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Integrated Intermediate Waveband and Wavelength Switching for Optical WDM Mesh Networks

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Integrated Intermediate Waveband and Wavelength Switching for Optical WDM Mesh Networks

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***Abstract*— As wavelength-division multiplexing (WDM) evolves towards practical applications in optical transport networks, waveband switching (WBS) has been introduced to cut down the operational costs and to reduce the complexities and sizes of network components, e.g., optical cross-connects (OXCs). This paper considers the routing, wavelength assignment and waveband assignment (RWWBA) problem in a WDM network supporting mixed waveband and wavelength switching. First, the techniques supporting waveband switching are studied, where a node architecture enabling mixed waveband and wavelength switching is proposed. Second, to solve the RWWBA problem with reduced switching costs and improved network throughput, the cost savings and call blocking probabilities along intermediate waveband-routes are analyzed. Our analysis reveals some important insights about the cost savings and call blocking probability in relation to the fiber capacity, the candidate path, and the traffic load. Third, based on our analysis, an online integrated intermediate WBS algorithm (IIWBS) is proposed. IIWBS determines the waveband switching route for a call along its candidate path according to the node connectivity, the link utilization, and the path length information. In addition, the IIWBS algorithm is adaptive to real network applications under dynamic traffic requests. Finally, our simulation results show that IIWBS outperforms a previous intermediate WBS algorithm and RWA algorithms in terms of network throughput and cost efficiency.**

I. INTRODUCTION

Since wavelength-division multiplexing (WDM) has been recognized as the most promising technique for the next-generation backbone networks [1], a lot of attention has been paid recently to improve the network operation and provisioning. To cut down the operational costs and to reduce the complexities and sizes of network components, waveband switching (WBS) was introduced in WDM networks [2], [3]. Such a network is called a waveband-routed WDM network (WBS network). Although previous studies on grooming of low rate end-user traffic into high speed lightpath in WDM networks are valuable for WBS study, the grooming algorithms cannot be applied directly in WBS networks because of the differences in techniques, network constraints, and objectives.

Unlike the traditional wavelength-routed WDM (WRN) networks that route each wavelength separately in a wavelength-route (lightpath), a WBS network groups a specific set of wavelengths into a waveband at a grouping node, e.g. an optical crossconnect (OXC) [4], [5], transmits the wavelengths as a single bundle along some common links, and disaggregates the waveband back into wavelengths at a disaggregating node, e.g., another OXC. A waveband-route is formed along

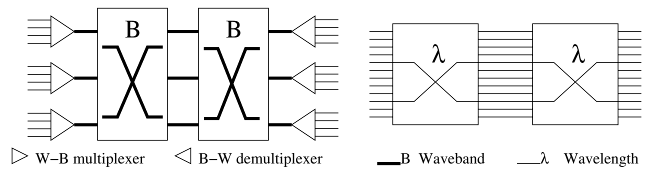

Fig. 1. Comparison of waveband switching and wavelength switching along a two-hop route.

these common links between the grouping node and the disaggregating node. The difference between waveband switching and wavelength switching is illustrated in Fig. 1. Note the increased number of ports needed at intermediate OXCs when only wavelength switching is available in the network.

Since WBS incorporates all-optical transmission and switching, a waveband from an input port is switched to a corresponding output port without any optical-electronic (O-E) and electronic-optical (E-O) conversions at each node [6], [7]. On the other hand, in the traditional WRN networks, each wavelength occupies an input and an output OXC port at each node and may go through O-E-O conversions depending on the adopted OXCs. Thus, a waveband-route reduces the cost of each OXC port and the number of OXC ports used compared with the corresponding wavelength-routes [8]. As the switching and transmission costs in the optical domain of a WDM network are dominated by the used OXC ports, the WBS technique has the potential of significant cost savings.

It has been recognized that the network throughput influences the generated revenue in connection-oriented networks. This is also true in a WBS network. In reality network equipment that has been deployed will remain unchanged for a certain period of time. Dynamically arriving traffic may be blocked due to lack of resources, which affects the network throughput. Thus, call blocking probability is an important parameter in WBS networks and should be studied [4], [5].

To accommodate a call, a waveband-route or a wavelength-route should be set up. This involves finding an available path, which is referred to as routing. A free wavelength should also be assigned along the path to forward the call. In addition, the wavelength may be grouped into a waveband-route or a new waveband-route may be set up. A free waveband along the path is required to set up a new waveband-route. The whole problem is called the routing, wavelength assignment

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and waveband assignment (RWWBA) problem. This contrasts with the well-studied RWA problem in WRN networks which only involves routing and wavelength assignment.

It is important to design a WBS algorithm to solve the RWWBA problem with low call blocking probability and reduced operational costs. Different WBS algorithms result in different network performances in terms of call blocking probability and operational costs. As most previous studies focused either on analyzing the reduced operational costs adopting WBS or on proving the feasibility of the WBS technique, the designing of an efficient WBS algorithm to achieve optimal cost savings and call blocking probability at the same time remains as an unexplored topic. This paper discusses the design of integrated WBS algorithm that can achieve both the goals. To focus on the RWWBA problem, we assume that each call requires a whole wavelength capacity.

According to its choice of grouping nodes and disaggregating nodes, a WBS algorithm can be classified as an end-to-end WBS (ETE-WBS) algorithm [9] and a more flexible intermediate WBS (IT-WBS) algorithm [3], [5]. The first study of IT-WBS considering both call blocking probability and cost savings is [5]. However, the study in [5] focused on the performance analysis of IT-WBS. The IT-WBS algorithm proposed in [5] was very simple and did not show any performance improvement in call blocking probability compared with ETE-WBS. This paper carries out a comprehensive study on designing an integrated IT-WBS algorithm. The efficiencies of the proposed IT-WBS algorithm in cost savings and call blocking probability are compared with the IT-WBS algorithm in [5] and the same routing and wavelength assignment (RWA) algorithm in the corresponding WRN network.

To enable WBS, a band demultiplexer can be adopted to demultiplex a fiber into bands of wavelengths (wavebands). A band multiplexer can be adopted to multiplex wavebands into a fiber. Additionally, micro-electro-mechanical systems (MEMS) can be deployed to switch wavebands all-optically. This paper investigates various techniques that make WBS practical and the costs of adopting them. Based on the investigation, a multi-granular optical crossconnect (MG-OXC) architecture is proposed to support waveband and wavelength (de)multiplexing at the same time. The mesh networks we consider consist of such MG-OXC nodes.

This paper addresses the problem of designing an efficient integrated IT-WBS algorithm under dynamic traffic requests. To find out how to optimally group and switch wavebands, the performance of a call along an intermediate waveband-route is analyzed. Our analysis reveals some important insights about the operational costs and call blocking probability along a candidate path in relation to the traffic load, fiber capacity, waveband granularity, and hop count of the path.

Based on the analysis, an online integrated intermediate waveband switching (IIWBS) algorithm is proposed. To determine the grouping of a call into an intermediate waveband-route, IIWBS collects the link utilization and the path length information. In addition, IIWBS determines how to set up a new waveband-route according to the node connectivity information. The rationale is that the nodal connectivity usually reflects the amount of bypassing traffic. By selecting a node with high connectivity as the grouping/disaggregating node, more calls can be switched through the waveband-route and IIWBS can achieve high cost savings. On the other hand, by not grouping a call at a node with low nodal connectivity, IIWBS reduces the waveband consumption at the node. Thus, it reduces the probability that other calls are blocked along this waveband-route due to lack of free wavebands. Our results show that IIWBS is more efficient than the IT-WBS algorithm in [5] and the corresponding RWA.

The remainder of the paper is organized as follows. Section II investigates the technologies that make WBS practical and illustrates the node architectures supporting WBS. Section III presents the network model and the dynamic RWWBA problem. Section IV analyzes the cost savings and the call blocking probability along intermediate waveband-routes. Based on the analysis, Section V describes the IIWBS algorithm. Section VI presents the results. Finally, Section VII concludes the paper.

