\
\sum V_{i, o, s, d}^{n, w} \leq A F_{i, o}^{n}+A B_{i, o}^{n, b}+A W_{i, o}^{n, w} \quad \forall i \in I_{n} \cup A_{n}, o \in O_{n} \cup D_{n} ;
\end{gathered}
$$

To convert above if-then relationship into linear expression, we introduce a large number $M$, and transform them into Equations (3.14-3.15). Note that the transformed linear expression is logically equivalent to the original form. In specific, if the considered wavelength $w$ belongs to band $b$ (i.e., $B W_{b, w}=1$ ), the right side of in Equation (3.14) equals 1, which exactly represents the first one of above $i f$-then relationships. On the other hand, if the considered wavelength $w$ does not belong to band $b$ (i.e., $B W_{b, w}=0$ ), this constraint is virtually omitted from the ILP model since $M$ dominates. The same technique is used to model the constraints in Equations (3.20) and (3.22).

$$
\begin{equation*}
A F_{i, o}^{n}+A B_{i, o}^{n, b}+A W_{i, o}^{n, w} \leq 1+\left(1-B W_{b, w}\right) * M \quad \forall i \in I_{n} \cup A_{n}, o \in O_{n} \cup D_{n} \tag{3.14}
\end{equation*}
$$

$$
\begin{equation*}
\left(B W_{b, w}-1\right) * M+\sum V_{i, o, s, d}^{n, w} \leq A F_{i, o}^{n}+A B_{i, o}^{n, b}+A W_{i, o}^{n, w} \quad \forall i \in I_{n} \cup A_{n}, o \in O_{n} \cup D_{n} ; \tag{3.15}
\end{equation*}
$$

In addition, the constraints in Equations (3.16-3.18) ensure that the traffic within the bypass fiber, bypass band or bypass wavelength can only be switched to the outgoing fiber exactly once. Equation (3.19) specifies that no traffic is added and dropped at the same node.

$$
\begin{gather*}
\sum A F_{i, o}^{n} \leq 1 \quad \forall i \in I_{n} \cup A_{n}, o \in O_{n} \cup D_{n} ;  \tag{3.16}\\
\sum A B_{i, o}^{n, b} \leq 1 \quad \forall i \in I_{n} \cup A_{n}, o \in O_{n} \cup D_{n}, 0 \leq b \leq B-1 ;  \tag{3.17}\\
\sum A W_{i, o}^{n, w} \leq 1 \quad \forall i \in I_{n} \cup A_{n}, o \in O_{n} \cup D_{n}, 0 \leq w \leq W-1 ;  \tag{3.18}\\
A F_{i, o}^{n}=A B_{i, o}^{n, b}=A W_{i, o}^{n, w}=0 \quad \forall b, w, i \in A_{n}, o \in D_{n} ; \tag{3.19}
\end{gather*}
$$

The constraints in Equations (3.20-3.25) are necessary to ensure that the bypass wavelength, and bypass waveband are demultiplexed/multiplexed using BTW/WTB, FTB/BTF demultiplexers/multiplexers. Equations (3.20-3.23) specify that a bypass wavelength has to go through WTB/BTF multiplexer and BTW/FTB demultiplexer before it can leave the node. Similarly, a bypass band has to go through BTF/FTB multiplexer/demultiplexer as shown in constraints (3.24-3.25).

$$
\begin{align*}
& W T B_{o}^{n, b} \geq A W_{i, o}^{n, w}+\left(B W_{b, w}-1\right) * M \forall o \in O_{n}, i \in I_{n} \cup A_{n} ;  \tag{3.20}\\
& B T F_{o}^{n} \geq W T B_{o}^{n, b} \forall o \in O_{n}, i \in I_{n} \cup A_{n} ;  \tag{3.21}\\
& B T W_{i}^{n, b} \geq A W_{i, o}^{n, w}+\left(B W_{b, w}-1\right) * M \forall o \in O_{n} \cup D_{n}, i \in I_{n} ;  \tag{3.22}\\
& F T B_{i}^{n} \geq B T W_{i}^{n, b} \forall o \in O_{n} \cup D_{n}, i \in I_{n} ;  \tag{3.23}\\
& B T F_{o}^{n} \geq A B_{i, o}^{n, b} \forall o \in O_{n}, i \in I_{n} \cup A_{n} ;  \tag{3.24}\\
& F T B_{i}^{n} \geq A B_{i, o}^{n, b} \forall o \in O_{n} \cup D_{n}, i \in I_{n} ; \tag{3.25}
\end{align*}
$$

Port Count: The following constraints specify the number of ports required at each layer of the MG-OXC.

$$
\begin{gather*}
W X C=\sum_{n} \sum_{i \in I_{n} \cup A_{n}, o \in O_{n} \cup D_{n}, w} A W_{i, o}^{n, w}  \tag{3.26}\\
B X C=\sum_{n}\left(\sum_{i \in I_{n} \cup A_{n}, o \in O_{n} \cup D_{n}, b} A B_{i, o}^{n, b}+\sum_{o \in O_{n}, b} W T B_{o}^{n, b}+\sum_{i \in I_{n}, b} B T W_{i}^{n, b}\right)  \tag{3.27}\\
F X C=\sum_{n}\left(\sum_{i \in I_{n} \cup A_{n}, o \in O_{n} \cup D_{n}} A F_{i, o}^{n}+\sum_{o \in O_{n}} B T F_{o}^{n}+\sum_{i \in I_{n}} F T B_{i}^{n}\right) \tag{3.28}
\end{gather*}
$$

### 3.3.2 Heuristic Algorithm for Non-uniform Waveband Switching

For a large network, the ILP model becomes intractable to solve in practice. We hence design an efficient heuristic scheme, namely, Simulated Non-uniform Waveband Assignment (SNWS), which can imitate non-uniform waveband switching using uniform waveband granularity.

The traffic between any node-pair $(s, d)$ is categorized into three tiers: Fiber-tier (FT[s][d]), Band-tier (BT[s][d]) and Wavelength-tier ( $W T[s][d]$ ) traffic as shown in Equations (3.29-3.31). To accommodate the traffic demands, SNWS employs four stages to efficiently group traffic with the same source or destination node and at least $\mathbb{W}$ overlapping hops along the routing paths. As to be shown, Fiber-tier traffic will be given the high priority to be accommodated first at the fiber layer in Stage 2, and Band-tier traffic is directly accommodated at the band layer in the Stage 3. For Wavelength-tier traffic, the lightpath demands are accommodated at the band layer when the number of lightpath demands is close to the band size as in Stage 3, and the remaining Wavelength-tier traffic is accommodated in Stage 4. In other words, we propose to accommodate $t$ lightpath demands using a bypass band even though $t$ is less than the band size $\mathbb{B}$, which may result in some wavelengths in a band are unused. We call such band as partially saturated band, which can simulate the non-uniform WBS by sacrificing certain unused wavelength(s).

$$
\begin{gather*}
F T[s][d]=\lfloor T[s][d] / W\rfloor  \tag{3.29}\\
B T[s][d]=\lfloor(T[s][d]-F T[s][d] * W) / \mathbb{B}\rfloor  \tag{3.30}\\
W T[s][d]=T[s][d] \% \mathbb{B} \tag{3.31}
\end{gather*}
$$

Stage 1: Path generation. We first use the $k$-shortest path algorithm [41], to generate the $k(k>=1)$ path(s), namely $P_{s, d}^{i}$, where $i=1,2, \ldots, k$, for each node-pair $(s, d)$. Then, starting with the node-pair having the largest traffic, we assign one of the $k$ path to a nodepair while minimizing maximum link load $M$, until all the node-pairs with traffic demands are considered. The maximum link load $M$ is defined as the largest link load among all the links in the network and the link load is defined as the summary of all traffic on the link. We denote the selected path for node-pair $(s, d)$ as Path $_{s, d}$, and the nodes along Path $_{s, d}$ are $s, s_{1}, s_{2}, \ldots, d$. The sub-path of Path $_{s, d}$ is called $S u b_{i, j}$, where $i, j$ are the first and the last node of the sub-path along $\mathrm{Path}_{s, d}$.

Stage 2: Fiber-tier traffic accommodation. Starting with the node-pair having the largest traffic demands, we use First-fit scheme to assign bypass fiber(s) in the selected routing path to satisfy the Fiber-tier traffic between this node pair, and update the respective $F T[s][d]$. If the selected routing path fails to satisfy the Fiber-tier traffic, the alternate routing paths from the $k$-shortest path $P_{s, d}^{i}$ will be checked according to the ascending order of the path length, to accommodate the Fiber-tier traffic.

Stage 3: Band-tier traffic accommodation. This stage efficiently accommodate traffic at the band layer using Algorithm 2, where $b$ (initialized to 0 ) is the index of the waveband from which to search an available waveband using First-fit scheme. There are two phases in this stage. In the first phase, $Q$ is initialized to $Q=\mathbb{B}$ and $T$ is the band-tier traffic $B T[s][d]$. We start with the node-pair $(s, d)$ with the longest routing path, and use Algorithm 2 to accommodate the traffic for $(s, d)$. Then Algorithm 2 is employed to accommodate the traffic for node-pairs along the same-source sub-paths $S u b_{s, s_{i}}$ and the same-destination sub-paths $S u b_{s_{i}, d}$ sequentially, until all the band-tier traffic is considered. Note that the sequential
accommodation of traffic along Path $_{s, d}$, the same-source and same-destination sub-paths of Path $_{s, d}$ are aiming to facilitate the formation of bypass fibers (by grouping these bypass band traffic).

After all the band-tier traffic is accommodated, we consider the node-pairs with Wavelength-tier traffic $W T[s][d]$ close to waveband granularity in the second phase. In specific, when the Wavelength-tier traffic $W T[s][d]$ and band size ratio $(W T[s][d] / \mathbb{B})$ is no less than a threshold $\theta$, we employ bypass band to accommodate the traffic at band layer at the expense of some unused wavelengths within the same band. Therefore, in the second phrase of this Stage, we set $Q=\theta * \mathbb{B}$ and $T=W T[s][d]$, and accommodate all the traffic between node-pairs with over $\theta * \mathbb{B}$ wavelength-tier traffic.

```
Algorithm 2 Traffic Accommodation Algorithm
    Begin:
    while \(T>=Q\) do
        Find free band \(m\) starting with \(b\) along the path;
        if the band \(m\) exists then
            \(b \leftarrow(m+1) \% \mathbb{B}\)
        else
            Select an alternative path for node pair \((s, d)\) from \(P_{s, d}^{i}\), update Path \(_{s, d}\)
            continue
        end if
        Assign band \(m\) to the traffic;
        Update \(T\);
    end while
```

Stage 4: Wavelength-tier traffic accommodation. Starting with the node-pair $(s, d)$ that has the maximum bypass traffic, we accommodate the remaining wavelength-tier traffic with more than $\mathbb{W}$ hops in the routing path by using the First-fit scheme. Then traffic along the same-destination sub-path $s u b_{s, s_{i}}$ and $s u b_{s_{i}, d}$ is sequentially considered using the First-fit scheme. Finally, the remaining traffic demands are accommodated by using Algorithm 2 with $Q=1$ and $T=W T[s][d]$.

### 3.3.3 Performance Evaluation and Comparison

In this section, we study the performance of SNWS and compare it with a representative waveband switching algorithm, namely, Balanced Path routing with Heavy-Traffic first waveband assignment (BPHT) [6]. We also study the impacts of the thresholds $\theta$ and $\mathbb{W}$.

Performance On a Six-node Network For the six-node network with $F=4$, a traffic matrix is randomly generated for each node-pair $(s, d)$, and the traffic size is randomly generated in the range of $[0,5]$. Two different representative random traffic patterns where the total traffic among all node-pairs is 16, and 25 respectively, are simulated using the ILOG CPLEX[47]. As shown in Table 3.2, we collect the port count from the Waveband Oblivious optimal Routing and Wavelength Assignment (WBO-RWA) [6], Optimal uniform WBS[6], Optimal non-uniform WBS, and the proposed heuristic SNWS algorithm.

Table 3.2. Performance for the six-node network

|  | WBO-RWA |  | Optimal Uniform WBS |  | Optimal Non-uniform WBS |  | SNWS |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\sum T_{s, d}$ | 16 | 25 | 16 | 25 | 25 | 58 | 16 | 25 |
| Port count | 64 | 106 | 48 | 74 | 36 | 46 | 68 |  |

From the table, we see that the performance of SNWS is close to that of the ILP model (Optimal Non-uniform WBS) and better than that of Optimal uniform WBS and WBO-RWA. The comparison between optimal uniform WBS and optimal non-uniform WBS indicates that non-uniform waveband switching achieves smaller node size (or more port saving) than uniform waveband switching does. Our studies also shows that in the process of minimizing the total number of ports, both our ILP solution and heuristic SNWS for non-uniform WBS may utilize a longer path even though a shorter path (that cannot be packed into a band) exists, which indicates the tradeoff between the required number of wavelength-hops (or wavelengths) and port saving in WBS networks.

For a large network with 100 wavelengths per fiber and $\mathbb{B}=10$ shown in Figure 3.4, the ILP becomes intractable, hence we only show the performance of the heuristic algorithm in the following.


Figure 3.7. WBS network with the same number of traffic demands at each node

Uniform Traffic To further evaluate the performance of SNWS, we compare it with BPHT, which has been proved to be near-optimal in uniform WBS networks [6]. The performance comparison is shown in Figure 3.7, where $\theta=0.7, \mathbb{W}=3, W=100$, and $\mathbb{B}=5$. The vertical axis stands for the total port count of the whole network, and the horizontal axis corresponds to the traffic size, $r$, equals to the number of lightpath requests from each node-pair. As shown in the figure, the proposed SNWS algorithm outperforms the BPHT algorithm by a noticeable margin (close to $20 \%$ on average) in WBS networks with the uniform traffic demands. In fact, the performance of SNWS may be further improved when we decrease $\theta$ in the case that the number of wavelength is sufficient. In addition, when the traffic demands for each node-pair $(r)$ are a multiple of $\mathbb{B}$, the performance of the two algorithms is similar as shown in the Figure 3.7 (i.e., $r=\mathbb{B}=5$ or $r=2 \times \mathbb{B}=10$ ). This is due to the high probability of grouping traffic into bypass bands by both algorithms when the traffic demands for each node-pair are a multiple of the waveband granularity.

Random Traffic Since random traffic can more accurately represent the real WBS network deployment, we also simulate both schemes under the random traffic scenarios in which the traffic demands are randomly generated within the range of $[0, r]$ for each nodepair. As shown in Figure 3.8, the proposed SNWS algorithm again outperforms the BPHT


Figure 3.8. WBS network with the random number (in the range of in $[0, r]$ ) of traffic demands
algorithm with a large improvement in the case with random traffic. In fact, our results show that the larger traffic demands, the higher port saving can be achieved by the proposed SNWS algorithm.
$\theta$ and $\mathbb{W}$ To further study the impacts of $\theta$ and $\mathbb{W}$ on the performance of the proposed SNWS algorithm, we run extensive simulations based on the traffic randomly generated within the range $[0,10$ ] (in terms of number of lightpaths). Figure 3.9 shows the average performance for numerous running instances of the simulation. In Figure 3.9, the X -axis represents the threshold $\theta$ (i.e., the traffic demands and band size ratio) and Y-axis stands for the ratio for wavelength usage and port saving comparing to traditional OXC network. More specifically, the wavelength usage ratio refers to the ratio between the number of wavelengths carrying traffic and the total number of wavelengths (include the unused wavelengths in partially saturated bands). The port saving ratio is the ratio between the number of reduced ports by MG-OXCs and the number of port used by T-OXCs. Clearly, the higher $\theta$ value indicates higher wavelength usage ratio since less wavelengths are unused in the partially saturated bands. The port savings decrease with $\theta$ when $\theta$ is larger than $20 \%$. This is because more traffic is operated at the WXC layer when $\theta$ increases. Figure 3.9 also shows


Figure 3.9. Port savings and wavelength usage
that a very small $\theta$ (e.g., $<20 \%$ ) does not help in port savings since numerous un-saturated bands are produced in earlier iterations, which hinder the usage of un-saturated bands in later iterations as well as the wavebanding.

