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Framework for waveband switching in multigranular optical networks: part II—wavelength/waveband conversion and survivability [Invited]

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We consider multigranular optical networks using waveband switching (WBS) technology. The use of advanced WDM has significantly increased the available bandwidth in backbone networks by increasing the number of wavelengths. As the number of wavelengths in a fiber is increased, the number of ports or the size of the optical cross connects increases rapidly. Using WBS, wavelengths are grouped into bands and switched as a single entity thus reducing the cost and control complexity of switching nodes by minimizing the port count. Part I of our study [J. Opt. Netw. **5**, 1043–1055 (2006)] compared the various cross-connect architectures for WBS including the three-layer and single-layer multigranular cross connects. It also discussed various issues relating to waveband switching networks that are different from traditional wavelength routing networks (WRNs), for example, traffic grooming, and it showed why techniques developed for WRNs cannot be simply applied to WBS networks. We study the effect of wavelength and waveband conversion on the performance of WBS networks with reconfigurable multigranular optical cross connects. We present an algorithm for waveband grouping in wavelength convertible networks and evaluate its performance with full, limited, and intraband wavelength conversion. We then focus on survivability in WBS networks and show how waveband and wavelength conversion can be used effectively to recover from failures in WBS networks.
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1. Introduction

Optical networks using WDM technology [1], which divides the enormous fiber bandwidth into a large number of wavelengths, are a key solution for keeping up with the tremendous growth in data traffic demand. However, as the WDM transmission technology matures and fiber deployment becomes ubiquitous, the ability to manage traffic in a wavelength-routed WDM network becomes increasingly complicated, critical, and prohibitively expensive. This is because traditional wavelength routing networks (WRNs) primarily handle traffic at the wavelength level, and subsequently employ switching elements or traditional optical cross connects (OXCs) that switch traffic only at the wavelength granularity. Accordingly, when the number of wavelengths in the fiber links of the network become huge, the number of ports (one per wavelength) becomes large, resulting in increased cost and control complexity of these OXCs.

As mentioned in Part I of this study [2], waveband switching (WBS) in conjunction with multigranular OXCs (MG-OXCs) can be used to reduce the port count, the associated control complexity and cost of OXCs [3–7]. The main idea of WBS is to group and route several wavelengths together as a band, and switch the whole band using a single port whenever possible (e.g., as long as it carries only bypass or express traffic), thereby using the same optical port to process multiple wavelengths simultaneously. With WBS, a fiber is demultiplexed into bands and bands demultiplexed into individual wavelengths only when some traffic needs to be added or dropped. Since most of the traffic in the network backbone is bypass traffic, only a limited number of fibers and bands need to be demultiplexed into wavelengths. Thus, not only the size of wavelength cross connects, but also the overall port counts of the cross connects can be reduced by using WBS. In Part I, we investigated and evaluated in detail the characteristics of various MG-OXC architectures. In particular, we presented multigranular photonic cross-connect switches for WBS based on the three-layer and single-layer architectures. The multigranular photonic cross connect consists of a MG-OXC and a digital cross connect (DXC). Based on the number of switching elements, we can have a single-layer MG-OXC or a three-layer MG-OXC. We compared the three-layer MG-OXC with the single-layer MG-OXC architecture and showed that the single-layer architecture is capable of reducing the port counts under static traffic conditions even further. However, the single-layer architecture lacks flexibility in terms of dynamically choosing bands to multiplex or demultiplex to switch dynamic traffic.

In this paper (Part II of our study on WBS), we examine new techniques and the use of wavelength and waveband conversion in WBS networks. We also show how wavelength and waveband conversion can be used effectively for WBS network survivability. Particularly, we introduce a novel failure recovery scheme based on band segments and show how backup bandwidth sharing among band segments can be achieved to not only reduce the wavelength usage but also the port counts. For intralink failures, we propose two new techniques called band swapping and band merging to recover from wavelength and waveband failures. We then consider the problem of WBS with wavelength conversion and present an algorithm called waveband assignment with path graph (WAPG). We show how WAPG can be used with a reconfigurable MG-OXC to do efficient waveband assignments. The goal of WAPG is to perform WBS by efficiently taking wavelength grouping and wavelength conversion into consideration when satisfying lightpath requests. We present results of the performance of the WAPG algorithm compared to FirstFit and RandomFit algorithms with full, intraband, and limited wavelength conversion.