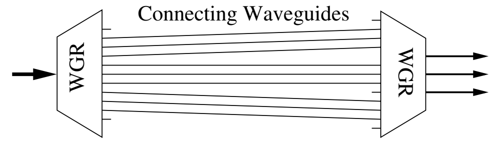

Fig. 2. A schematic illustration of the PLC-based waveband demultiplexer deploying two waveguide grating routers from [14].

II. Enabling Technologies for Waveband Switching

A. *Waveband (De)Multiplexing Techniques*

The developments in optical (de)multiplexers enable the (de)multiplexing of wavebands by adopting band filters. Such a (de)multiplexer is called a band (de)multiplexer, which is capable of separating an incoming optical spectrum into bands of wavelength-channels ideally with sharp passband corners. There are typically three banding filter techniques, which are thin-film interference filters [10], bulk gratings [11], and planar lightwave circuits (PLC) [12], [13].

Among the three techniques, the thin-film interference filters are widely deployed because of their low loss [10]. However, there are several disadvantages. First, deploying thin-film interference filters requires costly hermetic packages and complicated manual assembly. Second, they typically exhibit large chromatic dispersions and have strict requirements on passband corners. Finally, to demultiplex multiple wavebands, a cascade of thin-film interference filters are required to perform a serial of demultiplexings. Compared with thin-film interference, deploying bulk gratings can achieve dispersion-free and parallel demultiplexing of multiple wavebands. The disadvantages are the higher loss and larger size of the multiplexer. Recent studies demonstrate an alternative banding filter technique of using PLCs [14], [15] with advantages over the other two techniques.

Previous studies [12]–[15] successfully demonstrated the PLC-based band demultiplexers with no dispersion, no expensive hermetic packaging, no tedious manual setup, and low loss. As the authors in [12], [13] deployed a cascade of Mach-Zehnder interferometers (MZIs), the demultiplexing of multiple wavebands still requires a series of demultiplexers. In addition, by adopting the MZI technique, the demultiplexer becomes very large and constrains the minimum number of wavebands to be demultiplexed. Some studies [14], [15] have demonstrated a more compact PLC-based band demultiplexer, which adopts two perfectly sampled waveguide grating routers (WGRs). The PLC-based band demultiplexer can be found in [14] and is illustrated in Fig. 2. Mixed (de)multiplexer can be built by adopting PLC, which (de)multiplexes wavelengths and wavebands (from)into a fiber at the same time.

B. Selective Waveband Router

Practically, a large waveband switching system can be built based on hundreds of tiny moveable mirrors, called MEMS [16], and multiple optical add-drop band (de)multiplexers discussed in the previous subsection [12]–[15]. Another way to build a large WBS system is to deploy multiple 2×2 waveband selective routers as proposed in [17].

The tiny mirror in MEMS is even smaller than a human hair in diameter and can move in three dimensions. Tens to hundreds of the tiny mirrors are placed together in mirror arrays. Optical signals of a waveband from an input fiber are directed by a mirror to another mirror on a facing array, which reflects the signals down towards a corresponding output fiber. Advantage of deploying MEMS is low cost per switching element as it arranges many mirrors in a single chip. The disadvantage is that the speed in moving the mirrors to direct the optical signals is limited by the applying current [16], [18]. Pictures of the MEMS switch could be found in [16].

A thin-film filter based 2×2 waveband-selective router unit is proposed in [17] to build a large WBS system. An $N\times N$ waveband-selective router could be obtained by interlinking multiple 2×2 waveband selective router units in parallel. The interlinks could be fiber optics or free-space optics. The study in [17] demonstrated a 3×3 waveband selective router with a loss of 4.73 dB and a crosstalk of 20 dB. The disadvantages of deploying the technique compared with deploying MEMS are the high cost per switching port and relatively high loss. This paper considers the PLC-based band (de)multiplexer technology and the MEMS technology in a large WBS system.

C. Design of Optical Nodes Supporting Waveband Switching

Through mixed waveband and wavelength switching, the costs of the major optical components, such as the optical crossconnects (OXC), can be reduced. By adding the waveband crossconnect fabric and adopting mixed band (de)multiplexers, an OXC is capable of waveband switching, which is denoted as GOXC and is shown in Fig. 3. By adding the waveband (de)multiplexers, a GOXC can add and drop wavebands, which is denoted as MG-OXC and is shown in Fig. 4.

Table I illustrates the average market prices for some major wavelength and waveband switching components. The weighted costs of a wavelength crossconnecting

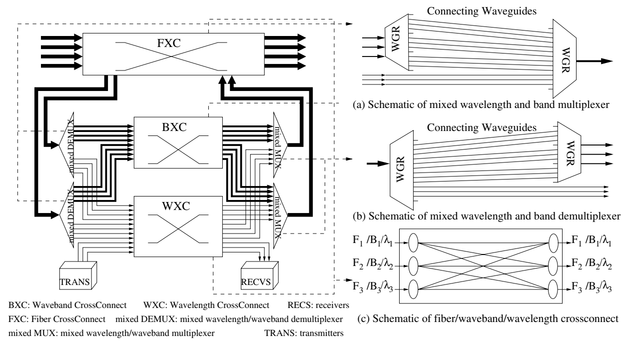

Fig. 3. An illustration of a hierarchical optical crossconnect (GOXC), which is capable of mixed waveband/wavelength switching without waveband adding/dropping functions.

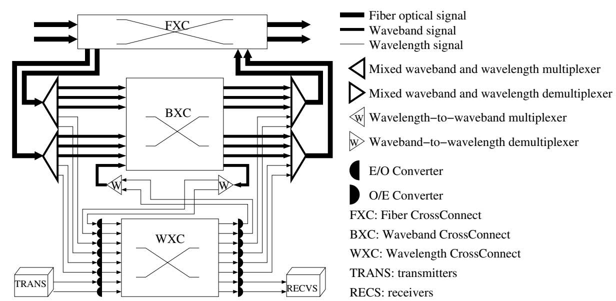

Fig. 4. An illustration of a multigranular optical crossconnect (MG-OXC), which is capable of mixed waveband/wavelength switching, wavebands adding, and wavebands dropping.

TABLE I

COSTS OF OPTICAL COMPONENTS, WHERE μ IS THE COST RATIO OF AN O-O-O SWITCHING PORT TO AN O-E-O SWITCHING PORT.

Component	Market Price
Waveband Filter	\$94
DEMUX/MUX (1528.77-1605.73nm, 80 wavelengths)	\$4,285
Switching Fabric	\$10,000 per port
WXC (with 480 wavelengths)	\$4,800,000
FXC (with 6 fibers)	\$60,000
BXC (with $\frac{\lambda}{G}$ wavebands)	$\frac{\$4,800,000\times\lambda}{G}\mu$

(WXC) port, a waveband crossconnecting (BXC) port, a (de)multiplexer, a mixed band (de)demultiplexer, and a waveband (de)multiplexer are defined based on the average price of an O-E-O WXC port and are shown in Table II. The weighted costs of an OXC, a GOXC, and an MG-OXC are the total weighted costs of the components. According to Table II, the weighted costs of an MG-OXC and a GOXC drop as the ratio of waveband switching increases. Let λ is the fiber capacity in terms of wavelengths, F is the number of fibers along a single link, G is the waveband granularity in terms of wavelengths, μ is the cost of a waveband switching port normalized to a wavelength switching port, and r is the proportion of wavelengths in a fiber that are switched in wavebands.

Below, we calculate the weighted costs of an OXC/GOXC/

TABLE II

ESTIMATED COSTS OF A GOXC AND AN MG-OXC COMPARING WITH AN OXC, WHERE A MIXED (DE)MULTIPLEXER IS SLIGHTLY MORE EXPENSIVE THAN A (DE)MULTIPLEXER BECAUSE OF THE WAVEBAND FILTERS.