### 3.4 Waveband Switching with Dynamic Traffic

In this section, we analyze the port saving and blocking in dynamic WBS networks. Our analysis include the usage pattern analysis of demultiplexers and multiplexers, the lower/upper bound of the design parameters of the reconfigurable MG-OXC. Based on the analysis, we also propose a novel dynamic WBS algorithm. The following notations are used through this section.
$X$ : Number of incoming fibers connected to a node;
$F$ : $\quad$ Number of wavelengths per fiber;
$B$ : Number of wavelengths per band;
$P: \quad$ Number of bands per fiber (i.e., $P=\frac{F}{B}$ );
$Y$ : Number of band cross-connect layer ports from fiber-toband (FTB) demultiplexers;
$D_{n}$ : Number of band-to-wavelength (BTW) demultiplexers at Node $n$;
$M_{n}$ : Number of wavelength-to-band (WTB) multiplexers at Node $n$;
$\alpha$ : The ratio of fibers (to the total number of fibers) that can be demultiplexed into bands using FTB ports;
$\beta$ : The ratio of bands that can be demultiplexed to wavelengths using BTW ports;
$\lambda_{s, d}$ : Arrival rate of the lightpath request from $s$ to $d$, which follows the Poisson process;
$\Lambda_{k}$ : The birth rate of an M/M/C/C Markov chain when $k$ servers are in use;
$\mu_{k}$ : The death rate of an $\mathrm{M} / \mathrm{M} / \mathrm{C} / \mathrm{C}$ Markov chain when $k$ servers are in use;
$P_{s, d}$ : The routing path for node-pair $(s, d)$ when adopting a fixed single path;
$P_{s, d}^{i}$ : The $i$-th routing path for node-pair $(s, d)$ when adopting multiple paths;
$H_{p}$ : Hop number of Path $p$.

### 3.4.1 Analysis of Port Usage with Reconfigurable Three-layer MG-OXC

Based on the three-layer MG-OXC, we elaborate the impacts of design parameters and analyze the port consumption pattern.

Design parameters of the reconfigurable MG-OXC architecture In the reconfigurable three-layer MG-OXC shown in Fig. 2.3, $X$ denotes the number of input fibers, $Y$ denotes the number of BXC ports from FTB demultiplexers. The parameter $\alpha(\leq 1)$ is the ratio of fibers (to the total number of fibers) that can be demultiplexed into bands using FTB ports, and the parameter $\beta(\leq 1)$ is the ratio of bands that can be demultiplexed to wavelengths using BTW ports. Therefore this MG-OXC architecture allows $\lfloor\alpha X\rfloor$ fibers to be demultiplexed into bands and $\lfloor\beta Y\rfloor$ of these bands to be demultiplexed into wavelengths simultaneously. Symmetrically, the limited deployment of BTF and WTB multiplexers only allows a limited number of bands and wavelengths to be multiplexed to fiber and band layer, respectively. We assume that $\alpha=1$, which means each MG-OXC node is equipped with the maximum number of FTB/BTF demultiplexers/multiplexers and all fibers can be demultiplexed to the BXC layer simultaneously ${ }^{3}$. The number of bands that can be demultiplexed to the WXC layer at Node $n$ is limited by $D_{n}=X \times P \times \beta$. Similarly, the number of bands that can be multiplexed from the WXC layer is limited by $M_{n}=X \times P \times \beta$. Hence, we hereafter only focus on the BTW/WTB demultiplexers/multiplexers. We refer to a band without traffic as an empty band. Following our convention, when all the lightpaths within one band go through only the BXC layer at a node, we call this band as a bypass band. Otherwise, the band is called as a non-bypass band, which has to be demultiplexed from or multiplexed to the BXC layer.

Allocation of multiplexers and demultiplexers In WBS networks, the consumption of demultiplexers/multiplexers is directly related to traffic grouping. Inefficient traffic

[^3]

Figure 3.10. Allocation of DEMUX/MUX to satisfy a new lightpath
grouping can lead to the exhaustion of the demultiplexers/multiplexers at an MG-OXC node, which may in turn block future traffic requests going through this node. For a specific lightpath request, we define the band with the wavelength for the lightpath in the input fiber as the input band, and the band with the wavelength for the lightpath in the output fiber as the output band. Due to the wavelength continuity constraint, input band and output band must have the same band index. Figure 3.10 shows an example of traffic grouping and the necessary allocation of demultiplexers/multiplexers (DEMUXs/MUXs). As shown in the figure, an existing lightpath resides in a bypass band from input band $A$ to output band $O$. To satisfy a new lightpath request from input band $I$ to output band $O$, the node has to allocate demultiplexers/multiplexers for the traffic grouping. This is because the bands from $A$ and $I$ have to be demultiplexed first at this node. Then the two lightpaths are multiplexed together to form the output band $O$. Such traffic grouping requires two additional demultiplexers and one multiplexer. If the node has less than two unused demultiplexers and one unused multiplexer, the new traffic has to be blocked by this node.

To accommodate a new lightpath request from input band $I$ to output band $O$, ten possible cases based on the existing configuration or traffic at this node can exist as shown in Fig. 3.11. The input band $I$ and output band $O$ can be bypass, non-bypass, or empty
band, which generate 9 combinations, namely, case (A), (B), (C), (E), (F), (G), (H), (I), and (J) as shown in Fig. 3.11. When both $I$ and $O$ are occupied by a bypass band, case (E) corresponds to the case that the bypass band through $I$ and the bypass band through $O$ are two different bypass bands. Hence, we need an additional case (D) to represent the possible bypass band from $I$ directly to $O$.

The example in Fig. 3.10 corresponds to the case (A). In case (B), the band through $I$ is empty and existing traffic from $A$ to $O$ is non-bypass band (going through DEMUXs/MUXs). Grouping the new lightpath request to $O$ only requires one more demultiplexer. In cases (C), no extra DEMUXs/MUXs are required since both $I$ and $O$ are empty bands. When the existing lightpath has the same input and output band as the new request, the wavebanding can be achieved without costing extra DEMUXs/MUXs as shown in case (D). Case (E) costs the most extra DEMUXs/MUXs among all the cases because we have to demultiplex/multiplex two bands for the grouping at this node. The amount of additional DEMUXs/MUXs required for this node to satisfy a new request in other cases can be similarly derived, which is shown in Table 3.3. Note that among all the 10 cases, four cases require 0 additional DEMUXs, two cases require 2 additional DEMUXs, and four cases require 4 additional DEMUXs. Similarly, four cases require 0 additional MUXs, two cases require 2 additional MUXs, and four cases require 4 additional MUXs.

Table 3.3. Ten possible cases of DEMUX/MUX consumption to satisfy a new lightpath

| request |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Case | Input band | Output band | Additional <br> DEMUX | Additional <br> MUX |  |
| A | Empty | Bypass | 2 | 1 |  |
| B | Empty | Non-bypass | 1 | 0 |  |
| C | Empty | Empty | 0 | 0 |  |
| D | New demand in the bypass <br> band from $I$ to $O$ | 0 | 0 |  |  |
| E | Bypass | Bypass | 2 | 2 |  |
| F | Bypass | Non-bypass | 1 | 1 |  |
| G | Bypass | Empty | 1 | 2 |  |
| H | Non-bypass | Bypass | 1 | 1 |  |
| I | Non-bypass | Empty | 0 | 1 |  |
| J | Non-bypass | Non-bypass | 0 | 0 |  |



Figure 3.11. Different cases for DEMUX/MUX increasing


Figure 3.12. The Markov chain for DEMUX usage

### 3.4.2 Analysis of the Design Parameter

Since the design parameter $\beta$ directly affects the number of DEMUXs/MUXs of an MG-OXC node (which further affects the blocking), we analyze the lower bound and upper bound of $\beta$ in the next.

Upper bound of $\beta$ Under the assumption that $\alpha=1$, the total number of ports, namely $T P$, required at an MG-OXC node can be calculated as in Eq. (3.32), where $X$ is the number of fibers, $F$ is the number of wavelengths per fiber, and $P$ is the number of bands per fiber. The total port number $T P$ consists of $4 \times X$ ports at the FXC layer, $2 \times(1+\beta) \times X \times P$ ports at the BXC layer, and $2 \times X \times P \times B \times \beta=2 \times X \times F \times \beta$ ports at the WXC layer. To be cost-efficient, the port number TP for the MG-OXC should be no more than that of the corresponding T-OXC (i.e., $T P<=2 \times X \times F$ ). Thus based on Eq. (3.32), the upper bound of $\beta$ can be obtained as in Eq. (3.33). For example, when $F=100$, $P=10$, we have $\beta<=0.8$, and $\beta=0.8$ is the upper bound.

$$
\begin{gather*}
T P=4 \times X+2 \times(1+\beta) \times X \times P+2 \times X \times F \times \beta  \tag{3.32}\\
\beta \leq 1-2 \times \frac{P+1}{P+F} \tag{3.33}
\end{gather*}
$$

Lower bound of $\beta$ Limited number of DEMUXs/MUXs in WBS networks with dynamic traffic requests can result in the call blocking. Hence, $\beta$ is also limited with a lower
bound by the allowable blocking probability in the network. Here we propose an analysis model to approximately derive the lower bound of $\beta$. We assume that for any node-pair $(s, d)$, a fixed routing path is calculated; the traffic arrival follows the Poisson distribution with rate $\lambda_{s, d}$ for a node-pair $(s, d)$; the service time for the call is exponentially distributed with a mean of 1 . Moreover, we assume that the available DEMUXs/MUXs are independent from one node to another. Given the symmetrical traffic demand and DEMUXs/MUXs in the network, only DEMUXs are considered in the steady state of the network. If the new lightpath requests are uniformly distributed into the ten cases in Fig. 3.11, the expectancy $E$ of additional DEMUXs for an incoming request is $E=0.2 \times 2+0.4 \times 1+0.4 \times 0=0.8$, since we have two cases, four cases, and four cases require 2, 1, and 0 additional DEMUXs, respectively. Thus we can calculate the Poisson rate for DEMUX usage at a specific Node $n$ as in Eq. (3.34).

$$
\begin{equation*}
\lambda_{n}=E \times \sum_{n \in P_{s, d}} \lambda_{s, d} \tag{3.34}
\end{equation*}
$$

We model the consumption of DEMUXs at Node $n$ using an $M / M / C / C$ Markov Chain (Repairman) Model as shown in Fig. 3.12, where $C=D_{n}=X \times P \times \beta$ as discussed above. The birth rate for this Markov chain is $\Lambda_{k}=\lambda_{n}$, for $k=0, \ldots, D_{n}-1$, and the death rate is $\mu_{k}=k$, for $k=1, \ldots . D_{n}$, and $\mu_{0}=\Lambda_{D_{n}}=0$. According to the Erlang's formula, we let $\pi_{n}(c)$ denote the probability that $c$ DEMUXs are in use at Node $n$. Then the blocking probability at Node $n$ is given in Eq. (3.35).

$$
\begin{equation*}
\pi_{n}\left(D_{n}\right)=\frac{\left(\lambda_{n}\right)^{D_{n}} / D_{n}!}{\sum_{j \in\left[0, D_{n}\right]}\left(\lambda_{n}\right)^{j} / j!} \tag{3.35}
\end{equation*}
$$

If the allowable blocking probability for node-pair $(s, d)$ is know, say $Q$, then the blocking probability along the route should be no more than $Q$, which constrains the lower bound of $\beta$ as shown in Eq. (3.36) after a substitution of $\pi_{n}\left(D_{n}\right)$ by Eq. (3.35), $\lambda_{n}$ by Eq. (3.34), and $D n$ by $X \times \beta \times P$.

$$
\begin{equation*}
1-\prod_{n \in P_{s, d}}\left(1-\pi_{n}\left(D_{n}\right)\right) \leq Q \tag{3.36}
\end{equation*}
$$

### 3.4.3 Weighted Graph-based Waveband Assignment (WGB)

When accommodating a new lightpath request along a selected path, additional demultiplexers/multiplexers may be used as enumerated in Fig. 3.11 and Table 3.3. Instead of randomly choosing or using a first-fit strategy to select the band (which in turn determines the required additional multiplexers/demultiplexers), we propose a weighted graph-based waveband assignment (WGB) algorithm. The proposed scheme works as follows.

1. First, we use the $k$-shortest path algorithm [41] to generate $k$ ( $k>=1$ ) path(s), namely $P_{s, d}^{h}$, where $h=1,2, \ldots, k$, for each node-pair $(s, d)$. And those paths are ordered nondecreasingly according to the hop number. For example, for the node-pair $(S, D)$ shown in Fig. 3.13(a), we may find the path $S-U-V-D$ and path $S-X-Y-Z-D$ when $k=2$.
2. Second, along each candidate path of the $k$-shortest path, we separate each node into $P$ band nodes. For the example shown in Fig. 3.13(a), along the first path, we create band nodes $U_{0}, U_{1}$ for Node $U$, and $V_{0}, V_{1}$ for Node $V$ as shown in Fig. 3.13(b) when $P=2$. The resulted graph is named as weighted graph and the weight assignment for each node will be described in the next step.
3. To explicitly see the path as well as the band that cause the least extra demultiplexers and multiplexers, we need to assign weights for each band node in the weighted graph. To obtain the weight, we further create an auxiliary graph named Band Graph for each Band Node. The extra demultiplexer/multiplexers of band $b$ depend on the current port usage from the input fiber to the output fiber. Note that the auxiliary graph is a complete bipartite graph. The bipartite graph has $\bar{X}$ nodes on each side ( $\bar{X}$ is the number of fibers per link) since band $b$ may come from any of the $\bar{X}$ input fibers and leave the node through any of the $\bar{X}$ output fibers. For example, the band graph corresponding to band node $V_{0}$ is shown in Fig. 3.14 when $\bar{X}=3$. Now it is

(a) 2 Shortest Paths

(b) Weighted Graph

Figure 3.13. 2-shortest paths and weighted graph


Figure 3.14. Weight assignment using the band graph
straightforward to assign weight to the edges for the bipartite graph at Node $n$ to reflect the cost $B T_{i, o}^{n, b}$ (in terms of additional demultiplexers/multiplexers) for a new lightpath request using the band $b$ of the corresponding input fiber $i$ (the corresponding vertex is $I F B_{i, b}$ ) to the band $b$ of the output fiber $o$ (the corresponding vertex is $O F B_{o, b}$ ) as in Eq. (37) based on these cases in Fig. 3.11. We finally go back to the weighted graph and assign the weight $W T_{n, b}$ for the band node representing Node $n$ at band $b$ with the minimum value among all $B T_{l, m}^{n, b}$ as shown in Eq. (3.38), where $l, m \in[0, \bar{X}-1]$.
4. Based on the weighted graph, use Algorithm 3 to accommodate the request.

The proposed scheme tries to conservatively allocate the demultiplexers/multiplexers in the waveband assignment process based on the auxiliary weighted graph. A band corresponds to the minimum weight is selected to preserve more demultiplexers/multiplexers for future traffic. For the weight assignment, Eq. (37) assigns the weight to the edges in Band Graph based on the available demultiplexers/multiplexers and the additional demultiplexers/multiplexers to satisfy a new request. For example, in case (E), the weight is set to $2 / \bar{D}_{n}+2 / \bar{M}_{n}$ at Node $n$ to reflect the request of two additional demultiplexers and two extra multiplexers, where $\bar{D}_{n}\left(\bar{M}_{n}\right)$ is the current available demultiplexers (multiplexers) at Node $n$.