Component	Cost Factor	# in an OXC	# in a GOXC	# in an MG-OXC
FXC Port	1	F	1	1
WXC Port	1	$F\lambda$	$(1-r)F\lambda$	$(1-r)F\lambda$
BXC Port	$\mu(\leq 1)$	0	$rF\lambda$	$rF\lambda$
DEMUX	0.5	F	0	0
MUX	0.5	F	0	0
MIX-DEMUX	≈0.5	0	F	F
MIX-MUX	≈0.5	0	F	F
BAND-DEMUX	$\frac{0.5G}{\lambda}$	0	0	$\frac{rF\lambda}{G}$
BAND-MUX	$\frac{0.5G}{\lambda}$	0	0	$\frac{rF\lambda}{G}$
Total Cost = $\sum_{Component_i} Cost_i \times \#\ of\ Component_i$				

MG-OXC when the WXC is O-O-O based. The cost of a BXC port normalized to a WXC port (μ) is 1. Assume that there are 6 fibers along an input fiber link, 80 wavelengths per fiber, 20% of the wavelengths are through the BXC, and the waveband granularity is 4. The weighted cost of an O-O-O based OXC is 492, which is the summation of the costs for WXC ports (80×6), FXC ports (6), BXC ports (0), DEMUXs/MUXs ($(0.5+0.5)\times6$), and BAND-DEMUXs/BAND-MUXs (0). The weighted cost of a GOXC is 420, which is the summation of $80\times6\times(1-0.2)+6+80\times6\times0.2/4+(0.5+0.5)\times6+0$. The weighted cost of an MG-OXC is 421.2, which is the summation of $80\times6\times(1-0.2)+6+80\times6\times0.2/4+(0.5+0.5)\times(4/80)\times(80\times6\times0.2/4)$.

Below, we calculate the weighted costs of an OXC/GOXC/MG-OXC when the WXC is O-E-O based, where μ is roughly 0.2. Following the same assumptions that F is 6, λ is 80, r is 20%, and G is 4, the weighted cost of an OXC is the same as the one in the above example as 492. The weighted cost of a GOXC is 400.8, which is the summation of $80\times6\times(1-0.2)+6+0.2\times(80\times6\times0.2/4)+(0.5+0.5)\times6$. The weighted cost of an MG-OXC is 402, which is the total value of $80\times6\times(1-0.2)+6+0.2\times(80\times6\times0.2/4)+(0.5+0.5)\times6+(0.5+0.5)\times(4/80)\times(80\times6\times0.2/4)$.

Both the above examples show that a GOXC/MG-OXC costs less than an OXC does. Since the weighted costs are defined based on the average cost of an O-E-O based WXC port, the cost-efficiency of WBS can be more accurately illustrated through the reduced cost of a GOXC/MG-OXC port. Fig. 5 presents the reduced cost of a GOXC/MG-OXC port under the same assumptions that λ is 80, F is 6, and G is 4.

D. Embedding Waveband-Switching Components

A more practical way to adopt WBS is to embed WBS components into the realistically utilized O-E-O OXCs. The advantages of embedding WBS components are the reduced cost and the high-speed of optical processing when switching a call

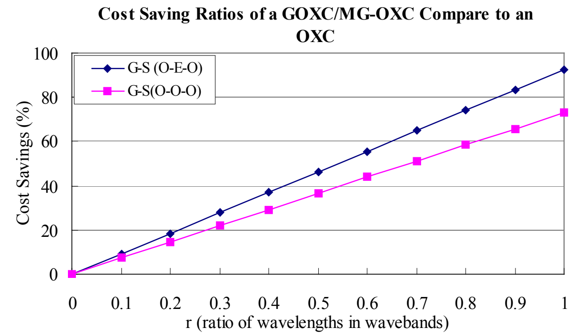

Fig. 5. Reduced cost of a GOXC and an MG-OXC comparing with an OXC, where G-S(O-E-O) and G-S(O-O-O) represent the results by comparing with an O-E-O based OXC and an O-O-O based OXC separately.

through BXC. In doing so, an O-O-O BXC fabric, mixed band (de)multiplexers, and/or waveband (de)multiplexers should be adopted. The cost of embedding these components depends on the size of the BXC fabric and the waveband granularity. F is defined in Section II-C. Let B be the number of wavebands in a fiber, W_b be the cost factor of a waveband (de)multiplexer, and μ be the factor of an O-O-O switching port versus an O-E-O switching port. The weighted cost of supporting waveband switching, waveband adding, and waveband dropping can be expressed as

$$C_{MG-OXC} = 2W_bBF + \mu BF. \quad (1)$$

Based on the estimated price listed in Table I and Table II, we can calculate the weighted cost of embedding the WBS components given the number of wavebands in a fiber. The number of wavebands in a fiber can be derived from the waveband granularity G and the number of wavelengths in wavebands rW as we consider uniform waveband switching. Section III describes the uniform waveband switching in detail. The weighted cost of an MG-OXC is the weighted cost of the OXC plus the weighted costs of the embedded WBS components. We normalize the weighted costs of an MG-OXC to the value of an O-E-O-based OXC. Fig. 6 shows the normalized costs of MG-OXCs embedded with different sizes of waveband switching components.

According to Fig. 6, embedding waveband-switching components introduces extra costs. However, the extra cost is small if the waveband granularity G is not very small and the proportion of wavelengths in wavebands is not very high. For example, if 50% of the wavelengths are through BXC and G is 4, the extra cost is only 3.7% of the original OXC. Studies on backbone network traffic show that most of the traffic along a node is bypassing traffic. Thus, when designing a WBS network, r could be in the range of 30% and 70%. Therefore, the highest normalized cost of an MG-OXC for a WDM network is 1.076 since the smallest waveband granularity is 2. Additionally, the extra costs of building an MG-OXC and a GOXC are very close. Thus, we consider adopting MG-OXCs in the network.

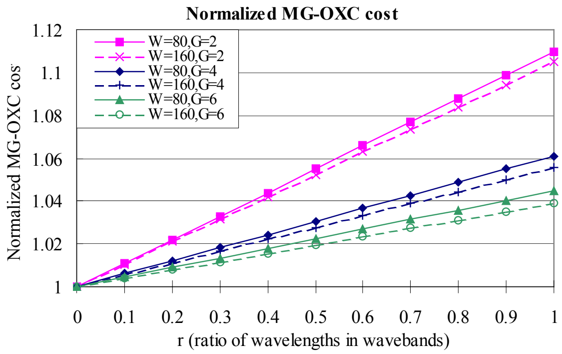

Fig. 6. The normalized cost of an MG-OXC, which is an O-E-O based OXC embedded with waveband switching components.

III. Network Model and Problem Statement

Previous studies consider the demultiplexing of a waveband into wavelengths after the waveband has been demultiplexed from the fiber [2], [3], [19]. We consider the mixed waveband-wavelength switching as discussed in the previous section, where the (de)multiplexings of wavebands and wavelengths from a fiber are performed at the same time by using mixed band (de)multiplexers. A node utilizing such mixed (de)multiplexers can switch the wavebands and wavelengths at the same time through different switching fabrics. Such a node is referred to as a node supporting mixed waveband and wavelength switching.

The deployed network components determine the initial network configuration. When a call is initiated by end-users or the upper layer applications, the source node tries to set up a wavelength-route/waveband-route or to group the call into an existing waveband-route. In doing so, the nodes communicate with each other about the current configurations to search for an available path.

Let the mesh network consist of N nodes and J unidirectional links. Each node is a routing node with an MG-OXC. Each link is a fiber link carrying W wavelengths and B wavebands. Each waveband may consist of at most G specific wavelengths, where G is also referred to as the waveband granularity. For a WBS network supporting mixed waveband-wavelength switching, only a fraction of wavelengths are grouped in wavebands. Therefore, a fiber link may contain both active wavelengths and active wavebands and $B \times G \leq W$. In addition, depending on the utilized MG-OXCs, the wavelengths in a waveband are specified beforehand. For example, a waveband b_i may consist of G contiguous wavelengths $w_{(i-1)G}, w_{(i-1)G+1}, ..., w_{iG-1}$.