In Algorithm 3, the cost $R T_{b, i}$ for using band $b$ along the $i$-th shortest path is obtained using Eq. (3.39) by considering both the port consumption and the hop number. A band (say band $b$ ) along the path (say $m$-th path) with the minimum $R T_{b, m}$ will be chosen to accommodate the new lightpath request since potentially it can preserve the most demultiplexers/multiplexers. The proposed scheme can also be implemented in a distributed manner. To achieve that, we can let each node construct the weighted graph independently. Then the control packet with fields $R T_{b, i}$ for each band $b$ can travel through the given $i$-th path. The value of $R T_{b, i}$ for each band $b$ is updated at each node (say Node $n$ ) by adding the corresponding weight $W T_{n, b}$. Finally, the $i$-th path and band $b$ with the minimum $R T_{b, i}$ can be chosen as the routing path and band, respectively.

$$
B T_{i, o}^{n, b}= \begin{cases}0, & \text { if } b \in \operatorname{case}(C, D, J)  \tag{3.37.1}\\ 1 / \bar{D}_{n}, & \text { if } b \in \operatorname{case}(B) \\ 1 / \bar{M}_{n}, & \text { if } b \in \operatorname{case}(I) \\ 1 / \bar{D}_{n}+1 / \bar{M}_{n}, & \text { if } b \in \operatorname{case}(H, F) \\ 2 / \bar{D}_{n}+1 / \bar{M}_{n}, & \text { if } b \in \operatorname{case}(A) \\ 1 / \bar{D}_{n}+2 / \bar{M}_{n}, & \text { if } b \in \operatorname{case}(G) \\ 2 / \bar{D}_{n}+2 / \bar{M}_{n}, & \text { if } b \in \operatorname{case}(E)\end{cases}
$$

$$
\begin{equation*}
W T_{n, b}=\min _{l, m} B T_{l, m}^{n, b} \tag{3.38}
\end{equation*}
$$

$$
\begin{equation*}
R T_{b, i}=\frac{\sum_{n \in P_{s, d}^{i}} W T_{n, b}}{H_{P_{s, d}}} \tag{3.39}
\end{equation*}
$$

```
Algorithm 3 Waveband Assignment for a request between node-pair \((s, d)\)
    if \(H_{P_{s, d}^{i}}<2\) for any \(i \in[1, k]\) AND there exist continuous available wavelength(s) along
    \(P_{s, d}^{i}\) then
        Use the first continuous available wavelength along \(P_{s, d}^{i}\) to accommodate the request;
        Exit;
    end if
    In the Weighted Graph, find a path (say the \(m\)-th path) with the minimum value of \(R T_{b, m}\)
    (using Eq. (3.39));
    if (No band has continuous available wavelength or ports along its path) then
        Block and Exit;
    end if
    Use the first continuous available wavelength in band \(b\) along the \(m\)-th path to accommo-
    date the request;
    Update \(\bar{D}_{n}, \bar{M}_{n}\) for each node along the \(m\)-th path;
```


### 3.4.4 Simulation and Performance Analysis

We simulate the proposed weighted graph-based waveband assignment (WGB) algorithm using the 14 -node NSF network, and the 24-node USANet network as the topology. For the comparison, we also simulate a First-fit scheme which uses a first-fit strategy to find a continuous available wavelength sequentially over the $k$-shortest paths. In both networks, there are two fibers for each link, with one per direction. We set $F=20, P=10$ (i.e., 2 wavelengths per band) for the 14 -node NSF network and $F=40, P=10$ for the 24 -node USANet network. The lightpath requests arrive at the network according to a Poisson process with arrival rate $\lambda$ and are randomly distributed over the all the node-pairs within the network. The request holding time is exponentially distributed with one unit as the mean value. All simulations are conducted with 5 thousands of dynamic lightpath requests, and results are collected as the mean of 100 running instances of the simulation.

The impact of the design parameter $\beta$ The blocking probability for the Firstfit waveband assignment and WGB in the NSF network with various $\beta$ are shown in Fig. 3.15. Figure 3.15 also shows the blocking probability due to the port insufficiency with various $\beta$. First, according to our discussion above, the upper bound of $\beta=1-2 \times \frac{P+1}{P+F}=$ $1-2 \times \frac{10+1}{10+20} \simeq 0.267$, which means $\beta$ should be no more than 0.267 to be cost-efficient. In Fig. 3.15, WGB can actually approach the lowest blocking probability with $\beta=0.2$. Second, when $\beta>=0.3$, further increasing $\beta$ (i.e., deploying more demultiplexers/multiplexers) does not help in WGB for reducing the blocking probability in the network. This can be seen from the relative stable trend of the blue line after $\beta>=0.3$. Alternatively, we can observe the blocking caused by port insufficiency with WGB (the red line) is 0 after $\beta>=0.3$. Those two observations indicates over-large $\beta$ may not help in reducing the blocking probability since most blocking is caused by wavelength shortage in such cases. Third, in contrast to WGB, the First-fit scheme has higher blocking when $\beta<=0.3$ and the blocking caused by port shortage becomes 0 only after $\beta>=0.5$ (the purple line). This indicates that to effectively use the reconfigurable MG-OXC nodes in WBS network, an intelligent algorithm is necessary. Fourth, First-fit algorithm can outperform WGB when $\beta$ is very large, this is because the First-fit strategy prefers to employ shorter paths to save wavelengths while the port shortage is not the concern in such cases. We also note that a lower bound for $\beta$ based on the simulation is around 0.1 if the allowable blocking probability is 0.01 . For the 24 -node network with $\lambda=600$, the blocking under various $\beta$ is shown in Fig. 3.16, which shows the same pattern as above. However, for this time, the blocking for both schemes goes to 0 when $\beta$ increases to certain value (e.g., $\beta \geq 0.4$ for WGB) since there is no blocking caused by the wavelength shortage in such cases. Also note that in this case, the upper bound for $\beta$ is $1-2 \times \frac{10+1}{10+40}=0.56$. We hence conclude that WBS network can save ports (by limiting $\beta$ ) and achieve an allowable blocking probability when accommodating dynamic traffic requests.

The impact of the parameter $k$ We also study the impact of the parameter $k$ (i.e., $k$-shortest path) on the blocking probability. For the NSF network, we set $\lambda=200, \beta=0.2$.


Figure 3.15. $\lambda=200, k=5$ inFigure 3.16. $\lambda=600, k=5$ in the NSF network


Figure 3.17. Blocking vs. Load in 14-node network

For the 24 -node network, we set $\lambda=600, \beta=0.4$. As shown in Table 3.4, for both First-fit scheme and the WGB algorithm, increasing $k$ helps in reducing the blocking probability. The reduction in blocking is obvious when $k$ is increased within a relatively small value, for example, $k<=4$. However, increasing $k$ over 4 does not reduce the blocking further for the WGB scheme. This is because both First-fit and WGB may explore more candidate paths with larger $k$. When blocking is caused by insufficient resources at certain nodes, exploring more paths provides the possibility of satisfying more traffic requests. When $k$ is sufficient large, further increasing might not help when all the candidate paths are congested.

| Table 3.4. Results with various $k$ |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $k$ | 1 | 2 | 3 | 4 | 5 |
| 14-node: First-fit | 0.058 | 0.027 | 0.022 | 0.021 | 0.015 |
| 14-node WGB | 0.046 | 0.023 | 0.014 | 0.008 | 0.008 |
| 24-node: First-fit | 0.108 | 0.085 | 0.075 | 0.061 | 0.052 |
| 24-node WGB | 0.042 | 0.013 | 0.008 | 0.001 | 0.001 |

Blocking probability under various traffic loads To study the performance of the proposed scheme under various traffic loads, we simulate the WGB and First-fit scheme in the NSF network with $\beta=0.2, k=5$ and the results are shown in Fig. 3.17. The results for the 24 -node network with $\beta=0.4$ and $k=5$ are shown in Fig. 3.18. The $x$-axis in Fig. 3.17 and Fig. 3.18 is the arrival rate of the lightpath request while $y$-axis is the corresponding blocking probability. Since larger $\lambda$ implies higher traffic load, we can see
the blocking probability is increasing for both WGB and First-fit scheme with the load. In both the NSF network and the 24-node network, we can observe that WGB can outperform First-fit by up to $100 \%$ in terms of the blocking probability.


Figure 3.18. Blocking vs. Load in 24-node network


Figure 3.19. 14-node network with incremental traffic

The performance of WGB under incremental traffic We test the performance of the WGB under incremental traffic with a comparison with the MOR algorithm [37], and First-fit scheme. With the incremental traffic, it is unfair to compare the average blocking probability since the incremental request holds the resources instead of releasing them after a holding time. Consequently, after the network resources are saturated, any request will be blocked regardless of the specific scheme. In the following, we hence compare the average


Figure 3.20. 24-node network with incremental traffic
first-blocking performance, which is measured as the total accommodated requests before the occurrence of the first blocking event in the network. The results are shown in Table 3.5 with $\lambda=200,600$ for the 14 -node and 24 -node network, respectively. From Table 3.5, we can observe that under various $\beta$, WGB can accommodate the largest number of requests among the 3 schemes, and the advantage of WGB are more obvious in the 24 -node network. We further show the results in the case that the total blocking events occur 10, 20, 30, 40, 50 times in Fig. 3.19 and Fig. 3.20. This metric is also interesting since the network provider may allow the blocking events up to a threshold before upgrading resources. Figure 3.19 shows that the number of satisfied requests before the respective number of blocking events occurs in the 14 -node network when $\beta=0.2$. Again, we can observe with the same number of blocking events, WGB can outperform both MOR and First-fit schemes. The results for 24 -node with $\beta=0.3$ are given in Fig. 3.20, which shows that WGB outperforms others by a even large margin (up to $40 \%$ ).

Table 3.5. Results for various schemes under incremental traffic

| $\beta$ | 0 | 0.1 | 0.2 |
| :---: | :---: | :---: | :---: |
| 14-node: First-fit | 189 | 199 | 218 |
| 14-node: MOR | 164 | 190 | 198 |
| 14-node: WGB | 189 | 204 | 229 |
| $\beta$ | 0.1 | 0.3 | 0.5 |
| 24-node: First-fit | 203 | 287 | 411 |
| 24-node: MOR | 186 | 310 | 403 |
| 24-node: WGB | 299 | 506 | 619 |

### 3.5 Wavelength Retuning in Dynamic WBS Networks

Since it is unavoidable to make short-sighted decision in dynamic WBS networks, we resort to a adaptive Re-optimization approach to adjust the resource allocation. In this dissertation, particularly, we study the approach of wavelength retuning.

### 3.5.1 The Concept of Wavelength Retuning

The idea of wavelength retuning is to change the wavelength of one lightpath without shifting the route of the lightpath. Retuning the wavelength of one lightpath (say $\lambda_{1}$ ) can release this wavelength at all the links that the lightpath spans. If one (or some) of these links reside(s) in the route of another upcoming lightpath request $l_{2}$, then $l_{2}$ may be able to use $\lambda_{1}$ along its route if $\lambda_{1}$ is also available in all the remaining links of $l_{2}$ 's route. This is particularly useful for avoiding the blocking of $l_{2}$ when $\lambda_{1}$ is the only continuous available wavelength along $l_{2}$ 's route. A retuning scheme normally consists of several components [48-51]: a decision on the choices of the existing lightpath(s) to be tuned; migration steps of the rerouted lightpaths; and the accommodation of the otherwise blocked new lightpath. The migration of the existing lightpath(s) introduces a disruption time to those lightpaths and may affect a large amount of traffic in optical networks. Thus minimizing the disruption time is one important goal for rerouting schemes. To achieve this goal, one can establish a new lightpath before stopping the old lightpath. The wavelength and resource along the old lightpath are released only after the new lightpath replaces the old one. Also, the retuning operations are generally applied only when a regular routing and wavelength assignment fails (i.e., a blocking event occurs). To reduce the number of connections influenced by rerouting (hence the total disruption time), one general strategy adopted is to limit the number of existing lightpaths to be retuned per blocking to be one [48,51].

In a dynamic WBS network, the blocking probability of lightpath requests can result from both the wavelength shortage, and the limited number of demultiplexers/multiplexers. Naive wavelength retuning approach in WBS networks may increase the available wavelength
resources at the expense of more used ports, which may not be helpful in reducing blocking probabilities. Thus, the wavelength retuning in WBS networks should take both the demultiplexers/ multiplexers and the wavelength usage into account.
3.5.2 Intra-band and Inter-band Retuning: Retuning Strategies in WBS Networks

We now present two retuning strategies, and analyze how the blocking caused by wavelength shortage and port shortage can be avoided by employing them.

Reducing Blocking Caused by Wavelength Shortage We first show how the blocking caused by wavelength shortage can be reduced with Inter-band, and Intra-band retuning.

Inter-band Retuning: We define Inter-band wavelength retuning as the wavelength retuning that can happen between any two wavelengths (from the same or different bands). As an example shown in Fig. 3.21, waveband $b_{0}, b_{1}$ contains 2 wavelengths each, and there are 5 existing lightpaths ( $L_{1}$ to $L_{5}$ ). A new lightpath request $L_{6}$ has to be blocked since no continuous free wavelength can be found along this route. However, using the Inter-band wavelength retuning, we can retune the lightpath $L_{3}$ from wavelength $\lambda_{2}$ to $\lambda_{3}$, then $\lambda_{2}$ can be used as a continuous free wavelength to accommodate $L_{6}$ as shown in Fig. 3.22. Note that, after the retuning, the $b_{1}$ at Node 2 has to be demultiplexed using BTW DEMUX and multiplexed again using WTB MUX since the lightpath $L_{3}$ and $L_{5}$ have different outgoing links. Hence, the Inter-band wavelength retuning can lead to more ports used in WBS networks, which may in turn result in port shortage (particularly BTW DEMUX and WTB MUX) and cause higher blocking of future lightpath requests.

Intra-band Retuning: One way to cut down the port increase is the Intra-band retuning technique. Instead of allowing a lightpath to be retuned from one wavelength to another wavelength from different bands, the lightpath can only be retuned to a wavelength within the same band. Intra-band retuning does not cause port increase since all the wavelengths within the same band exactly have the same configuration. An example of Intra-band retuning is


Figure 3.21. Unable to accommodate lightpath $L_{6}$


Figure 3.22. Lightpath $L_{6}$ can be accommodated after Inter-band retuning

$-----------------\rightarrow \mathrm{L}_{4}$
New request L6 along 1-2-3-4

Figure 3.23. Unable to accommodate lightpath $L_{6}$


Figure 3.24. Lightpath $L_{6}$ can be accommodated after Intra-band retuning
shown in Fig. 3.23. There are two wavebands $b_{0}, b_{1}, 5$ existing lightpaths $L_{1}$ to $L_{5}$. Without retuning, a new lightpath request $L_{6}$ has to be blocked since there is no continuous free wavelength. We now retune the lightpath $L_{1}$ from wavelength $\lambda_{1}$ to $\lambda_{2}$ (both within band $b_{0}$ ) using Intra-band wavelength retuning as shown in Fig. 3.24. After the retuning, the lightpath $L_{6}$ can be accommodated using $\lambda_{1}$. Note that although retuning $L_{1}$ from $\lambda_{1}$ to $\lambda_{3}$ can also release $\lambda_{1}$ for the new request $L_{6}$, it is not allowed in the Intra-band wavelength retuning since $\lambda_{1}$ and $\lambda_{3}$ are from different bands. In Intra-band retuning, one can see that the allowable retuning is restricted within the same band, which may not be flexible enough to identify available wavelength resources. For example, if we consider using the Intra-band wavelength retuning in Fig. 3.21, lightpath $L_{6}$ can not avoid being blocked.

Reducing Blocking Caused by Port Shortage Retuning includes the operation of creating an alternative lightpath for the existing lightpath, switch and release the existing lightpath. As there are ten cases for the port consumption of creating a new lightpath, the same pattern applies for creating the alternative lightpath. For instance, to retune the existing lightpath to a wavelength between $I$ and $O$ in Case (A), we need 2 additional DEMUXs to demultiplex both band $A$ and $I$, and 1 extra MUX for band $O$. Moreover, we note that although creating the alternative lightpath could cause extra demultiplexers/multiplexers, the following releasing operation may decrease the number of demultiplexers and multiplexers at the nodes along its path. The port increase/decrease due to the releasing as well as the new lightpath accommodation can be similarly analyzed as the cases in Table 3.3. Consequently, with an appropriate selection of the retuned lightpath and its alternative lightpath, the overall retuning process may reduce the overall active ports (e.g., the case with no extra demultiplexers/multiplexers consumed in the retuning, and port saving in the releasing operation).

Inter-band Retuning: As we discussed above, the overall retuning could save active ports along the existing lightpath's route. If the new lightpath is blocked due to the shortage of demultiplexers/multiplexers at a node (say $n$ ), and retuning an existing lightpath can release
demultiplexers/multiplexers at Node $n$, then the otherwise blocked new lightpath may be accommodated after the retuning operation.

Intra-band Retuning: Compared to Inter-band retuning, one may believe the Intra-band Retuning cannot save active ports since the retuning only happens within the original band and does not affect demultiplexers/multiplexers. However, interestingly, Intra-band Retuning can indeed reduce the blocking caused by the insufficiency of ports. For example, assume that a new request can only be accommodated in a band $b$ without causing blocking due to the shortage of active ports. Meanwhile, no continuous free wavelength is available in the band $b$ for the new request. An Intra-band Retuning of one existing lightpath, however, could release a continuous free wavelength in band $b$ to accommodate the new request.

### 3.5.3 Port-aware Wavelength Retuning Scheme for WBS networks

Based on the discussion above, Inter-band retuning is flexible but could cause port increase, while Intra-band retuning cause no port increase but could underutilize the available wavelength resources. To avoid the disadvantages of both strategies, we present a new portaware wavelength retuning (PAWR) scheme.

Wavelength Retuning Process We name the existing lightpath to be retuned as $L_{r}$, whose current wavelength is $w$. After the retuning, $L_{r}$ will use wavelength $\bar{w}$. The wavelength retuning operations are triggered in the case that a blocking event occurs when accommodating a new lightpath request with a normal WBS algorithm (i.e., First-fit algorithm for this work). When a new lightpath $L$ comes, the following process is adopted:

1. Accommodate $L$ using the First-fit algorithm, if fails, goto step 2;
2. Determine a retuned lightpath $L_{r}$ and $\bar{w}$ using Algorithm 4 shown below, if no retuning lightpath exists, block the request and exit;
3. Use $\bar{w}$ to establish a new lightpath for $L_{r}$;
4. Switch the retuned lightpath $L_{r}$ from $w$ to $\bar{w}$, then stop the transmission on $w$;
5. Accommodate the new lightpath $L$ using $w$;

Selection of the Retuning Lightpath We only allow one lightpath to be considered for retuning per blocking. This restriction can make the retuning simple and fast to implement. We note that there are several requirements for one existing lightpath to be selected to be retuned: First, the existing lightpath has a route that overlaps with the new lightpath request; Second, along the existing lightpath's route, there is at least one continuous free wavelength that this lightpath can be retuned to as well as sufficient demultiplexers/multiplexers to support the retuning; Third, retuning this existing lightpath can allow the otherwise blocked new lightpath request to be accommodated.

The Ports Used in Retuning Among the candidate lightpaths, we need to decide the lightpath $L_{r}$ and the wavelength $\bar{w}$ to retune. We assume the decreased number of demultiplexers and multiplexers due to the releasing of the existing lightpath are $d d x_{n}$ and $d m x_{n}$ at Node $n$. Based on the analysis of the previous section, we can see that retuning to different wavebands can cause various number of port increase. We assume that the increased demultiplexers and multiplexers are $i d x_{n}$ and $i m x_{n}$. For example, in the Case (D) of Fig. 3.11, the band from $I$ to $O$ is a bypass band, if we use a free wavelength within this band to accommodate the retuned lightpath which also goes from $I$ to $O$, no extra port will be needed (i.e., $i d x_{n}=0$ and $i m x_{n}=0$ ). Meanwhile, since the releasing of the existing lightpath could decrease the active number of ports at Node $n$, the overall change in demultiplexers and multiplexers are $i d x_{n}-d d x_{n}$ and $i m x_{n}-d m x_{n}$, respectively. As a result, for each band $b$ at Node $n$, we can assign a weight $W T_{n, b}$ using Eq. 3.40.1 to 3.40 .7 to reflect the port increase according to the 10 cases, where $\bar{D}_{n}, \bar{M}_{n}$ are the current available BTW DEMUXs and WTB MUXs at Node $n$. The weight for using band $b$ takes both the current available DEMUXs/MUXs and the potential port increase into consideration. With the weight for each band at any node, the total cost of retuning $L_{r}$, denoted as Cost_of_Retune, can be calculated as in Eq. 3.41 (by choosing the band with the minimum weight for retuning), where $N S_{L_{r}}$ denotes the set of nodes that reside in the route of $L_{r}$. On the other hand, after
the retuning, we will use the wavelength $w$ to accommodate the new lightpath request $L$, which may require additional ports. Similarly, we can calculate the cost of using wavelength $w$, namely, Cost_of_Accommodate, to accommodate the new lightpath $L$ as shown in Eq. 3.42 , where $p$ is the band that $w$ belongs to. Finally, we can obtain the total cost for this wavelength retuning process by adding the cost from retuning the existing lightpath and accommodating the new lightpath.

$$
\begin{align*}
& W T_{n, b}= \begin{cases}\frac{-d d x_{n}}{\bar{D}_{n}}+\frac{-d m x_{n}}{\bar{M}_{n}}, & \text { if } b \in \operatorname{case}(C, D, J) \\
\frac{1-d d x_{n}}{\bar{D}_{n}}+\frac{-d m x_{n}}{\bar{M}_{n}}, & \text { if } b \in \operatorname{case}(B) \\
\frac{1-d m x_{n}}{\bar{M}_{n}}+\frac{-d d x_{n}}{\bar{D}_{n}}, & \text { if } b \in \operatorname{case}(I) \\
\frac{1-d d x_{n}}{\bar{D}_{n}}+\frac{1-d m x_{n}}{\bar{M}_{n}}, & \text { if } b \in \operatorname{case}(H, F) \\
\frac{2-d d x_{n}}{\bar{D}_{n}}+\frac{1-d m x_{n}}{\bar{M}_{n}}, & \text { if } b \in \operatorname{case}(A) \\
\frac{1-d d x_{n}}{\bar{D}_{n}}+\frac{2-d m x_{n}}{\bar{M}_{n}}, & \text { if } b \in \operatorname{case}(G) \\
\frac{2-d d x_{n}}{\bar{D}_{n}}+\frac{2-d x_{n}}{\bar{M}_{n}} . & \text { if } b \in \operatorname{case}(E) \\
\text { Cost_of_Retune }=\min _{b} \sum_{n \in N S_{L_{r}}} W T_{n, b}\end{cases} \\
& \text { Cost_of_Accommodate }=\sum_{n \in N S_{L}, w \in p} W T_{n, p}
\end{align*}
$$

Port-aware Wavelength Retuning (PAWR) We accommodate a new lightpath request with the First-fit algorithm by finding the first continuous free wavelength along the shortest path. If no wavelength or no available ports can be found along its path, the wavelength retuning algorithm shown in Algorithm 4 is used, where $P_{s, d}$ is the routing path for the node-pair $(s, d)$. Specifically, Step 4 of Algorithm 4 is for Intra-band retuning, and Step 5 is for Inter-band retuning. Step 6 identifies the retuning process that has the minimum cost. Note that the retuning operations in Step 4, 5 are not committed to the physical lightpaths. Instead, we only test and collect the weight by virtually committing these retuning operations. Assume that $H$ is the maximum hop number among all the routes. In the worst case, Step 1 might check $\mathbf{O}(H * F)$ lightpaths, where $F$ is the fiber size. Step 3 has time complexity $\mathbf{O}(H)$. Step 4 has time complexity $\mathbf{O}(B * H)$, in which $B$ is the band size. Step 5 has time complexity $\mathbf{O}(P * H)$ where $P$ is the number of bands per fiber.

Consequently, the overall worst case complexity for this algorithm is $\mathbf{O}\left(H^{2} * F *(B+P)\right)$.
In addition, we also implement two retuning algorithms which employ only either the Inter-band or Intra-band retuning discussed above. The first one is called Inter-band wavelength retuning which adopts the First-fit strategy to find a feasible lightpath (i.e., in terms of continuous available wavelength and demultiplexers/multiplexers) and retunes the lightpath to the first available band. The other algorithm, namely, Intra-band wavelength retuning, uses a First-fit strategy to find a feasible retuning lightpath and retune the lightpath to the first available wavelength within its current band.

```
Algorithm 4 Wavelength Retuning to accommodate a lightpath \(L\) between node-pair \((s, d)\)
    for all the lightpaths whose routes overlap with \(P_{s, d}\) do
        Select one lightpath \(L_{i}\) which uses wavelength \(w\) and belongs to band \(b\);
        Check whether use \(w\) (after retuning \(L_{i}\) ) can accommodate \(L\); if yes, calculate Cost_of_Accommodate; if not, Continue;
        Retune \(L_{i}\) to another wavelength within band \(b\), if success, set Cost_of_Retune \(=0\), and goto step 6 ;
        Retune \(L_{i}\) to another waveband \(\bar{b}\) that has continuous available wavelength along \(L_{i}\) 's route, and \(\bar{b}\) produces the minimum
        cost for retuning (i.e., Cost_of_Retune);
        Update the retuning process that has the minimum total cost of (Cost_of_Retune + Cost_of_Accommodate);
    end for
    Retune the existing lightpath that produces the minimum cost; if none exists, block;
```


### 3.5.4 Performance Evaluation and Analysis

We simulate above schemes using the 24-node USANet network as the topology. There are two fibers for each link, with one per direction. The lightpath requests arrive at the network according to a Poisson process with rate $\lambda$, and is randomly distributed over the whole network. The request holding time is exponentially distributed with one unit as the mean value. All simulations are conducted with a large number of dynamic lightpath requests, and results are collected as the mean of multiple running instances of the simulation.

Traffic Load and Blocking Probability Figure 3.25 shows the blocking probability under various network traffic load for the First-fit wavelength assignment combined with three retuning algorithms (i.e., PAWR, Inter-band, Intra-band) as well as the First-fit wavelength assignment without retuning when $F=40, P=10, \beta=0.5$. Note that in this case the upper bound for $\beta=1-2 * \frac{10+1}{10+40}=0.56$. When the traffic load is light (e.g., $\lambda<350$ ), there


Figure 3.25. Traffic load and blocking probability
is no obvious difference among those schemes. When traffic load grows larger, however, one can see that PAWR outperforms both the Intra-band and Inter-band wavelength retuning. The schemes with retuning can outperform First-fit without retuning by a large margin. We also note that the Inter-band wavelength retuning in some cases has a very close performance to the proposed PAWR scheme (e.g., $\lambda<450$ ). However, to achieve the same blocking, the Inter-band retuning triggers more retuning operations (hence longer overall disruption time) according to our results. In general, we can observe that Intra-band retuning is not as good as Inter-band retuning and PAWR due to its limited searching space for retuning. However, as to be shown, the performance of Intra-band retuning can be improved with the increase of band size $B$.

Band Size and Intra-band Retuning Intuitively, bigger band size could improve the Intra-band retuning's performance, thus we test the Intra-band retuning with various band size here. To have a fair comparison, we consider two scenarios, one with $P=10, B=$ $4, F=40, \beta=0.3$, and the other one with $P=5, B=8, F=40, \beta=0.6$. Note that the wavelength number and demultiplexer/multiplexer number $(P \times \beta=3)$ are the same for both scenarios. As shown in Fig. 3.26, the case with larger band size indeed has a better performance in terms of the blocking probability. For both scenarios, the corresponding results from the proposed PAWR scheme are better than the Intra-band retuning. However,


Figure 3.26. Impacts of the band size
the Intra-band retuning under $B=8$ has a comparative performance with the proposed scheme under $B=4$. This implies that the Intra-band retuning can be a good choice under some scenarios considering its simplicity. Furthermore, the results for the proposed PWAR scheme under different band size also show that the case with bigger band size produces a better performance. This can be explained by the fact that the case with bigger band size (i.e., $B$ ) has a smaller band number (i.e., $P$ ) if the wavelength per fiber (i.e., $F=B \times P$ ) is the same. With the same number of demultiplers/multiplexers, the case with smaller band number will have less chances to be blocked caused by the shortage of ports.

Blocking Reduced by Wavelength Retuning We further study how much blocking can be reduced by wavelength retuning as shown in Table 3.6 where we set $P=10, F=40$ for the proposed PAWR scheme. With the same traffic load, one can see that bigger $\beta$ corresponds to less percentage of blocking in port shortage. With the same $\beta$, the same pattern happens with the increase of $\lambda$. This is because with a heavier traffic load, it is more possible to reduce the blocking due to shortage of ports by retuning than to reduce the blocking due to shortage of wavelengths. For the blocking caused by the port shortage, we can observe that a large portion can be reduced (no less than 20\%) in all the cases, although the portion shrinks with the increase of the traffic load. In fact, wavelength retuning can reduce the blocking caused by wavelength shortage except for the case with heaviest traffic and least
ports (when $\lambda=400, \beta=0.1$ ).

Table 3.6. Blocking reduced by retuning

|  | $\lambda=200$ |  | $\lambda=300$ |  | $\lambda=400$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\beta$ | 0.1 | 0.2 | 0.1 | 0.2 | 0.1 | 0.2 |
| Blocking by Port Shortage (\%) | 99.1 | 89.1 | 95.9 | 77.4 | 92.8 | 69.9 |
| Reduced in Port Shortage(\%) | 50.4 | 57.5 | 38.1 | 45.5 | 20.7 | 37.2 |
| Reduced in Wavelength Shortage(\%) | 65 | 37.5 | 22.2 | 28.2 | 0 | 21.6 |

### 3.6 Waveband Protection

In this section, we start with two motivating examples that illustrate the problem of directly applying existing protection schemes in WBS networks. We then introduce the band-segment concept and protection schemes based on this concept for WBS networks.

### 3.6.1 Protection in WBS Networks

For WBS networks, the goal of port reduction brings several new features to the protection schemes. However, none of existing work has addressed challenges brought by these features in WBS networks as explained below.

Resource Sharing in Shared Protection: If not considered properly, the sharing of resources between backup lightpaths could lead to a dramatic increase of the port number. Figure 3.27 illustrates the problem of directly applying the shared path protection (SPP) in WBS networks. As shown in Fig. 3.27, there are two backup lightpaths along path $B P_{1}$ and $B P_{2}$ to protect the active lightpaths along path $A P_{1}$ and $A P_{2}$, respectively. Since $A P_{1}$ and $A P_{2}$ are disjoint, the backup lightpaths along $B P_{1}$ and $B P_{2}$ can share the wavelength $\lambda_{3}$. The shared wavelength $\lambda_{3}$ is switched to node 4 or 5 depends on the failure from $A P_{1}$ or $A P_{2}$. As a result, even if all the remaining wavelengths (i.e., $\lambda_{1}$ and $\lambda_{2}$ ) in the band $b_{0}$ travel to node 4 , band $b_{0}$ has to be configured with demultiplexing/multiplexing capability at node 3 to cope with the failure of $A P_{2}$. Such demultiplexing/multiplexing can degrade the WBS performance in terms of port reduction.