In a WBS network, waveband granularity is an important factor in achieving maximum cost savings and minimum call blocking probability. However, it is difficult to define an optimal waveband granularity under dynamic traffic request because the current optimal configuration of waveband granularity may no longer be optimal in future. To make it flexible, one solution is to allow an MG-OXC to support a set of granularities, referred to as a non-uniform WBS [6]. Another method is called uniform WBS. Although uniform WBS only allows a fixed granularity for an MG-OXC [2], it permits idle wavelengths to be grouped into wavebands. Later on, if a call has a candidate path through such a waveband-route, the idle wavelength can be assigned to the call provided that the wavelength is available along the remaining links. The call is transmitted along the waveband-route. Compared with the non-uniform WBS, uniform WBS is simpler and easier to implement. We consider such uniform WBS in this paper.

In a WBS network, a dynamically arriving call should be provisioned either along a wavelength-route or along an intermediate/end-to-end waveband-route. The problem of provisioning a call in a WBS network could be divided into searching for a candidate path, referred to as routing, searching for a free wavelength with or without waveband grouping requirements, referred to as wavelength assignment, and searching for a free waveband along the sub-paths of the candidate path, referred to as waveband assignment. The whole problem is then called routing, wavelength and waveband assignment (RWWBA) problem. To focus on adopting WBS technique in a WBS network, it is assumed that each call requires a whole wavelength capacity.

A WBS algorithm solves the RWWBA problem by determining how to set up a new waveband-route and how to group a call into an existing waveband-route. As shown in [2], [6] and Fig. 7, a waveband-route should be at least two-hop long to be cost-efficient. In addition, an active waveband should contain at least two wavelengths to be cost-efficient. There are two types of WBS algorithms, namely end-to-end WBS (ETE-WBS) algorithms and intermediate WBS (IT-WBS) algorithms. An ETE-WBS algorithm always selects the source node to be the grouping node and the destination node to be the disaggregating node if the call is to be switched along a waveband-route. An IT-WBS algorithm is more flexible in that it may select an intermediate node along the path to be the grouping or disaggregating node.

The advantage of IT-WBS over ETE-WBS in cost savings can be illustrated through an example shown in Fig. 7(c). In the example, there are four calls originating from two different source nodes and destined to two different destination nodes. In IT-WBS, the four calls can be grouped into a waveband-route B_1 at intermediate node S and disaggregated at intermediate node D. This reduces the number of ports at wavelength crossconnect (WXC) stage from node S to node D. On the contrary, in ETE-WBS, the four calls cannot be grouped into a waveband-route. Thus, IT-WBS reduces the number of ports used and the operational costs more than ETE-WBS does in this situation. On the other hand, switching a call along an intermediate waveband-route may increase the call blocking probability, since the call is also constrained by the waveband availability and waveband continuity along the route. In addition, switching a call along an intermediate waveband-route may increase the length of the route, which in turn increases the call blocking probability. Thus, it is important to analyze the effects of IT-WBS on network performance in terms of cost savings and call blocking probability.

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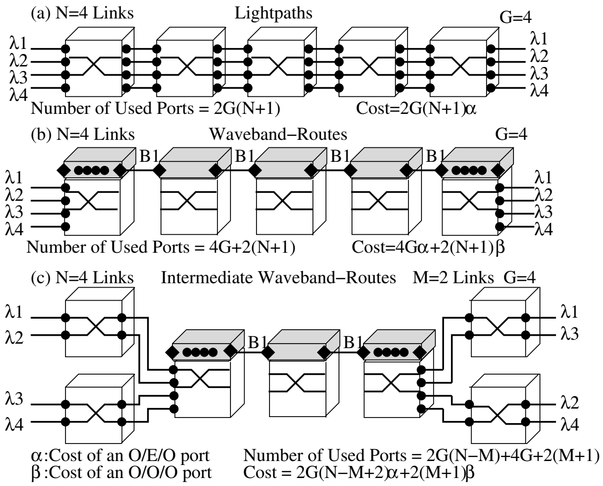

Fig. 7. Comparison of switching calls along wavelength-routes, end-to-end waveband-routes, and intermediate waveband-routes.

IV. Performance Analysis Of Intermediate Waveband Switching

In this section, we identify the effects of IT-WBS on the reduction of the operational costs and the call blocking probability. Given an intermediate waveband-route, the operational costs and blocking probability of a call can be derived. These are determined by the waveband switching algorithm in solving the routing, the waveband grouping, and the wavelength/waveband assignment problems.

A. Network Configuration Assumptions

The analysis is based on the following network environment assumptions. The network consists of N nodes, which are MG-OXCs, and J uni-directional links, each of which carries W wavelengths and B wavebands. A waveband b_i may consist of at most G wavelengths and is constrained to wavelengths i, $i+B$, ..., $i+(G-1)B$, where $1 \leq i \leq B$. A fiber link may contain both active wavelengths and wavebands. Thus, $B \times G \leq W$. A dynamically arriving call can be provisioned through either a wavelength-route or an intermediate waveband-route.

B. Operational Costs of an Intermediate Waveband-Route

We calculate the operational costs of a candidate intermediate waveband-route. An example is shown in Fig. 7(c). The operational costs consist of the costs of the occupied MG-OXC ports. If the cost of each MG-OXC port is the same, the operational costs can be represented by the number of occupied switching ports. Otherwise, we can define cost factors to represent the costs of different switching ports. As the transmission along a waveband-route dose not require the O-E-O conversions, the waveband switching ports are O-O-O ports. On the contrary, the wavelength switching ports are usually O-E-O ports. Let α represent the cost of an O-E-O switching port and β represent the cost of an O-O-O switching port.

Generally there are three types of candidate routes for a call, which are wavelength-routes, end-to-end waveband-routes, which are also referred to as waveband-routes, and intermediate waveband-routes. An intermediate waveband-route for a call consists of two parts, which are the waveband-route and the remaining wavelength-route(s), since the call is grouped at an intermediate or the source node and disaggregated at another intermediate or the destination node. Considering a call traversing along an N-hop route and $N \geq 2$ as shown in Fig. 7(a), if the route is a wavelength-route, the total operational costs are

$$P_\lambda = 2(N+1)\alpha. \tag{2}$$

If the call also traverses along an M-hop waveband-route as shown in Fig. 7(c), the total operational costs of the call are

$$P_c = 2(N-M)\alpha + \frac{4G'\alpha + 2(M+1)\beta}{G'}, \tag{3}$$

where G' is the number of active wavelengths in that waveband-route. Thus, the cost saving ratio for switching a call along an intermediate waveband-route instead of along a wavelength-route can be expressed as follows.

$$S_{p_c} = 1 - \frac{P_c}{P_\lambda} = \frac{M-1}{N+1} - \frac{(M+1)\beta}{G'(N+1)\alpha}, \tag{4}$$

where $2 \leq M \leq N$.

The expected cost saving ratio by adopting IT-WBS can be derived from (4) by letting $G' = G$. The expected port saving ratio can also be derived from (4) by setting $G' = G$, $\alpha = 1$ and $\beta = 1$. Moreover, we can conclude that the expected cost saving ratio and the expected port saving ratio are proportional to the length of the waveband-route and the number of active wavelengths in the waveband. In addition, the cost factors of wavelength switching ports and waveband switching ports influence the expected cost savings. Fig. 8 shows the expected port saving ratio and the expected cost saving ratio of a call along an intermediate waveband-route in proportion to the waveband granularity and the number of links that are not in the waveband-route.

C. Call Blocking Probability Along an Intermediate Waveband-Route

The blocking probability of a call along an intermediate waveband-route depends on the wavelength availability and the waveband availability along the route. Thus, different decisions on selecting a waveband-route result in different call blocking probabilities.