Port Savings in Dedicated Protection: In the dedicated protection, to achieve the


Figure 3.27. An example of wavelength-level shared protection


Figure 3.28. An example of active and backup traffic sharing the same band
goal of reducing node size, the combination of the active traffic and backup traffic in the same band should be carefully considered. Figure 3.28 shows an example of the dedicated path protection (DPP). As shown in Fig. 3.28, a lightpath along the path $A P_{1}$ is used to accommodate the traffic demand between $(1,4)$ using wavelength $\lambda_{1}$. Along the path $A P_{2}$, $\lambda_{1}$ and $\lambda_{2}$ are used to accommodate the traffic demands between $(1,5)$. Now to protect the lightpath along $A P_{1}$, a backup lightpath along the path $B P_{1}$ is deployed using $\lambda_{3}$. Since both the active lightpaths along $A P_{2}$ and the backup lightpath along $B P_{1}$ are within the band $b_{0}, b_{0}$ has to be demultiplexed at node 3 to switch the wavelengths to nodes 4 and 5 separately, which again cause extra port consumption.

### 3.6.2 Band-segment-based Protection in WBS Networks

To resolve issues discussed above, we introduce the concept of band-segment in WBS networks, based on which a new protection scheme is proposed.

The Concept of Band-segment The band-segment (BS) of a given band $b$ is defined as the portion of the fiber route between two MG-OXCs such that $b$ is formed at the first MG-OXC, say node $i$, and then demultiplexed at the second MG-OXC, say node $j$. We denote this BS as $A S_{i, j, f, b}$ where $f$ is the fiber that contains band $b$ at the first hop of this BS. Within one band-segment, all the wavelengths are kept at the band layer (i.e., without going through wavelength-to-band/band-to-wavelength multiplexers/demultiplexers). To form the band-segment in WBS networks, we separate the traffic into the Band-tier traffic and the Wavelength-tier traffic. For example, assume that the band size, $B$, is 5 , and the traffic demand between the node-pair $(s, d)$ is 12 lightpaths, then the Wavelengthtier traffic $W T[s][d]$ is $2(W T[s][d]=T[s][d] \% B)$, and the Band-tier traffic $B T[s][d]$ is 2 $(B T[s][d]=(T[s][d]-W T[s][d]) / B)$. This separation can simplify the band-segment formation since the Band-tier traffic is automatically satisfied using band-segments at the band layer. In addition, this separation can assure that all the Band-tier traffic has a higher priority to be accommodated as band-segments, which in turn can save more ports in the process of satisfying the backup traffic. With an efficient WBS algorithm, we can also construct the Wavelength-tier traffic as band-segments.

Waveband Protection Based on Band-segment Based on band-segments, we can effectively implement protection schemes in WBS networks while addressing the issues shown in Fig. 3.27 and Fig. 3.28. For the dedicated protection, one can accommodate the active traffic and transform them into active band-segments (ABSs). Then we can protect each ABS using a backup band-segment (BBS). In this way the BBS can be accommodated at the band layer without affecting the ABS. For the shared protection, we observe that properly constructing ABSs and realizing the sharing at the band level are appealing in WBS
networks. For example, in Fig. 3.29, there are 3 disjoint active band-segments $A B_{1}, A B_{2}$, and $A B_{3}$. To protect $A B_{1}$, one can employ the band $b_{0}$ along 1-2-3-4, which can be shared along 1-2-3 to protect $A B_{2}$. Moreover, the BBS along $B B_{3}$ for $A B_{3}$ may share the band $b_{0}$ along 1-2-3 without additional ports at node 3 (since the input fiber is supposed to be demultiplexed into BXC layer). We further note that this band-level sharing can even reduce the port number. For example, at node 2, all the three backup band-segments can share the ports at the BXC layer. Based on these observations, we now introduce two efficient band-segment protection schemes for WBS networks: the shared band-segment protection scheme (SBSP), and the dedicated band-segment protection scheme (DBSP). The notations below are used in the following discussion.

| ASet: | The set of all the active band-segments; |
| :--- | :--- |
| Sub $_{i, j}:$ | The sub-path of Path $_{s, d}$ with two end nodes $i$ and $j ;$ |
| Hops $_{\text {Path }_{s, d}:}:$ | The hop number of Path $_{s, d} ;$ |
| $A S_{i, j, f, b}:$ | The band-segment using band $b$ within fiber $f$ at the |
|  | first hop, and starting from node $i$ to $j ;$ |
| $B B S_{A S_{i, j, f, b}:}:$ | The backup band-segment for $A S_{i, j, f, b}$. |

Our wavebanding policy is to group traffic between the node-pairs which have the same source or destination node and have at least $W(W \geq 2)$ overlapping hops in the routing paths. There are four steps in the proposed schemes. Stage 1 produces the routes for the active traffic, and Stage 2 and 3 are for the Band-tier traffic and the Wavelength-tier traffic accommodation (along with the band-segment formation). In Stage 4, we consider the protection of active band-segments formed in the previous two stages.

Stage 1: Active path generation. First, use the $k$-shortest path algorithm [41] to generate $k$ path(s) for each node-pair $(s, d)$. Second, starting with the node-pair $(s, d)$ which has the longest shortest-path, select the routing path $\mathrm{Path}_{s, d}$ that minimizes the overlapping with already selected paths. Assume that the nodes along $\operatorname{Path}_{s, d}$ are $s, s_{1}, s_{2}, \ldots, d$. Third, for all the same-source sub-paths $S u b_{s, s_{i}}$ and same-destination sub-paths $S u b_{s_{i}, d}$ of Path $_{s, d}$, if


Figure 3.29. Band-segment protection in WBS networks
this sub-path has at least $W$ overlapping hops with Path $_{s, d}$, we choose the sub-path as the active path for the respective node-pair. Continue this process until all routing paths are selected.

```
Algorithm 5 Band-tier Traffic Accommodation for \((s, d)\)
    while \(B T[s][d]>=B\) do
        Find a free band \(m\) starting with \(b\) along the path;
        if the band \(m\) exists then
            \(b \leftarrow(m+1) \% B\)
        else
            \(W T[s][d] \leftarrow B T[s][d] * B+W T[s][d]\)
            exit
        end if
        Assign the band \(m\) to this traffic;
        \(B T[s][d] \leftarrow B T[s][d]-1\)
        Add the \(A S_{s, d, f, m}\) to the ASet;
    end while
```

Stage 2: Band-tier traffic accommodation. The major aim of this stage is to accommodate the Band-tier traffic at the band layer using Algorithm 5, where $b$ (initialized to 0 ) is the index of the waveband from which to search an available waveband using the First-fit scheme. We start with the node-pair $(s, d)$ with the longest routing path, and use Algorithm 5 to accommodate the traffic demand of $(s, d)$. Then Algorithm 5 is employed to accommodate the traffic for node-pairs along the same-source sub-paths $S u b_{s, s_{i}}$ and the same-destination
sub-paths $S u b_{s_{i}, d}$ sequentially, until all the Band-tier traffic demands are considered. At the end of this stage, all the Band-tier traffic demands are accommodated and formed as active band-segments along the respective paths.

Stage 3: Wavelength-tier traffic accommodation. In this stage, the band-segments are constructed using Algorithm 6 based on the band-segment overlapping. Note that the overlapping of two band-segments indicates that they use the same band of the same fiber at their common link(s). In lines 1 to 10 of Algorithm 6, we use First-fit scheme to assign a free wavelength to accommodate the current Wavelength-tier traffic demand. Once the wavelength is assigned, lines 11 to 24 update the active band-segments in Aset.

For all the node-pairs with $\operatorname{Hops}_{\text {Path }_{s, d}} \geq W$, following steps are adopted to accommodate the Wavelength-tier traffic demands and form the active band-segments.

1. Starting with the node-pair $(s, d)$ that has the longest routing path, use Algorithm 6 to accommodate its traffic demands.
2. Use Algorithm 6 to accommodate the traffic demands from the same-source sub-paths $S u b_{s, s_{i}}$ that satisfy our wavebanding policy.
3. Update $w$ to be the first wavelength of the next band.
4. Use Algorithm 6 to accommodate the traffic demands from the same-destination subpaths $S u b_{s_{i}, d}$ that satisfy the wavebanding policy. Then goto Step 1, until all traffic demands for node-pairs with $\operatorname{Hops}_{\text {Path }_{s, d}} \geq W$ are satisfied.

At the end of this stage, the traffic demands for node-pairs having less than $W$-hops routing paths are accommodated at the band layer before being considered at the wavelength layer using Algorithm 6.

Stage 4: Band-segment protection. In this stage, we create backup band-segments to protect all active band-segments. For the dedicated band-segment protection (DBSP), we first generate $l$ disjoint backup paths for each active band-segments. Then starting with $A S_{i, j, f, k}$ from $A S e t$ that has the longest path, we form the backup band-segment $B B S_{A S_{i, j, f, k}}$

```
Algorithm 6 Wavelength-tier Traffic Accommodation for \((s, d)\)
    while \(W T[s][d]>0\) do
        Find a free wavelength \(n\) starting with \(w\) along the path;
        if the wavelength \(n\) exists then
            \(t \leftarrow\lfloor n / B\rfloor\)
            \(w \leftarrow(n+1) \% F\)
        else
            Break
        end if
        Assign wavelength \(n\) to this traffic;
        \(W T[s][d] \leftarrow W T[s][d]-1\)
        if \(A S_{s, d, f, t}\) already exists in \(A S e t\) then
            Update \(A S_{s, d, f, t}\) and Continue;
        else
            Create the band-segment \(A S_{s, d, f, t}\);
        end if
        for all \(A S_{i, j, x, t}\) that overlaps with \(A S_{s, d, f, t}\) do
            Add the overlapping ends to array MarkC;
            Split and update \(A S_{i, j, x, t}\) based on these ends;
        end for
        Add \(s, d\) to MarkC if not contained, sort MarkC according to the node sequence of
        Path \(_{s, d}\);
        for \(i=1\) to size of MarkC-1 do
            Add \(A S_{\text {MarkC }[i], M a r k C[i+1], g, t}\) to ASet;
        end for
    end while
```

using a free waveband along the shortest path among $l$ candidate backup paths. This process is continued until all the active band-segments are protected.

For the shared band-segment protection (SBSP), the band-level sharing is only allowed among the backup band-segments whose active band-segments are disjoint. First, for each active band-segment, we find $l$ disjoint backup paths. Second, starting with $A S_{i, j, f, k}$ that has the longest routing path, we select one path from the $l$ backup paths which has the maximum overlapping with existing backup band-segments to form $B B S_{A S_{i, j, f, k}}$. Then $B B S_{A S_{i, j, f, k}}$ is accommodated by sharing the allocated waveband in the overlapping links. If no sharing can be achieved, we use the Last-fit scheme to assign a free band for the backup band-segment. Third, for each sub-path of $B B S_{A S_{i, j, f, k},}$, if it is used by any unprotected active band-segment, say $A S_{a, z, x, q}$, as a candidate backup path, we use this sub-path of $B B S_{A S_{i, j, f, k}}$ to form the backup band-segment of $A S_{a, z, x, q}$ (i.e., $B B S_{A S a, z, x, q}$ ). This process is continued until all active band-segments in $A S e t$ are protected.

### 3.6.3 Performance Evaluation

The performance of the above schemes are studied by comparing with the dedicated path protection (DPP) and the shared path protection (SPP) discussed in Fig. 3.27 and Fig. 3.28. The simulations are on the 24 -node USANet network with $X=2, F=100, B=5$. For various combinations of $X, F, B$, we omit the results here if the same patterns can be observed.

Figure 3.30 shows the performance comparison between BPHT (without protection), dedicated path protection (DPP), and DBSP with $W=5$. Without providing any protection, BPHT requires the minimum number of ports among the three schemes. DPP requires more than twice of the port count required by BPHT. The reason is that the dedicated path protection scheme realizes the wavelength assignment using the First-fit and the Last-fit scheme on the active path and the backup path, respectively. As a result, the accommodation of the active traffic and the backup traffic within the same band cannot be avoided (as discussed in Fig. 3.28). The proposed DBSP outperforms DPP by more than $25 \%$ on


Figure 3.30. Port count under dedicated protection


Figure 3.31. Port count under shared protection
average in terms of port reduction, which indicates that the band-level protection is more appealing than the wavelength-level protection in WBS networks. Note that the difference in the port count among these schemes becomes smaller when the traffic demand is a multiple of the band size (e.g., 5,10 ). This is due to the fact that all the traffic demands only contains the Band-tier traffic and are operated at the band layer in above three schemes.

We collect the port count from SPP, DBSP, SBSP and DPP in Fig. 3.31, and the parameter $W$ is set to 5 . As shown in Fig. 3.31, DPP outperforms SPP since the wavelengthlevel sharing degrades the wavebanding performance as explained in Fig. 3.27. The proposed SBSP outperforms DBSP in terms of port reduction, this is because the band-level sharing will not affect the wavelengths within a band, and the ports along the shared band-segments
can be saved as shown in Fig. 3.29. We further note that the port count from band-segment schemes (DBSP and SBSP) are lower than the ones obtained from path protection schemes (i.e., DPP and SPP), though the difference becomes less when the traffic demands are a multiple of the band size. This smaller difference is again because that only the Band-tier traffic exists in this case. Hence, different from the findings in [40], the simulation results show that band-segment sharing can improve resource utilization without degrading the performance of port reduction.

Moreover, our simulation indicates that the parameter $W$ has a direct impact on the performance of port reduction as shown in Fig. 3.32. The X -axis denotes the traffic size in terms of lightpath requests and Y-axis represents the total port count required in the network (without considering the protection). The figure shows that larger the $W$, smaller the node size (given the same amount of traffic demand). This is because longer overlapping (with larger $W$ ) facilitates wavebanding in WBS networks and more Wavelength-tier traffic demands are accommodated at band layer at the end of Stage 3. However, our study also shows that overlarge $W$ (e.g., $W>7$ ) reduces the probability of grouping traffic demands from different node-pairs into bands and hence negatively impacts the performance, and over-small $W$ (e.g., $W<4$ ) does not help in either the port reduction or the band-segment formulation. Therefore, we set the $W$ to 4-6 in the USA backbone network. When the traffic is a multiple of the band size (e.g., 5,10 ), the port count required in the network drops significantly since the wavelength assignment is operated at the band layer.


Figure 3.32. Port count under different $W$

## PART 4

## SPECTRUM-SLICED ELASTIC OPTICAL PATH NETWORKS: A NEW FRONTIER

In this chapter, we move on to the study of the spectrum-sliced elastic optical path (SLICE) networks, an emerging technology launched as the long-term solution for the future Internet. We first discuss the drivers of the SLICE networks, the unique challenges in SLICE networking, and review the related literature work. We then present our timely study on the resource (i.e., sub-carrier) management in SLICE networks.

### 4.1 Drivers, Challenges, and Literature Review

The major driver that motives the development of SLICE networks is to overcome the in-efficient spectrum management of WDM networks. This can be observed through a comparison of the spectrum management between the SLICE networks and WDM networks, as shown in Figure 4.1(a), 4.1(b), respectively. The smallest granularity for carrying user's request is sub-carrier (e.g., $S_{1}$ ) in SLICE networks, which has a smaller capacity than the counterpart wavelength (e.g., $\lambda_{1}$ ) in WDM networks. Given the same available optical spectrum resource, SLICE networks can significantly improve the bandwidth utilization due to two main reasons. First, to accommodate the sub-wavelength traffic (which has bandwidth less than a wavelength) in WDM networks, one wavelength has to be assigned and partially wasted. In contrast, SLICE networks can reduce this waste since the sub-carrier has finer granularity. Second, wavelengths in WDM networks are separated from neighbors by the reserved guard-band frequencies [2,3], to ensure that the user demand carried by one wavelength will not interference the demand of a different user on a neighboring wavelength. However, when one user requests multiple wavelengths (i.e., super-wavelength traffic), the guard-band is unused and wasted. In contrast, sub-carriers of SLICE networks, enabled

(a) Wavelengths in WDM networks

(b) Sub-carriers in SLICE networks using OFDM

Figure 4.1. Optical spectrum management
by OFDM (Orthogonal Frequency Division Multiplexing) [17], can partially overlap with the neighbors (without guard-band) since different sub-carriers are orthogonal and hence interference-free [15, 16, 52].

To achieve the elastic and fine-granular bandwidth allocation in SLICE networks, a similar process as the RWA in WDM networks, namely routing and spectrum allocation (RSA) has to be employed [15]. In specific, the RSA process routes and allocates spectrum resources to form the spectrum path, which is an all-optical trail established between the source and sink nodes by using one or multiple consecutive sub-carriers. Similar to the lightpath in WRN networks, the spectrum path has to ensure the continuous availability of the allocated sub-carriers along its routing path. However, the RSA problem is different from and more challenging than the traditional RWA problem due to the following factors. First, OFDM technology requires that for a given spectrum path, the allocated sub-carriers have to be consecutive in spectrum domain to be effectively modulated [52]. We refer to this requirement as the sub-carrier consecutiveness constraint. Second, although the sub-carriers of the same spectrum path can be consecutive and overlapping in the spectrum domain, two spectrum paths have to be separated in the spectrum domain by guard frequencies when these two spectrum paths share one or more common fiber links. These guard frequencies are referred to as guard-carriers, which is used to facilitate the physical frequency filtering. Third, unlike the WDM network where guard-band frequencies are pre-allocated and fixed,
the guard-carriers in SLICE network can be any of the sub-carriers and are determined in the process of spectrum paths establishment.

Hence, the solution for the RWA problem of WRNs cannot be directly applied to SLICE networks. Similarly, the RSA problem is also different from the routing and wavelength/waveband assignment in waveband switching (WBS) networks, where the major goal is to reduce the number of ports in the network. In WBS networks, a number of wavelengths are grouped into a common optical tunnel, namely waveband, and switched as a single entity whenever possible [6]. Conceptually, grouping wavelengths is similar to the allocation of consecutive sub-carriers for a given spectrum path in SLICE networks. However, different from the consecutive sub-carriers of a spectrum path, the grouped wavelengths can be from various node-pairs sharing at least one common fiber [6]. The wavelengths within a band are not necessarily consecutive [20,33], and grouping wavelengths is primarily for the sake of port savings. In contrast, the SLICE network has to ensure the consecutiveness of sub-carriers for effective modulation $[16,52]$.

In the literature, the study in [15] raised the challenges for the future optical networks while exploring the possibility and feasibility of adopting SLICE networks for nextdecade networks. The concept of routing and spectrum allocation was introduced in [15] for the first time, and later studied in $[53,54]$. The enabling technologies of SLICE networks were firstly elaborated in [16]. For example, the node architecture based on bandwidthvariable wavelength-selective switch (WSS) was presented in [16] to support the spectrum path switching in SLICE networks. The authors of $[52,55]$ studied some unique features of SLICE networks. In [52], the filtering characteristics of SLICE networks were studied, and the spectrum efficiency of SLICE networks was shown to be better than that of WDM networks by a large margin. The authors of [55] investigated a unique feature of bandwidthsqueezing restoration in SLICE networks, where the bandwidth of the failed spectrum path can be squeezed to achieve the minimal connectivity. Recently, the study in [56] introduced the concept of distance-adaptive spectrum resource allocation in SLICE networks, where the modulation level and filter width for a given spectrum path can be adaptively chosen based
on the path length. The efforts on the standardization of the Frequency Slot in SLICE networks was also discussed in [56], which indicates that one may realize the routing and spectrum allocation based on the Frequency Slot instead of sub-carriers. The extended optical reach in SLICE networks supported by the OFDM technology as well as the flexibility in the modulation level, enables the virtualization of the spectrum resources in the optical domain, which was discussed in [57].

### 4.2 Routing and Spectrum Allocation (RSA) in SLICE Networks: Definition and Complexity

The elastic right-size bandwidth allocation in SLICE networks is achieved with the aid of optical orthogonal frequency-division multiplexing (OFDM) technology, where neighboring sub-carriers can overlap in the frequency domain without interferences due to the orthogonality. In optical networks, OFDM can be implemented either using an electronic approach (through FFT) or using an optical approach through coupling the individually modulated optical sub-carriers $[16,17]$. In the frequency domain, one sub-carrier normally corresponds to several $G H z$, and the capacity of one sub-carrier is in the order of Gbps (depending on the modulation level). OFDM enables both the sub-wavelength and super-wavelength accommodation in the SLICE network. Specifically, sub-wavelength accommodation can be achieved in the optical domain since a single sub-carrier has a much lower data rate than one wavelength of WDM networks. For super-wavelength traffic demands, optical or spectrum paths can be created by assigning multiple consecutive sub-carriers, which can overlap in the frequency domain at the OFDM transponders [16].

For a given traffic demand, the request can be translated into a number of sub-carriers, and accommodated through the establishment of the corresponding spectrum path. To form the spectrum path for the traffic demand using multiple sub-carriers, the SLICE network may deploy bandwidth-variable (BV) transponders at the network edge and bandwidthvariable wavelength cross-connects (WXCs) in the network core, which can be built based on the continuous bandwidth-variable wavelength-selective switch (WSS) $[16,58,59]$. Note
that two spectrum paths that share one or more common fiber links, have to be separated in frequency domain to enable the optical signal filtering. In other words, two set of subcarriers within the two spectrum paths have to be isolated by a guard-carrier. The size of the guard-carrier, however, is not trivial and may be in the order of one or multiple sub-carrier(s) [52]. In the following discussion, we assume that the guard-carrier required to separate two spectrum paths are formed by sub-carriers of size $G C$. One example of routing the spectrum paths using the WXC node in a SLICE network is shown in Fig. 4.2, where Fig. 4.2(a) is a star network with 2 directional fibers per link and $G C=1$. The BV WSSs in Fig. 4.2(c) are arranged with a broadcast-and-select configuration. The local traffic can be added and dropped through the connection to the OFDM transmitter and receiver, respectively. In Fig. 4.2(a), there is a spectrum path $S P_{1}$ of 2 sub-carriers from $A$ to $B$, and there is another spectrum path $S P_{2}$ of 2 sub-carriers from $A$ to $C$. Figure 4.2(b) shows the spectrum allocation on Fiber $F_{1}$ for $S P_{1}$ and $S P_{2}$. As shown in Fig. 4.2(b), each sub-carrier on the fiber has an index. The sub-carriers with index 1 and 2 are assigned to $S P_{1}$ which requires 2 consecutive sub-carriers. The sub-carriers with index 4 and 5 are assigned to $S P_{2}$. Note that the sub-carriers within $S P_{1} / S P_{2}$ are consecutive and no guard frequency (i.e., guard-carrier) is needed within $S P_{1} / S P_{2}$. The sub-carrier with index 3 is assigned as the guard-carrier between $S P_{1}$ and $S P_{2}$ since they are overlapping on Fiber $F_{1}$. As a result, to accommodate $S P_{1}$ and $S P_{2}$, Fiber $F_{1}$ requires 5 sub-carriers. Clearly, the required number of sub-carriers on Fiber $F_{1}$ depends on the employed sub-carrier with the maximum index denoted by $M_{F_{1}}$. We use $M S=\max _{\forall f} M_{f}$ to represent the maximum index of the sub-carriers allocated among all the fibers in a SLICE network. Hence, if there are no other traffic demands in Fig. 4.2(b), MS of the network will be 5. Figure 4.2(c) shows the switching configuration at Node $S$, where the traffic from $A$ to $S$ (through Fiber $F_{1}$ ) is sent to BV WSSs 2 and 3 to filter out to the Node $B$ or $C$. In the following, we formally define the routing and spectrum allocation (RSA) problem in the case with off-line or static traffic.

Definition: Static Routing and Spectrum Allocation problem - given a network $G(V, E, S)$, where $V$ is the set of nodes, $E$ is the set of directional fibers between nodes in


Figure 4.2. Bandwidth selective WXC in the RSA
$V$, and $S$ is the set of sub-carriers on each fiber. For a predefined set of requests $\left\{t_{i}\right\}$, where $t_{i}$ is the request size (in terms of the number of sub-carriers) of the $i$-th traffic demand, is it possible to determine the path for each request and establish each spectrum path in the set using consecutive sub-carries, while satisfying the guard-carrier constraint?

As shown in the definition, RSA contains both the routing decision and the sub-carrier allocation to create spectrum paths. When the routing is known or predetermined, the RSA problem turns out to be the static spectrum allocation (SRA) problem, which was shown to be NP-Complete [18]. Therefore the optimal RSA problem which jointly optimizes the routing and spectrum allocation is NP-Hard. As to be shown below, one objective of the optimal RSA problem is to minimize the maximum number of sub-carriers required in any fiber of a SLICE network.

### 4.3 ILP Model for the Optimal RSA

In this section, we develop formulations to model the optimal RSA problem using the Integer Linear Programming (ILP) technique.

### 4.3.1 Notations and Variables

$\phi: \quad$ The number of sub-carriers on a fiber;
$I_{n}: \quad$ The set of nodes connected to Node $n$ by incoming fibers to $n$;
$O_{n}: \quad$ The set of nodes connected to Node $n$ by outgoing fibers from $n$;

T: $\quad$ Traffic demands matrix; the element $T_{n, m}$ represents the traffic demands between Node $n$ and Node $m$ in terms of number of the sub-carriers;
$G C$ : The size of a guard-carrier in terms of the number of sub-carriers;
$V_{i, o, s, d}^{w}: 1$, if there is a spectrum path using sub-carrier $w$ to satisfy the traffic demand between node-pair $(s, d)$ going from Node $i$ to Node $o$, and 0 otherwise;
$M S$ : The maximum index of the sub-carriers allocated among all the fibers in the network;
$M I_{i, o}$ : The maximum index of the sub-carriers over the fiber from Node $i$ to $o$.
4.3.2 Objectives of the RSA problem

$$
\begin{equation*}
\text { Minimize } M S \tag{4.1}
\end{equation*}
$$

$$
\begin{equation*}
\text { Minimize } \sum_{i, o \in O_{i}} M I_{i, o} \tag{4.2}
\end{equation*}
$$

One objective considered in this study is to minimize the maximum sub-carrier index among all the fibers, which is shown in Eq. (4.1) ${ }^{1}$. Another objective is to minimize the

[^4]total allocated sub-carriers over all the fibers as shown in Eq. (4.2). Meanwhile, we need Eq. (4.3) and Eq. (4.4) to obtain the maximum index of the allocated sub-carriers among all the fiber links and over a single fiber, respectively.
\[

$$
\begin{gather*}
M S \geq w * V_{i, o, s, d}^{w} \quad \forall w, i, o, s, d ;  \tag{4.3}\\
M I_{i, o} \geq w * V_{i, o, s, d}^{w} \quad \forall w, s, d ; \tag{4.4}
\end{gather*}
$$
\]

### 4.3.3 Constraints

Traffic Demand Constraint Equations (4.5-4.6) specify that the traffic demands for node-pair $(s, d)$ should be exactly added at Node $s$ and dropped at Node $d$. Equation (4.7) makes sure that no traffic is added and dropped at the same node.

$$
\begin{gather*}
\sum_{w, o=d, i \in I_{o}} V_{i, o s, d}^{w}=T_{s, d} \forall s, d ;  \tag{4.5}\\
\sum_{w, i=s, o \in O_{i}} V_{i, o, s, d}^{w}=T_{s, d} \quad \forall s, d ;  \tag{4.6}\\
\sum_{s=d, w} V_{i, o, s, d}^{w}=0 \quad \forall i, o ; \tag{4.7}
\end{gather*}
$$

Sub-carrier Capacity Constraint Equation (4.8) guarantees that one sub-carrier can only be used for satisfying one spectrum path.

$$
\begin{equation*}
\sum_{s, d} V_{i, o, s, d}^{w} \leq 1 \quad \forall w, i, o ; \tag{4.8}
\end{equation*}
$$

Spectrum Continuity Constraint The spectrum continuity constraint specifies that the spectrum path should use the same spectrum(s) along its routing path, which is shown in Eq.(4.9).

$$
\begin{equation*}
\sum_{o \neq d, i \in I_{o}} V_{i, o, s, d}^{w}=\sum_{o \neq s, p \in O_{o}} V_{o, p, s, d}^{w} \forall s, d, o, w ; \tag{4.9}
\end{equation*}
$$

Guard-Carrier Constraint When two spectrum paths are overlapping in terms of their routing path, the corresponding allocated spectrum slices have to be separated by a guard-carrier of $G C$ sub-carriers. Thus, if $V_{i, o, s, d}^{w}=1$ for some $w$ on Fiber $i-o$, then all the
sub-carriers within $[w-G C, w+G C]$ cannot be used for any other node-pairs' spectrum paths. To model above $i f$-then relationship using ILP, we introduce a large number $B$ (e.g., $B=\phi$ ), and use Eq. (4.10) to represent the constraint. Clearly, if $V_{i, o, s, d}^{w}$ equals 1, then it exactly represents the above if-then relationship. On the other hand, if the considered sub-carrier $w$ is not used for the node-pair $(s, d)$, this constraint is virtually omitted from the ILP model since the left side of Eq. (4.10) is small enough ( $B$ dominates) to make the Eq. (4.10) a tautology. The same technique is used in Eq. (4.11) and Eq. (4.12).

$$
\begin{equation*}
\left(V_{i, o, s, d}^{w}-1\right) * B+\sum_{\bar{w} \in[\max (0, w-G C), \min (\phi, w+G C)]}^{(\bar{s}, \bar{d} \neq(s, d)} V_{i, o, \overline{,}, \bar{d}}^{\bar{d}} \leq 0 \quad \forall w, i, o ; \tag{4.10}
\end{equation*}
$$

Sub-carrier Consecutiveness Constraint The sub-carrier consecutiveness constraint requires for a given spectrum path, the employed sub-carriers are consecutive in the frequency domain. Equivalently, we transform this constraint as: if $V_{i, o, s, d}^{w}=1$ and $V_{i, o, s, d}^{w+1}=0$, all the sub-carriers with index higher than $w+1$ will not be used for the spectrum path of node-pair $(s, d)$ on Fiber $i-o$. The equation to represent this constraint is shown in Eq. (4.11). And Eq. (4.12) makes sure that the size of consecutive sub-carriers is $T_{s, d}$ if $V_{i, o, s, d}^{w}=1$.

$$
\begin{gather*}
\left(V_{i, o, s, d}^{w}-V_{i, o, s, d}^{w+1}-1\right) *(-B) \geq \sum_{\bar{w} \in[w+2, \phi]} V_{i, o, s, d}^{\bar{w}} \quad \forall w, i, o, s, d ;  \tag{4.11}\\
\quad\left(V_{i, o, s, d}^{w}-1\right) * B+T_{s, d} \leq \sum_{\bar{w} \in[1, \phi]} V_{i, o, s, d}^{\bar{w}} \forall w, i, o, s, d ; \tag{4.12}
\end{gather*}
$$

### 4.4 Lower/Upper Bounds Analysis for the Number of Sub-carriers in SLICE Networks

In this section, we analyze the lower/upper bounds for the maximum sub-carrier index (i.e., $M S$ ) within the SLICE network. We assume that for a network with $N$ nodes (and $|E|$ edges), there are 2 unidirectional fibers per link and uniform traffic demands $X$ sub-carriers between each node-pair.