According to [2], to be cost-efficient, a waveband-route should be at least two-hop long. Given an h-hop candidate route for a call, where $h > 2$, the call can traverse through different waveband-routes as shown in Fig. 9. As illustrated in Fig. 9, there are $h-1$ possible waveband-routes along the h-hop path, where the grouping node is the source node. There are $h-2$ possible waveband-routes along the path, where the grouping node is the second node along the path. As the waveband-route should contain at least two hops to be cost-efficient, the last possible waveband-route is a 2-hop route, where the disaggregating node is the destination node. Thus,

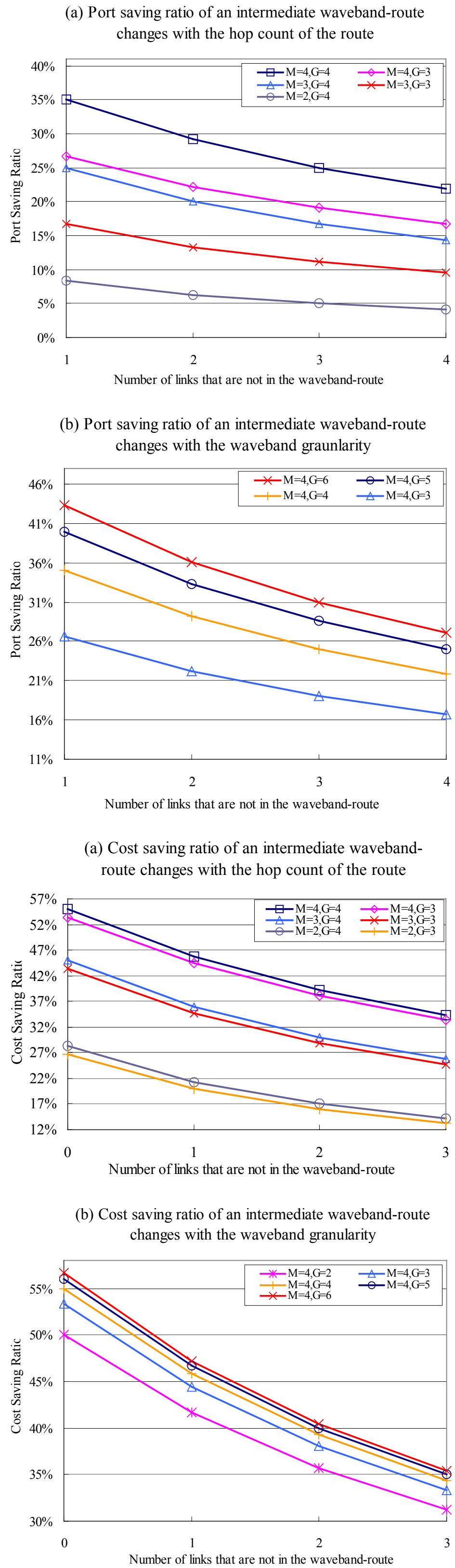

Fig. 8. Operational cost savings and port savings of an intermediate waveband-route,where M is the hop count of the waveband-route and G is the number of wavelengths in the waveband. (a) Port savings (%) change with the route length, where $\alpha = 1$, $\beta = 1$. (b) Port savings (%) change with the waveband granularity, where $\alpha = 1$, $\beta = 1$. (c) Operational cost savings (%) changes with the route length, where $\alpha = 5$, $\beta = 1$. (d) Operational cost savings (%) changes with the waveband granularity, where $\alpha = 5$, $\beta = 1$.

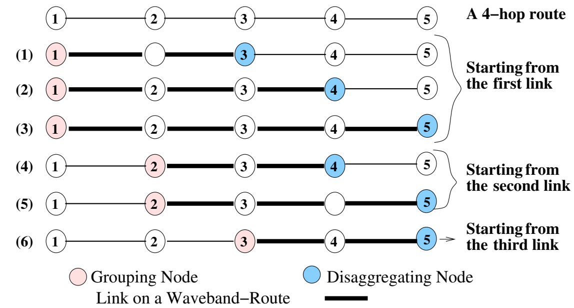

Fig. 9. Possible intermediate waveband-routes along a 4-hop path. There are a total of (4-1)4/2=6 possible waveband-routes along this 4-hop path.

let m be the number of possible waveband-routes along an h-hop path, then

$$m = \sum_{i=1}^{h-1} (h - i) = \frac{(h-1)h}{2}. \tag{5}$$

Given a route L_c with h hops and $h \geq 2$, the call may be provisioned through one of the m candidate intermediate waveband-routes. A call $c(s, d)$ is blocked if it is blocked on the selected i-hop waveband-route B_c^i or along the remaining wavelength-links. Let W_c^{h-i} be the remaining wavelength-links. Let $P^0_{W_c^{h-i}}$ be the probability that there are no common free wavelengths along the links W_c^{h-i}. $P^0_{W_c^{h-i}}$ can be calculated through the method presented in study [5]. Let $P^0_{B_c^i}$ be the probability that the call c is blocked along the waveband-route B_c^i because of no common free waveband. Let $P^0_{W_c^i}$ be the probability that the call is blocked along waveband-route B_c^i because of no common free wavelength. $P^0_{B_c^i}$ and $P^0_{W_c^i}$ can also be calculated as shown in study [5]. The event that the call is blocked along a waveband-route because of no common free waveband and the event that the call is blocked along the waveband-route because of no common free wavelength are independent. Thus, the probability that the call is blocked along the candidate waveband-route B_c^i is

$$p_b(B_c^i = 0) = P^0_{B_c^i} + P^0_{W_c^i} - P^0_{B_c^i} \times P^0_{W_c^i}. \tag{6}$$

We assume that the link utilizations of individual links are independent from each other. Thus, the event that the call is blocked along the waveband-route B_c^i and the event that the call is blocked along the remaining wavelength-links W_c^{h-i} are independent. The probability that the call is blocked along the route traversing through the candidate waveband-route B_c^i is

$$\begin{aligned} p(L_c) &= 1 - (1 - P^0_{W_c^{h-i}}) \times (1 - p_b(B_c^i = 0)) \\ &= P^0_{W_c^{h-i}} + P^0_{B_c^i} + P^0_{W_c^i} - P^0_{W_c^{h-i}} P^0_{B_c^i} - P^0_{W_c^{h-i}} P^0_{W_c^i} \\ &\quad - P^0_{B_c^i} P^0_{W_c^i} + P^0_{W_c^{h-i}} P^0_{B_c^i} P^0_{W_c^i}. \end{aligned} \tag{7}$$

According to (6), $P^0_{B_c^i}$ increases as the hop count of B_c^i increases and decreases as the number of wavebands in a fiber B increases. $P^0_{W_c^{h-i}}$ and $P^0_{W_c^i}$ increase as the hop count of W_c^{h-i} increases and decrease as the fiber capacity in terms

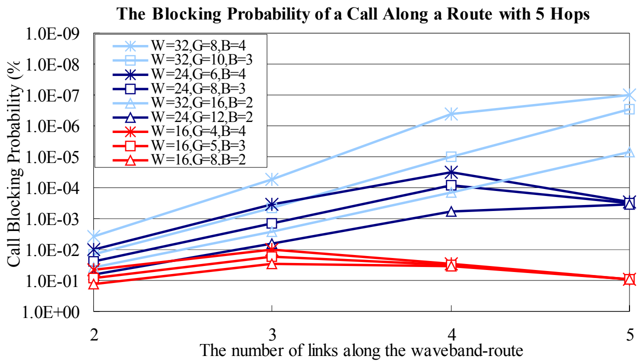

Fig. 10. An illustration of the analytical results on call blocking probability for a call along a 5-hop route traversing along an waveband-route, where the link traffic load is $L = 5$, W is the fiber capacity, G is the waveband granularity, and B is the number of wavebands in a fiber.

of wavelengths W increases. Additionally, since $W \gg B$, $P^0_{W^i_c} \ll P^0_{B^i_c}$.

To design an efficient WBS algorithm, it is important to study the effects of hop count of the waveband-route, the fiber capacity, and the traffic load on the call blocking probability. Recall that a waveband-route should be at least 2 hops long and the call blocking probability for ETE-WBS has been studied in [5], we only focus our study on paths that are h-hop long and traverse an intermediate waveband-route with h_b hops, where $h > 2$ and $2 \leq h_b \leq h$. Our study reveals the following important insight. If $\frac{W}{L} = i$ and $i \geq 2$, the call blocking probability decreases as h_b increases from 2 to i and increases as h_b increases from i to h, where W is the fiber capacity and L is the average link load in Erlang. In addition, our study reveals another important insight that the call blocking probability slightly decreases as the waveband granularity G decreases.

We illustrate the results along a 5-hop intermediate waveband-route in Fig. 10. Assume that the traffic arrives at each link is Poisson at rate $\lambda = 5$ and the service time is exponential with a unit mean. Thus the average link load is $L = \frac{\lambda}{\mu} = 5$ Erlang. The call blocking probability can be derived given the traversed waveband-route, the fiber capacity and the waveband granularity. Fig. 10 presents the call blocking probabilities along different intermediate waveband-routes. According to Fig. 10, when $W = 16$ and $\lfloor \frac{W}{L} \rfloor = 3$, the call blocking probability decreases as the hop count of the waveband-route increases from 2 to 3 and then decreases as the hop count of the waveband-route increases from 3 to 5. When $W = 24$ and $\lfloor \frac{W}{L} \rfloor = 4$, the call blocking probability decreases as the hop count of the waveband-route increases from 2 to 4 and then decreases as the hop count increases to 5. When $W = 32$ and $\lfloor \frac{W}{L} \rfloor = 6$, the call blocking probability decreases as the hop count of the waveband-route increases from 2 to 5. Based on the observation, we can predict that the call blocking probability increases as the hop count increases from 5 when $\lfloor \frac{W}{L} \lfloor \leq 5$. According to Fig. 10, the call blocking probability also slightly decreases as G decreases.

V. The Online Integrated Intermediate Waveband Switching Algorithm

Based on the analytical results, we propose an online integrated intermediate waveband switching (IIWBS) algorithm to solve the RWWBA problem. When a call arrives dynamically, IIWBS determines whether to set up a new waveband-route, to group the call into an existing waveband-route, or to create a new wavelength-route.

A. *Setting Up A New Waveband-Route*

To efficiently set up a new intermediate waveband-route, we first analyze the nodes' connectivity along the path. Based on the nodal connectivity we classify the nodes in the network into three categories, which are the low-connected nodes, the mid-connected nodes, and the high-connected nodes. In a real world network, it is highly possible that the high-connected node is the one with heavy traffic. By selecting the nodes with as high nodal connectivities as possible to be the grouping and disaggregating nodes, it is expected that the created waveband-route could provide WBS to as many calls as possible.

An illustration of the node classification on the NSFNET topology is shown in Fig. 11. The light grayish circles represent the low-connected nodes, the white circles are the mid-connected ones, and the dark gray circles are the high-connected ones. When a call arrives, IIWBS searches for up to k candidate paths. If none of the paths contain any active waveband-routes, IIWBS determines whether to set up a new waveband-route. Starting from the shortest candidate path, the IIWBS algorithm decides the setting up of a new waveband-route along the path according to the policy shown in Fig. 13.

It is worth noting that the preference on grouping and disaggregating nodes may concentrate traffic on these nodes. This is because waveband switching is encouraged in a WBS network. The concentration of traffic at low-connected nodes may use up the free resources at these nodes very easily, which may affect the throughput at these nodes. Therefore, we try to avoid creating new waveband-routes along low-connected nodes. On the other hand, by attracting traffic to be grouped or disaggregated at high-connected nodes, the benefits of WBS can be highly appreciated. In addition, previous analysis shows that the longer the waveband-route is, the more the cost savings that can be achieved. Thus, for a path with mid-connected nodes only, the longest possible waveband-route can be created. Our study of the NSFNET with different node classifications show that to achieve optimal performance the percentages of low-connected nodes and high-connected nodes should be in the range of $10\% - 20\%$.

The policy for creating a new waveband-route is illustrated in Fig. 12 and described in Fig. 13. If there is any low-connected node along the path, no new waveband-route will be set up. If there are more than one high-connected nodes along the path, a new waveband-route is set up between two of the high-connected nodes with the longest distance provided that the hop count is greater than one and there are enough resources. If there is only one high-connected node, a new

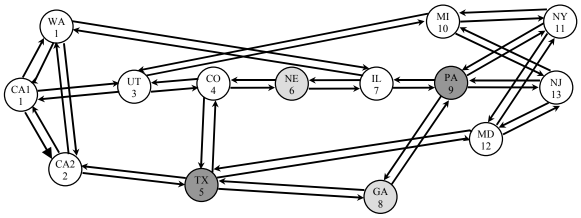

Fig. 11. Classification of nodes in the NSFNET, where the grayish nodes are low-connected, the white nodes are the mid-connected nodes, and the gray nodes are the high-connected ones.

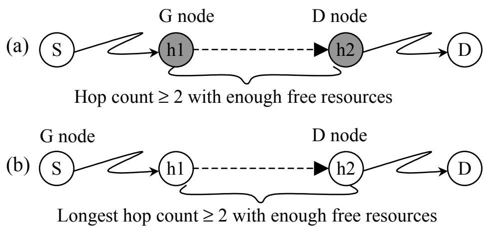

Fig. 12. Policy on creating a new waveband-route along an h-hop path, where $h > 2$.

Policy on creating a new waveband-route

1. If there is any low-connected node along the route or $\lfloor \frac{W}{L} \rfloor \leq i$ and $i < 2$, no new waveband-route is created.
2. If there are at least two high-connected nodes along the path and the longest hop count between two of them is greater than one with free wavebands/wavelengths, set up a waveband-route between these two high-connected nodes.
3. If there is only one high-connected node along the path, search for a available mid-connected node with the greatest hop count away from the node which is at least two hops away, set up a new waveband-route between these two nodes.
4. If there is no high-connected node, determine the setting up of a new waveband-route as follows.

   List all pairs of nodes, which are i-hop to two-hop away. Select the pair with the most free wavebands and wavelengths to be the grouping and disaggregating nodes. If no such pair exists, no new waveband-route is created.

Fig. 13. Policy on selecting grouping node and disaggregating node along an h-hop path, where $h > 2$.

waveband-route can be set up between the node and a mid-connected node with the longest distance greater than one hop and with enough resources. Otherwise, a new waveband-route is set up between two mid-connected nodes with the longest distance.

B. Grouping A Call Into an Active Waveband-route

If there are available active waveband-routes along some of the candidate paths, IIWBS determines the switching and grouping of the call as follows. For each candidate route L_c,

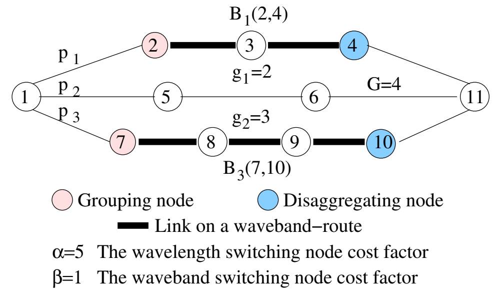

Fig. 14. An example of a call 1 with three candidate routes, p_1, p_2, and p_3. Route p_1 traverses along a two-hop waveband-route $B_1(2,4)$. Route p_3 traverses along a three-hop waveband-route $B_3(7,10)$.

IIWBS defines a weight according to its expected operational costs and expected call blocking probability as discussed in Section IV. We define the weight of a candidate route L_c as follows.

$$w(L_c) = H - M + 1 + \frac{M\beta}{G\alpha} + \rho_w + \rho_s, \quad (8)$$

where α is the cost factor of an O-E-O port, β is the cost factor of an O-O-O port, H is the hop count of the candidate route, M is the hop count of the available active waveband-route and $2 \leq M \leq H$, ρ_w is the largest link utilization ratio along the path, and ρ_s is the ratio of free wavelengths in the waveband to the waveband granularity. If the route does not traverse an active waveband-route, ρ_s is 1. As discussed before, the value of α can be set to 5 and the value of β can be set to 1. The first two multinominals reveal the operational costs of the call along the candidate route. The last two multinominals reflect the call blocking possibility along the candidate route under current network utilization. By selecting the route with the minimum weight, IIWBS tries to accommodate the call with minimum operation costs and minimum call blocking probability.