### 4.4.1 $M S$ with Predetermined Routing (i.e., the SRA problem)

Lower Bound In the case that the routing path is predetermined, we can estimate the load on a given fiber $j$ using Eq. (4.13), where $I$ is the total number of spectrum paths using the fiber and $p_{l}$ is routing path of a spectrum path $l$. Then the load $L D$ on the most congested fiber determines the minimum number of sub-carriers on a fiber as shown in Theorem 1.

$$
\begin{equation*}
L_{j}=\sum_{j \in p_{l}} t_{l}+G C *(I-1) \tag{4.13}
\end{equation*}
$$

Theorem 1: If the routing is predetermined, and the most congested fiber has load of $L D=\max _{\forall j} L_{j}$, then $M S \geq L D$.

This lower bound is applicable to the network with non-uniform traffic but may not be achievable due to the spectrum continuity, and sub-carrier consecutiveness constraints. For example, in Fig. 4.3, there are 4 spectrum paths along the path $A-B-C-D, B-C-D-A, C-D-$ $A-B$, and $D-A-B-C$, respectively. With $G C=1$, the load on each fiber is $3+2=5$. All the other spectrum paths overlap with the spectrum path along $B-C-D-A$ that uses Sub-carrier 3, and 4. Therefore, the Sub-carrier 3 and 4 can not be used along Fiber $A-B$, and at least 7 sub-carriers are required. Moreover, if one extra spectrum path with 2 sub-carriers along $A-B$ is added into the network, due to the sub-carrier consecutiveness constraint, we need at least 3 more sub-carriers with one of them as the guard-carrier.

Upper Bound In the case that the paths are pre-determined, we can obtain the upper bound by constructing the interference graph (IG) of the spectrum paths [3].

We construct the interference graph (IG) by viewing each spectrum path as a vertex. Vertexes are adjacent if the corresponding spectrum paths share at least one common fiber. Consequently, the node-degree in IG for a vertex $V_{l}$ of spectrum path $l$ indicates the number of other spectrum paths that overlap with $l$. For example, the IG for the example in Fig. 4.3 is shown in Fig. 4.4 which has 4 vertexes corresponding to respective spectrum paths.


Figure 4.3. An example for the case of predetermined routing


Figure 4.4. The interference graph

The node-degree of each vertex is 3 since each spectrum path in Fig. 4.3 overlaps with 3 other spectrum paths. Without loss of generality, we assume that the set of vertexes labeled as $V_{1}, V_{2}, V_{3} \ldots$ in the IG are ordered decreasingly based on the node-degree (i.e., $\left.d_{V_{1}} \geq d_{V_{2}} \geq d_{V_{3}} \ldots\right)$. We have the upper bound as shown in Theorem 2.

Theorem 2: If the routing is predetermined, the node-degree sequence in the IG is $d_{V_{1}}, d_{V_{2}}, d_{V_{3}} \ldots$, in the descending order, then $M S \leq M D *(X+G C)-G C$, where $M D=$ $\max _{\forall l} \min \left[d_{V_{l}}+1, l\right]$.

Proof: First, we note that for the IG, the chromatic number $\chi$ satisfies $\chi(I G) \leq M D=$ $\max _{\forall l} \min \left[d_{V_{l}}+1, l\right][60]$. This upper bound of $\chi(I G)$ can be achieved with the WelshPowell algorithm [60]. In other words, $M D$ colors are sufficient to color the vertices of the IG. Correspondingly, we requires $M D$ set of sub-carriers in the original SRA problem. Since each spectrum path requires exactly $X+G C$ consecutive sub-carriers, the required number of sub-carriers on one fiber is bounded by $M S \leq M D *(X+G C)-G C$ after excluding the guard-carrier for the spectrum path that owns the sub-carrier with the largest index.

We note that this upper bound is better than the one (i.e., $M S \leq(\triangle+1) *(X+$ $G C)-G C$ ) obtained in [18], where $\triangle=d_{V_{1}}$. This is because we can easily see that $M D \leq \triangle+1=d_{V_{1}}+1$. With applying Theorem 2 on the IG of the example shown in Fig. 4.3, we have $M D=3$ since $d_{V_{1}}=d_{V_{2}}=d_{V_{3}}=d_{V_{4}}=3$. Thus we can obtain the tight upper bound $(3+1) * 2-1$, which equals to the lower bound 7 .

### 4.4.2 $M S$ without Predetermined Routing

Lower Bound For the case where the routing is not predetermined, we use the cutset (CS) technique [61-63] to analyze the lower bound of $M S$. A cut separates the network with $N$ nodes into 2 disjoint induced sub-graphs. All the traffic demands between those 2 disjoint sub-graphs are carried by the links that composes the cut. If we assume the two sub-graphs contains $S$ and $N-S$ nodes, respectively, the traffic demands carried by the cut $U$ are $2 * S *(N-S) * X$ sub-carriers. Since there are $2 * S *(N-S)$ various node-pairs, we need $2 * S *(N-S) * G C$ sub-carriers as the guard-carriers. The number of sub-carriers


Figure 4.5. A ring network with $N$ nodes
required on one fiber is the ratio between the traffic demands carried by the cut $U$ and the number of fibers in the cut (i.e., $2 *|U|$, due to 2 unidirectional fibers per link) ${ }^{2}$. Moreover, for the spectrum path that has the largest sub-carrier index, it does not need a guard-carrier above the spectrum path with the largest index. Thus we can reduce $G C$ sub-carriers from the above ratio, which finally yields the lower bound as in Eq. (4.14).

$$
\begin{equation*}
M S \geq\left(\max _{\forall c u t}\left\lceil\frac{S *(N-S)}{|U|}\right\rceil\right) *(X+G C)-G C \tag{4.14}
\end{equation*}
$$

Ring topology has been widely adopted in the optical network due to its sparse link connection and inherent robustness under any single link failure. Here we specifically analyze the lower bound of $M S$ in a ring network with even and odd number of nodes as shown in Fig. 4.5. In a ring network, a cut contains 2 links, and the cut that yields the lower bound is the one that divides the ring nodes equally. Thus we can choose the cut (i.e., the dotted line) to generate two disjoint node sets with the same or almost the same size as shown in Fig. 4.5(a) and Fig. 4.5(b). Consequently, we have Theorem 3.a and 3.b.

Theorem 3.a: If $N$ is even in a ring network, then $M S \geq(X+G C) *\left\lceil\frac{N^{2}}{8}\right\rceil-G C$.
Theorem 3.b: If $N$ is odd in a ring network, then $M S \geq(X+G C) * \frac{N^{2}-1}{8}-G C$.

[^5]For a mesh network, the number of various cuts is significant and can be up to $\sum_{n=1}^{|E|-1} \frac{\binom{|E|}{n}}{2}$, which makes Eq. (4.14) hard to resolve. An alternative method, namely evenload $(E L)$ method, however, can approximate the lower bound $S_{L}$. The $E L$ method assumes that the network load is evenly distributed over all the $2 *|E|$ fiber links within the network. We can obtain the average load per fiber as shown in Eq. (4.15), where $H_{\text {avg }}$ is the average shortest path length over all the node-pairs and $N *(N-1) * H_{\text {avg }}$ is the total path length.

$$
\begin{equation*}
L_{a v g}=\left\lceil\frac{(X+G C) * N *(N-1) * H_{\text {avg }}}{2 *|E|}\right\rceil-G C \tag{4.15}
\end{equation*}
$$

Then we have the lower bound as shown in Theorem 4.
Theorem 4: For a mesh network with $N$ nodes, $M S \geq L_{\text {avg }}=\left\lceil\frac{(X+G C) * N *(N-1) * H_{\text {avg }}}{2 *|E|}\right\rceil-$ $G C$.

In a ring topology, the $E L$ lower bound actually matches the CS lower bound under the uniform traffic. Here we only show the case with even number of nodes. Without loss of generality, for Node 1 in Fig. 4.5(a), its shortest distance to Node $2, \ldots, \frac{N}{2}$ is $1, \ldots, \frac{N}{2}-1$, and the same to Node $N-1, N-2, \ldots, \frac{N}{2}+2$, and the distance to Node $\frac{N}{2}+1$ is $\frac{N}{2}$. Thus the total routing path length for $N$ nodes is $N *\left(2 *\left(1+2+\ldots+\frac{N}{2}-1\right)+\frac{N}{2}\right)=\frac{N^{3}}{4}$. Since the total fiber number is $2 * N$, the lower bound is $(X+G C) *\left\lceil\frac{N^{3} / 4}{2 * N}\right\rceil-G C=(X+G C) *\left\lceil\frac{N^{2}}{8}\right\rceil-G C$.

Upper Bound For the case without predetermined routing, we obtain the upper bound by adopting the shortest path routing since which can minimize the path length and the overlapping. We first show a way to obtain the upper bound only based on the maximum path length $M$ among all the shortest-paths and the maximum fiber usage $R$, where $R$ is the maximum number of various spectrum paths that use the same fiber. We have the upper bound as shown in Theorem 5.

Theorem 5: Given the maximum fiber usage $R$ and maximum path length $M$ under the shortest path routing, $M S \leq((R-1) * M+1) *(X+G C)-G C$.

Proof: Since the maximum fiber usage is $R$, there are maximum $R$ spectrum paths overlapping in one single fiber. In the interference graph (IG), the maximum degree hence
is $(R-1) * M$. According to Brook's Theorem [64], for a graph with maximum degree $\triangle$, a greedy coloring requires $\triangle+1$ different colors. In the interference graph, we thus only requires $\Delta+1=(R-1) * M+1$ set of sub-carriers. Since each spectrum path requires at most $X+G C$ consecutive sub-carriers, the required number of sub-carriers on one fiber is bounded by $M S \leq((R-1) * M+1) *(X+G C)-G C$ after excluding the guard-carrier for the spectrum path that owns the sub-carrier with the largest index.

Note that we may improve this upper bound based on the exact node-degree of each spectrum path in the IG. With a similar argument as we obtain Theorem 2, we can have the upper bound as shown in Theorem 6.

Theorem 6: If the node-degree sequence in the IG corresponding to the shortest path routing is $d_{V_{1}}, d_{V_{2}}, d_{V_{3}} \ldots$, in the descending order, then $M S \leq A *(X+G C)-G C$, where $A=\max _{\forall l} \min \left[d_{V_{l}}+1, l\right]$.

Tight Bounds in Ring Networks To complete the story about the ring network, we further show that ring networks have a tight upper bound for the number of sub-carriers as shown in Theorem 7.

Theorem 7: The lower bound and the upper bound on $M S$ are tight in a ring network with uniform traffic demands.

Proof: Using induction, we can prove Theorem 7 by showing that employing shortest path routing and a specific spectrum allocation can achieve the lower bound in the ring network. Note that two fibers per link create a clockwise and a counterclockwise ring. The proof includes 2 cases as follows.

Case 1- Ring with even number of nodes: To simplify the proof, we first assume $X=1$ and $G C=0$. As the basis, Figure 4.6 shows that $\left\lceil\frac{2^{2}}{8}\right\rceil=1$ sub-carrier is enough for the case $N=2$, and $\left\lceil\frac{4^{2}}{8}\right\rceil=2$ sub-carriers are sufficient for the case $N=4$. For the node-pairs $(1,3)$ and $(2,4)$ in Fig. 4.6(b) that have the maximum distance $\frac{N}{2}$, we assign one sub-carrier along the clockwise ring and one along counterclockwise ring to carry the traffic. There are
$\frac{N}{2}$ node-pairs with the maximum distance in a ring network. We distribute them evenly on the clockwise and counterclockwise rings to minimize the maximum number of sub-carriers of a fiber. For the remaining spectrum paths (with less than $\frac{N}{2}$ hops), we only show the connection for one direction (say clockwise) in Fig. 4.6. We use the fibers along the opposite ring (say counterclockwise) for the connection of the other direction. Now we assume that $\left\lceil\frac{N^{2}}{8}\right\rceil$ sub-carriers are sufficient for any ring with $N$ nodes. As shown in Fig. 4.7, we add 2 extra nodes (Node $N+1$ and $N+2$ ) diametrically opposite to each other. The extra traffic introduced includes the traffic between Node $N+1, N+2$ to the left-half and right-half original $\frac{N}{2}$ nodes, as well as the traffic between Node $N+1$ and $N+2$. For the former part, we note that only $\frac{N}{2}$ sub-carriers are necessary. This is because the sub-carriers used from Node $N+1$ (or $N+2$ ) to the left-half can be reused from Node $N+1$ (or $N+2$ ) to the right-half nodes. Moreover, for the left (or right) half only, the same sub-carriers can be reused for one node to both Node $N+1$ and $N+2$. For example, Sub-carrier 1 (in red) can be used from Node $N+1$ to Node 1, then reused between Node 1 and Node $N+2$. Thus we can conclude that the extra sub-carriers required due to the traffic from $N+1$ and $N+2$ to original $N$ nodes are $\frac{N}{2}$. For the traffic between Node $N+1$ and $N+2$ (with the maximum distance), however, whether it causes extra sub-carriers or not depends on the parity of $\frac{N}{2}$. Accordingly, we further separate the proof into two scenarios:
Case 1.1: When $N=4 * k$ for some integer $k$, we have $\left\lceil\frac{N^{2}}{8}\right\rceil=\frac{N^{2}}{8}$, and the basis is $N=4$. After adding 4 nodes to this ring, the sub-carrier increase for the traffic between original nodes and the new 4 nodes is $\frac{N}{2}+\frac{N+2}{2}=N+1$. In addition, we need 1 extra sub-carrier for the traffic from $N+1$ to $N+2$ and $N+3$ to $N+4$. Hence the additional number of sub-carriers is $N+1+1=N+2$. The number of sub-carrier required for the ring with $N+4$ nodes consequently is $\frac{N^{2}}{8}+N+2=\frac{(N+4)^{2}}{8}$.
Case 1.2: When $N=4 * k+2$ for some integer $k$, we have $\left\lceil\frac{N^{2}}{8}\right\rceil=2 * k^{2}+2 * k+1$ and the basis is $N=2$. Adding 4 nodes increases the number of sub-carriers by $N+2=4 * k+4$. Thus the number of sub-carriers required for ring with $N+4$ nodes is $\left\lceil\frac{N^{2}}{8}\right\rceil+N+2=2 * k^{2}+6 * k+5=\left\lceil\frac{(N+4)^{2}}{8}\right\rceil$.


Figure 4.6. A ring network with $N$ nodes $(N=2,3,4)$

Case 2- Ring with odd number of nodes: As the basis shown in Fig. 4.6, $\frac{3^{3}-1}{8}=1$ sub-carrier is enough for the case $N=3$. Assume the bound is tight for any $N$, and we add 2 extra nodes diametrically opposite to each other as shown in Fig. 4.7(b). One can see that there are $\frac{(N+1)}{2}$ and $\frac{(N-1)}{2}$ nodes from the original network located at the left and right half of the ring, respectively. To satisfy the demands from Node $N+1$ to the nodes at the left half, we need $\frac{(N+1)}{2}$ sub-carriers, which can also be reused for the demands from Node $N+1$ to the right half. These $\frac{(N+1)}{2}$ sub-carriers can be reused for the traffic from Node $N+2$ to the nodes at the left half. These $\frac{(N+1)}{2}$ sub-carriers can further be reused for the traffic between Node $N+2$ to the $\frac{(N-1)}{2}$ nodes at the right half, and the traffic from Node $N+2$ to Node $N+1$. As a result, for the new ring with $N+2$ nodes, we need $\frac{N^{2}-1}{8}+\frac{(N+1)}{2}=\frac{(N+2)^{2}-1}{8}$ sub-carriers.