We consider an example shown in Fig. 14 to illustrate how IIWBS determines the grouping of a call along multiple candidate routes. As shown in Fig. 14, there is a call $c(1, 11)$ from node 1 to node 11. The k-shortest path algorithm returns with three candidate paths, which are $p_1(1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 11)$, $p_2(1 \rightarrow 5 \rightarrow 6 \rightarrow 11)$, and $p_3(1 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow 10 \rightarrow 11)$. Assume that along path p_1 there is an active waveband-route $B_1(2, 4)$ from node 2 to node 4 grouped with two active wavelengths. Along path p_3 there is an active waveband route $B_3(7, 10)$ from node 7 to node 10 grouped with three active wavelengths. For simplicity, we assume that there are no other candidate routes except for the above three and no other traffic. Additionally, let $W = 16$, G=4, $B = 4$, $\alpha = 5$, and $\beta = 1$. link λ is 5.

The weights of the three paths can be calculated according to (8). According to Fig. 14, the hop count H of p_1 is 4 and the hop count M of the active waveband-route $B_1(2, 4)$ is 2. The heaviest utilized link along path p_1 is link $(2, 3)$ and $(3, 4)$ with two used wavelengths. Thus, the highest link utilization ratio ρ_w along p_1 is $\frac{2}{W} = 0.125$ and the ratio of free wavelengths in B_1 is $\frac{2}{G} = 0.5$. Consequently, the weight of path p_1 along the

Algorithm IIWBS

1. Search for up to k shortest paths (denoted by S_P={$p_1, p_2, \ldots, p_k$}) for the call.
2. Set $minC = \infty$.
3. **For** each path $p_i \in S_P$, where $i \in [1..k]$ in increasing order.
   a Search for the available active intermediate waveband-routes S_B={$B_1, \ldots, B_m$}.
   b If $S_B = \phi$, determine whether to set up a new waveband-route according to Fig. 13 and go to Step 5. Otherwise, continue.
   c **For** each $B_j \in S_B$ with waveband b_i, where $j \in [1..m]$ in increasing order.
      i Calculate its weight w_j.
      ii If $w_j < minC$, set $minC = w_j$ and record B_j.
4. Set up a wavelength-route, group it into the recorded waveband-route, and return. If no recorded waveband-route, go to Step 6.
5. Set up a new intermediate waveband-route and a wavelength-route accordingly and return. If no new waveband-route be set up, go to Step 6.
6. Try to set up a wavelength-route along the shortest possible path. If all attempts fail, the call is blocked.

Fig. 15. Description of the online integrated intermediate waveband switching (IIWBS) algorithm.

waveband-route B_1 is $4 - 2 + 1 + \frac{2\times1}{4\times5} + 0.125 + 0.5 = 3.725$. In the same way, we can get the weight of path p_2, which is 4, and the weighted cost of path p_3 along the waveband-route B_3, which is 3.5875 and is the smallest. Therefore, a wavelength-route traversing path p_3 and grouped into the waveband-route B_3 at node 7 is selected for call $c(1, 11)$.

After the candidate route is chosen and the grouping node and disaggregating node are determined, the call is assigned to a free wavelength, grouped, and transmitted. Different from the algorithm in [9] which determines the wavelength, the route, and the waveband grouping for a call separately, our algorithm integrates them all. When IIWBS assigns a wavelength to a call ϕ_x, it first checks whether ϕ_x could be grouped into a waveband-route along its candidate route. If it could be grouped into a waveband-route B_y, IIWBS will assign ϕ_x with the first available (free) wavelength in B_y to the call. Otherwise, IIWBS will assign the first available (free) wavelength along the candidate route to ϕ_x.

In summary, the IIWBS algorithm adopts k-shortest path algorithm, first-fit wavelength assignment (FFWA), and first-fit waveband assignment (FFBA). Other wavelength assignment algorithms and waveband assignment algorithms are simulated as well. However, their performance is not better than that of FFWA and FFBA. The detailed description of IIWBS is shown in Fig. 15.

C. IIWBS Complexity Analysis

The complexity of the IIWBS algorithm is analyzed below. For each call, IIWBS adopts the k-shortest path algorithm to collect a set of at most k candidate paths. We use Yen's k-shortest paths algorithm [20], whose worst-case running time in a directed network is $\Theta(k|V|(|E|+|V|log|V|))$, where k is a positive integer, $|V|$ is the number of nodes in the network, and $|E|$ is the number of unidirectional links in the network.

Consider a candidate path p_i with l_i hops, there are at most mB active waveband-routes along it, where m is defined in (5) and B is the maximum number of wavebands in a fiber. However, in reality, the number of active waveband-routes along p_i is much less than mB. Actually, our observation shows that the average number of active waveband-routes along p_i is even less than m. Thus, the average time to search for active waveband-routes along a path p_i is $\Theta(m)$ and the worst-case running time is $\Theta(mB)$. It takes a constant time to determine which waveband-route along p_i should be adopted. After selecting the intermediate waveband-route, the first-fit wavelength assignment (FFWA) algorithm assigns the first available wavelength in the waveband to the call, which takes $\Theta(G)$ worst-case running time. The grouping of the wavelength into the waveband takes a constant time. If a new waveband-route is to be set up along a path p_i with l_i hops, the decision on how to set it up takes $\Theta(m)$ worst-case running time according to Fig. 13, where m is defined in (5). It takes $\Theta(B)$ worst-case running time to find the available waveband along the candidate path and $\Theta(G)$ worst-case running time to find the available wavelength in the waveband. To set up a wavelength-route for the call along path p_i, it takes $\Theta(Wl_i)$ worst-case running time.

We can summarize the running time for IIWBS working on each candidate path p_i. It takes $\Theta(mBG)$ worst-case running time and $\Theta(mG)$ average time to set up a wavelength-route and group it into the selected active waveband-route. It takes $\Theta(m^2B(G + B))$ worst-case running time and $\Theta(mB(G + B))$ average time to set up a new waveband-route for the call. And it takes $\Theta(Wl_i)$ worst-case running time to set up a new wavelength-route. Thus, the total worst-case running time for IIWBS accommodating a call is $\Theta(kmBG + km^2B(G + B)+kWl_i+k|V|(|E|+|V|log|V|))$. The average-case running time for IIWBS accommodating a call is $\Theta(kmG+km^2(G+B) + kWl_i + k|V|(|E| + |V|log|V|))$. According to (5), $m = \frac{l_i(l_i-1)}{2}$. In addition, l_i is bounded by $|V| - 1$ because the longest path should have at most $|V| - 1$ hops. Moreover, $B \ll W$, $G \ll W$, $B \times G \leq W$ and $|E| \leq |V|(|V| - 1)$ for a directed graph. Therefore, the upper bound worst-case running time for IIWBS is $\Omega(k|V|^4W(1 + \frac{B^2}{W}))$.

VI. Numerical Results

We conduct simulations on the NSFNET with 14 nodes and 42 uni-directional links shown in Fig. 11. Each node is an MG-OXC. The cost factor is 1 for an O-O-O port and 5 for an O-E-O port. Each simulation result is obtained by running 1,000,000 calls. Poisson traffic is generated for the network with a rate λ and is uniformly distributed in the

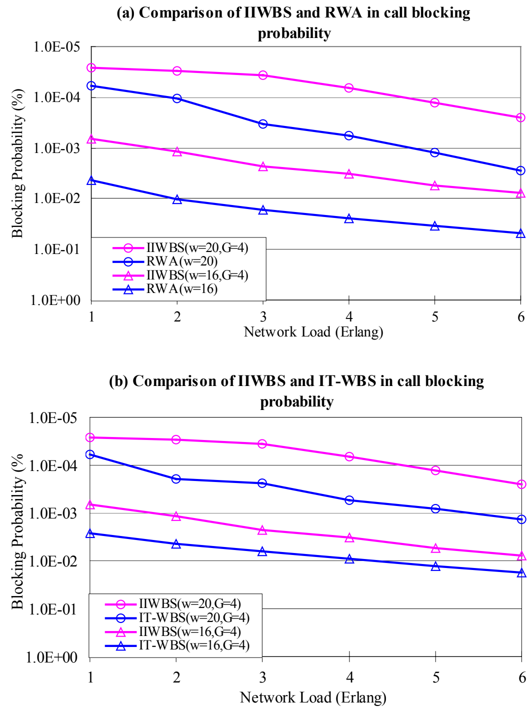

Fig. 16. Performance evaluation of the IIWBS algorithm on the NSF network under different network loads in terms of call blocking probability. (a) Comparison with the RWA. (b) Comparison with the IT-WBS proposed in [5].

network. The call holding time is exponential with a mean $\frac{1}{\mu}$. Thus, the network load in terms of Erlang is $L = \frac{\lambda}{\mu}$. The following notations are used in this section. W is the fiber capacity. G is the waveband granularity. B is the maximum number of active (used) wavebands in a fiber. IT-WBS is the intermediate WBS algorithm in [5]. RWA refers to the same routing and wavelength assignment algorithm without waveband switching.

The simulations are conducted under different network configurations, where $W = \{16, 20, 24, 28, 32\}$, $G = \{2, 4, 8\}$, and $L = \{80, 85, 90, 95, 100, 105\}$. Previous study on backbone network traffic shows that about 60% to 70% of traffic is bypassing. Thus, we define the upper bound of B to be $\lfloor \frac{0.7W}{G} \rfloor$. Our simulations show that increasing the upper bound does not improve the network performance.

Fig. 16 illustrates the performance improvements of IIWBS in terms of call blocking probability compared with the corresponding RWA algorithm and the IT-WBS algorithm in [5] under different network loads. Fig. 16(a) compares IIWBS and RWA and Fig. 16(b) compares IIWBS and IT-WBS in call blocking probability. As can be seen, the IIWBS algorithm has smaller blocking probabilities under various scenarios than the other algorithms, which are about 1/3 the values of IT-WBS and 1/8 the value of RWA.

Fig. 17 demonstrates the blocking probabilities of IIWBS under different waveband granularities. According to Fig. 17, the blocking probability of the IIWBS algorithm slightly increases as the waveband granularity increases, which is the same result as in our analysis in Section IV. This is reasonable

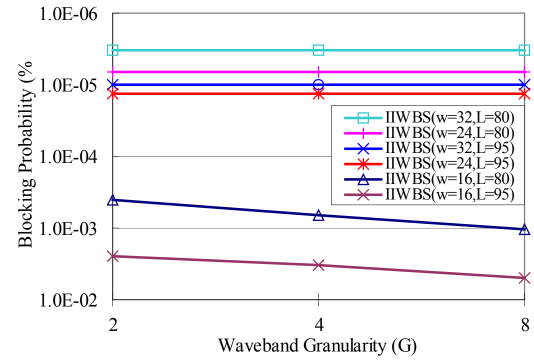

Fig. 17. Call blocking probability of the IIWBS algorithm on the NSF network under different waveband granularities.

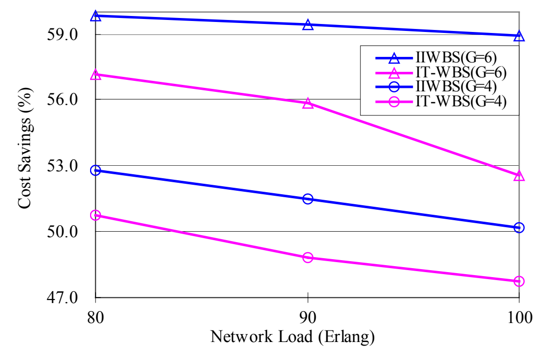

Fig. 18. Comparison of the IIWBS algorithm and IT-WBS on the NSF network in cost savings under different network loads, where $\alpha = 5$ and $\beta = 1$.

as the probability that many calls can be grouped together is small. If the waveband granularity continues to increase, more wavelengths in the waveband will be left unused and the waveband utilization becomes low.

Fig. 18 illustrates the performance improvements in cost savings of IIWBS compared with IT-WBS in [5]. The cost savings of the WBS algorithms is defined as the ratio of the operational costs difference between the WBS algorithm and the RWA algorithm to the operational costs of RWA. As can be seen, IIWBS can achieve slightly higher cost savings than IT-WBS under different scenarios. Given that the cost factor of an O-O-O port is 1 and the cost factor of an O-E-O port is 5, IIWBS outperforms IT-WBS in terms of cost savings by about 1% to 3%. By multiplying the savings with the network provisioning costs, the actual money saving by adopting IIWBS is significant.

Fig. 19 shows the cost savings of IIWBS under different network loads. As can be seen, the cost savings decrease slightly as the network load increases because of the increased blocking of traffic under heavy load. Fig. 20 illustrates that the cost savings increase with the fiber capacity. This is because a larger fiber capacity leads to a smaller call blocking probability. In conclusion, IIWBS achieves significant cost savings ranging from 25% to 60% over RWA.

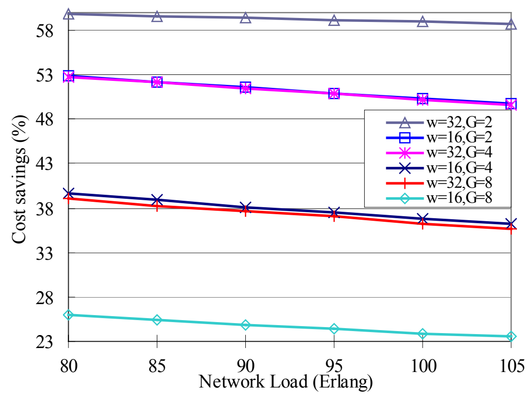

Fig. 19. Cost savings of the IIWBS algorithm on the NSF network under different network loads, where $\alpha = 5$ and $\beta = 1$.

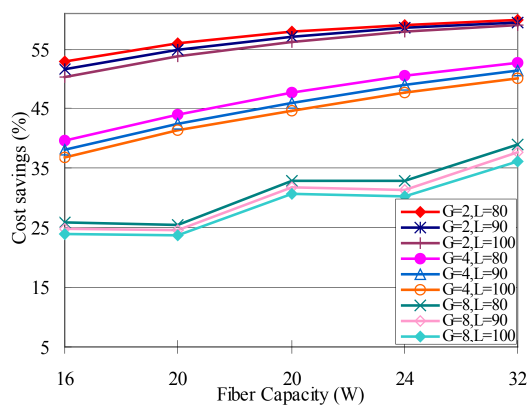

Fig. 20. Cost savings of the IIWBS algorithm on the NSF network under different fiber capacities, where $\alpha = 5$ and $\beta = 1$.

VII. Conclusions

Intermediate waveband switching (IT-WBS) is a practical cost-efficient approach to operate WDM networks. However, designing an integrated IT-WBS algorithm with maximum cost savings and minimum call blocking probability is an open problem. To solve the problem, we first analyzed the operational costs and the call blocking probability of a call along an intermediate waveband-route. Our analysis reveals some important insights about how to achieve optimal performances under the current network configurations. Based on these insights, we proposed the online integrated intermediate waveband switching (IIWBS) under dynamic traffic requests. IIWBS controls the creation of a new waveband-route according to the hop count of the waveband-route, the fiber capacity, the waveband granularity, and the traffic loads. In addition, IIWBS determines the grouping node and disaggregating node for a call according to the nodal connectivity along the candidate route. By assigning weights to the candidate paths and choosing the one with the minimum weight, IIWBS provisions the call with minimum costs and resources. Thus, IIWBS decreases the call blocking probability. Our simulation results show that the IIWBS algorithm can achieve better performances in cost savings and call blocking probability than the previous IT-WBS algorithms and the RWA algorithm.

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