Now we consider the general case with $X \geq 1, G C \geq 0$, the sub-carrier and guardcarrier allocation is equivalent to the allocation of a set of $(X+G C)$ sub-carriers. Thus a total of $\left\lceil(X+G C) * \frac{N^{2}}{8}\right\rceil$ (or $\left.(X+G C) * \frac{N^{2}-1}{8}\right)$ sub-carriers are enough in the ring network. Moreover, since the sub-carrier index is allocated incrementally, the traffic demands with maximum hop-distance $\frac{N}{2}$ are assigned last (i.e., owning the largest sub-carrier index). The last assigned spectrum path does not need a guard-carrier. Thus $\left\lceil(X+G C) * \frac{N^{2}}{8}\right\rceil-G C$ (or $\left.(X+G C) * \frac{N^{2}-1}{8}-G C\right)$ sub-carriers are sufficient, which equals to the lower bound in Theorem 3.


Figure 4.7. Illustration of adding 2 nodes to a $N$-node ring

### 4.5 Heuristic Algorithms for the RSA problem

The proposed ILP model is tractable when the problem size (e.g., network topology, traffic demands) is small. For a large scale problem, we have to rely on heuristic algorithms to obtain a practical solution within reasonable time. To achieve the goal of minimizing the maximum number of sub-carriers on a fiber (i.e., $M S$ ), we propose two algorithms to choose the routing paths and maximize the reuse of sub-carriers in the spectrum allocation process.

### 4.5.1 Shortest Path with Maximum Spectrum Reuse (SPSR)

For a given set of spectrum path request pair $\left.S P=\left\{<p_{l}, t_{l}\right\rangle\right\}$, where $p_{l}$ is the path and $t_{l}$ is the request size (in terms of the number of sub-carriers) of the $l$-th spectrum path, intuitively, the more the sub-carrier reuse can be achieved, the more we can reduce the maximum number of sub-carriers. Thus we propose the shortest path with maximum spectrum reuse (SPSR) algorithm which combines the shortest path routing with the maximum reuse spectrum allocation (MRSA) algorithm shown in Algorithm 7. In Algorithm 7, the spectrum path requests are first sorted according to the size of the traffic demand. Larger traffic demand has a higher priority since the sub-carrier consecutiveness constraint makes it harder to find available consecutive sub-carriers for the larger traffic demand. Note that only link-disjoint spectrum paths may reuse the same sub-carriers, we hence use $S$ to record the set of spectrum paths that are accommodated in the current iteration and employ a first-fit
strategy to find available consecutive sub-carriers as shown in Line 5 and 9 .

```
Algorithm 7 Maximum Reuse Spectrum Allocation (MRSA)
    Sort the spectrum path requests in the descending order of the traffic demands;
    while There exists non-zero traffic demands do
        \(S \leftarrow \emptyset\)
        Take the request with the maximum demands (say \(t_{j}\) );
        Accommodate \(t_{j}\) using the first available consecutive sub-carriers;
        \(S \leftarrow S \cup p_{j}\)
        for all the remaining requests having non-zero traffic demands do
            if \(p_{m}\) is disjoint with all the paths in \(S\) then
                Accommodate \(<p_{m}, t_{m}>\) using the first available consecutive sub-carriers;
                \(S \leftarrow S \cup p_{m} ;\)
            end if
        end for
    end while
```


### 4.5.2 Balanced Load Spectrum Allocation (BLSA)

In this subsection, we propose another method, namely, Balanced Load Spectrum Allocation (BLSA), which determines the routing by balancing the load within the network to potentially minimize the maximum number of sub-carriers on a fiber. As shown in the following 3 stages, BLSA also employs the spectrum allocation scheme in Algorithm 7.

Stage 1: Path generation. In this stage, we use the $k$-shortest path algorithm [41] to generate the $k(k>=1)$ path(s), namely $P_{s, d}^{h}$, where $h=1,2, \ldots, k$, for each node-pair $(s, d)$.

Stage 2: Path selection. In this stage, we decide the path for each spectrum path with the goal of balancing the load among all the fibers within the network. The load of a fiber $j\left(L_{j}\right)$ is estimated using Eq. (4.13), where $I$ is the number of various spectrum paths using the fiber. The goodness of a path is evaluated by calculating the maximum link load $L D=\max _{\forall j} L_{j}$ in the network. The candidate path that produces the smallest $L D$ is used as the routing path for the corresponding spectrum path request. More specifically, starting from the spectrum path with the largest traffic demand, assign one of the $k$ paths to it while minimizing $L D$, until all the node-pairs with non-zero traffic demands are considered.

Stage 3: Spectrum allocation. In this stage, we use Algorithm 7 to accommodate all the spectrum path requests.

### 4.6 Simulations and Performance Analysis

In this section, we present the simulation results of the proposed ILP model, heuristic algorithms and the bound analysis. The ILP model is implemented using the ILOG CPLEX [47].

### 4.6.1 ILP, Heuristic Algorithms and Bound Analysis

Table 4.1 shows the results when applying the bound analysis on the 14 -node NSF network with $G C=1$. The uniform traffic demand $X$ between each node-pair is 1 or 2 . The lower bound (LB) and upper bound (UB) for BLSA and SPSR are obtained using Theorem 1 and 2 after the routing phase is completed. The LB, and UB in the first two columns are obtained using Theorem 4 and 6, respectively. From Table 4.1, we can see that the BLSA and SPSR can achieve the lower bound in both cases while BLSA produces a better lower bound/upper bound due to the load balancing among all the fiber links.

Table 4.1. Bound analysis on the 14 -node NSF network

| X | LB | UB | BLSA | LB/UB for BLSA | SPSR | LB/UB for SPSR |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 18 | 63 | 27 | $27 / 84$ | 29 | $29 / 63$ |
| 2 | 31 | 95 | 41 | $41 / 128$ | 44 | $44 / 95$ |

We also simulate with ring networks with $4-8$ nodes ( $R_{4}-R_{8}$ ) with uniform traffic demand of $X$ sub-carriers. The maximum sub-carrier index employed among all the fibers or $M S$ is shown in Table 4.2. In specific, the lower bound are obtained using both the cut-set (CS) method and the even-load (EL) method. For example, in $R_{4}$ with $X=1$ and $G C=2$, the CS lower bound is $(1+2) * \frac{4 * 4}{8}-2=4$. The upper bound is obtained using Theorem 6. From Table 4.2, one can observe that the CS lower bound exactly match the EL lower bound, and the ILP model can also produce the optimal solutions that equal to the lower bounds. More importantly, the upper bounds equal to the lower bounds, which
further confirms the tightness of $M S$ on ring networks as stated in Theorem 7.

Table 4.2. ILP model and the bounds analysis

|  | $\mathbf{X = 1 , G \mathbf { G C = 1 }}$ |  | X=1,GC=2 |  | $\mathbf{X = 2 , \mathbf { G C } = \mathbf { 1 }}$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | CS/EL/ILP | UB | CS/EL/ILP | UB | CS/EL/ILP | UB |
| $R_{4}$ | $3 / 3 / 3$ | 3 | $4 / 4 / 4$ | 4 | $5 / 5 / 5$ | 5 |
| $R_{5}$ | $5 / 5 / 5$ | 5 | $7 / 7 / 7$ | 7 | $8 / 8 / 8$ | 8 |
| $R_{6}$ | $9 / 9 / 9$ | 9 | $13 / 13 / 13$ | 13 | $14 / 14 / 14$ | 14 |
| $R_{7}$ | $11 / 11 / 11$ | 11 | $16 / 16 / 16$ | 16 | $17 / 17 / 17$ | 17 |
| $R_{8}$ | $15 / 15 / 15$ | 15 | $22 / 22 / 22$ | 22 | $23 / 23 / 23$ | 23 |

We further study the performance of the ILP model and heuristic algorithms on a random six-node network where the traffic demands are randomly generated within $[0,3]$ sub-carriers for each node-pair. The $M S$ (with the objective of Eq. (4.1)) and the total number of sub-carriers (with the objective of Eq. (4.2)) for 3 representative traffic demands where the summation of sub-carrier requests are 10, 20, 30, respectively, are shown in Table 4.3. For the $M S$, BLSA has a slightly better performance than SPSR. This is because SPSR adopts the shortest-path routing scheme while BLSA can balance the traffic load in the network. For the total number of sub-carriers employed in the network shown in the last row of Table 4.3, however, SPSR outperforms BLSA. This is because shortest path routing potentially minimizes the total hops that spectrum paths span over the whole network.
Table 4.3. Results for the six-node network

|  | ILP |  |  | BLSA |  |  |  | SPSR |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\sum t_{i}$ | 10 | 20 | 30 | 10 | 20 | 30 | 10 | 20 | 30 |  |
| $M S$ | 2 | 5 | 6 | 2 | 6 | 7 | 2 | 6 | 8 |  |
| Total | 21 | 35 | 55 | 24 | 43 | 71 | 22 | 43 | 62 |  |

### 4.6.2 Heuristic Algorithms in a Large Network

For large-scale networks where the ILP model is intractable and the analysis becomes computational intensive, we further study the performance of heuristic algorithms with both uniform and non-uniform traffic pattern. The performance of the heuristic algorithms under uniform and non-uniform traffic demands is presented below.

For uniform traffic pattern, we simulate the 14-node NSF network with $X=2, G C=1$


Figure 4.8. Estimated load, number of sub-carriers for BLSA
and $k=5 .{ }^{3}$ In Fig. 4.8 and Fig. 4.9, the $x$-axis is the ID for each fiber. The $y$-axis represents the estimated load on each fiber using Eq. (4.13) after the routing is determined. The $y$-axis also represents the required number of sub-carriers on each fiber after applying the BLSA algorithm. According to Theorem 1, the lower bound for $M S$ should be the number of sub-carriers on the most congested fiber. For most fibers, the estimated load and the required number of sub-carriers do not exactly match due to the spectrum continuity constraint and/or the sub-carrier consecutiveness constraint. On the most congested fiber, the required number of sub-carriers of BLSA equals to the maximum estimated load, which indicates that BLSA algorithm achieves the lower bound in this case. When comparing the number of sub-carriers over each fiber in Fig. 4.9, we can see that BLSA outperforms SPSR in terms of the load balancing in the network since the variance of number of sub-carriers in BLSA is smaller. At the same time, BLSA produces smaller $M S$ since which has less sub-carriers on the most congested fiber.

For uniform traffic, we also compare the performance under various combinations of traffic demands and guard-carrier size $G C$ in Fig. 4.10 and Table 4.4. In Fig. 4.10, the $M S$ value is compared under various $X, G C$ combinations, where the $x$-axis is the uniform

[^6]

Figure 4.9. Number of sub-carriers per fiber
traffic demand $X$ and $y$-axis is the maximum number of sub-carriers among all the fibers in the network. Clearly, for the same $X$, bigger $G C$ implies more overhead for the guardcarrier and thus requiring more sub-carriers. Interestingly, we observe that the cases with $(X=1, G C=3),(X=2, G C=2)$, and $(X=3, G C=1)$ require almost the same $M S$ as indicated by the dashed line in Fig. 4.10. This is because the $(X+G C)$ value is the same for three cases and the small difference among the above 3 cases is due to the difference in the guard-carrier size for the spectrum path with the largest sub-carrier index. The total number of sub-carriers consumed over all the fibers are compared in Table 4.4. The total number of sub-carriers for above 3 cases (which have the similar $M S$ value), however, is not close since the difference at each fiber is accumulated when counting the total number of sub-carriers. For the total number of sub-carriers, the results show that SPSR outperforms BLSA due to the shortest path routing.

Table 4.4. Results for the 14-node network

|  | GC=1 |  | GC=2 |  | GC=3 |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Total | BLSA | SPSR | BLSA | SPSR | BLSA | SPSR |
| $X=1$ | 956 | 884 | 1413 | 1305 | 1870 | 1726 |
| $X=2$ | 1455 | 1347 | 1912 | 1768 | 2369 | 2189 |
| $X=3$ | 1954 | 1810 | 2411 | 2311 | 2868 | 2652 |

For non-uniform traffic, we collect the results by randomly generating the traffic within $[0, r]$, where $r$ is the maximum traffic demands. Figure 4.11 shows the lower bound (LB)
(using Theorem 1) for $M S$ under the balanced load routing and shortest path routing as well as the $M S$ from BLSA and SPSR. As shown in Fig. 4.11, the LB of BLSA is smaller than that of SPSR due to the load-balanced routing. However, the gap of $M S$ between BLSA and its LB is larger than that of SPSR. This is because the shortest path routing can potentially reduce the overall path lengths and path overlapping, while balanced load routing may introduce longer routing paths and overlapping as a tradeoff of the load balancing. When comparing the total number of sub-carriers used over the whole network in Fig. 4.12, once again we observe that BLSA consumes more sub-carriers than SPSR, which implies that the shortest path routing facilitates the goal of minimizing total number of sub-carriers. In general, we may conclude that SPSR outperforms BLSA in minimizing the total number of sub-carriers, while BLSA outperforms SPSR in minimizing the maximum sub-carrier index (i.e., $M S$ ).


Figure 4.10. $G C$ and $M S$


Figure 4.11. Lower bound and number of sub-carriers


Figure 4.12. Total number of sub-carriers

## PART 5

## CONCLUSIONS AND FUTURE WORK

In the foreseeable future, the Internet traffic is expected to proceed the climbing. In this dissertation, we target on relieving the bandwidth concern of the current Internet Infrastructure with optical networking technologies that are viable in the short term (i.e., waveband switching) and in the long term (i.e., SLICE networks).

Overall, we have resolved the fundamental problem of How to efficiently provision user demands via resource management in multi-granular optical networks. In WBS networks, the granularity consists of the fiber, waveband, and wavelength. While in SLICE networks, the traffic granularity refers to the fiber, and the variety of the demand size (in terms of number of sub-carriers).

The first half of the dissertation focuses the multi-granular waveband switching networks, a promising solution to scale the wavelength routed WDM networks. We have extensively review the related work and presented a classified overview of the literature study. The proposed multi-granular optical switching framework have addressed critical issues of waveband switching including: the static non-uniform waveband switching, the static and dynamic uniform waveband switching, and the waveband protection. When combined with the literature study, the proposed framework can enable a survivable waveband switching network for composing the Internet backbone in the short or middle term.

The recent advancement in OFDM-based optical networks, namely spectrum-sliced elastic optical path (SLICE) networks, is reflected in the second part of this dissertation. We have extensively analyzed and studied the routing and spectrum allocation problem in SLICE networks, a fundamental piece for building a SLICE-based Internet. Compared to WDM networks, SLICE networks have the advantage of elastic and fine-granular spectrum management, thus implying abundant bandwidth to carry the ever-lasting traffic explosion in
the long term.
For the waveband switching network, in the future, we plan to study its energy perspective and propose energy-efficient routing and wavelength assignment algorithms towards a Green Internet. For SLICE networks, we will further study the protection, dynamic traffic accommodation, spectrum conversion as well as energy-efficient routing and spectrum allocation algorithms.

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[^0]:    ${ }^{1}$ This is because the overlapping hops between lightpath along $A-B-C$ and $A-B$ is only one, which cannot save ports.

[^1]:    ${ }^{1}$ Other components such as dynamic non-uniform waveband switching have been well addressed in the literature, thus not included here.

[^2]:    ${ }^{2}$ The same pattern can be observed for other deployments. Thus it is not shown here.

[^3]:    ${ }^{3}$ Being aware the dynamic traffic pattern, it is reasonable to expect that all the fibers have to be demultiplexed.

[^4]:    ${ }^{1}$ This maximum index determines how many sub-carriers per fiber should be deployed in a green-field network design, hence implying the potential cost, footprint and power consumption of the switching equipments.

[^5]:    ${ }^{2}$ The maximal number of sub-carriers on a fiber of the cut $U$ is minimized (i.e., the lower bound) when traffic demands are evenly distributed among all the fibers of cut $U$.

[^6]:    ${ }^{3}$ Other combinations with different $X, G C$ and $k$ which show the same performance pattern are omitted here.