Much of the research work on routing and wavelength assignment (RWA) only considers routing at the wavelength level in wavelength routed networks (WRNs) as in Refs. [8,9]. Correspondingly a large amount of research has been devoted to the use of wavelength conversion in WRNs, for example, [10–13]. Wavelength conversion can be achieved through the use of optoelectronic techniques, which require O–E–O conversion at the OXCs, or by using fast and transparent all-optical techniques requiring no O–E–O conversion at the OXC nodes. Wavelength converters can be dedicated or shared; further, this sharing can be done on a per-node or per-link basis. Other research has focused on the effect of using sparse location of wavelength converters in the network and sharing of wavelength converters at the switching ports of an OXC. The authors in Ref. [14] study the effect of limited-range wavelength conversion in WDM networks. Similarly a lot of research addresses various issues relating to survivability in WRNs [15–17]. Recently, research on multigranular WBS networks has increasingly received attention [3,6,7,18–23]. Although wavelength routing is still fundamental to a WBS network, the challenging issues in a WBS network are quite different from existing work on WRNs. For example, a common objective in designing a WRN is to reduce the number of wavelengths required or the number of wavelength hops used (which is a weighted sum taking into account the number of hops a wavelength path spans) [8,9]. However, as Ref. [7] shows, minimizing the number of wavelengths or wavelength hops does not lead to the minimization of the port count of the MG-OXCs (which is one important objective in WBS networks) in WBS networks. In fact, studies have indicated that using the optimal RWA algorithm with wavelength grouping (to form bands) afterward can increase the number of ports needed [7], which indicates that new algorithms taking advantage of wavebanding need further exploration. Works in Refs. [4,5,7,18,24,25] used various two-layer and three-layer [with an added fiber cross-connect (FXC) layer] MG-OXC architectures for WBS. On the other hand, a single-layer cross-connect architecture for WBS was proposed in Refs. [19,26]. However none of these studies considered the use of wavelength and/or waveband conversion in the network and the possibility of efficiently using conversion capabilities for WBS.

Issues related to conversion and survivability in WBS networks are different from those in WRNs. For example, waveband conversion can convert a group of wavelengths simultaneously in WBS networks [27], which differs from limited wavelength conversion studied in the context of WRNs. The authors of Ref. [27] were one of the first to demonstrate all-optical waveband conversion; however, the authors did not provide any algorithms or techniques that used conversion effectively in WBS networks. In Ref. [28], the authors used four-wave mixing techniques to simultaneously perform wavelength conversion on a number of wavelengths, thus simulating waveband conversion. The authors also implemented experimentally a tunable waveband converter based on the dual-pump configuration. Some limited work on survivability in WBS networks was presented in Ref. [22], wherein the authors tackled the problem of protection for single link failures in WBS networks with static traffic and no wavelength conversion. While Ref. [29] proposed an integer linear programming (ILP) model for waveband protection in hierarchical hybrid optical networks, the work of Ref. [21] considered the problem of dedicated path protection in WBS networks with shared risk link groups (SRLG) constraints. The authors proposed two schemes to protect a working waveband path. In the protecting-waveband-at-waveband-level (PBABL) scheme a waveband path is always protected by a backup waveband, whereas in the mixed-protection-at-waveband-and-wavelength-level (MPABWL) scheme the backup can be either a waveband or multiple backup lightpaths. Simulation results show that the MPABWL scheme is more cost-effective in terms of switching and transmission costs. Much research remains to be done to effectively use conversion in WBS networks and also to develop new techniques for failure recovery.

This paper is organized as follows: After introducing the WBS problem and reviewing some of the related work on WBS in Section 1, we briefly describe a reconfigurable cross connect for WBS in Section 2. Section 3 describes wavelength and waveband conversion in WBS networks. Techniques for failure recovery, using wavelength conversion are described in Section 4. In Section 5, we describe our algorithm for WBS with wavelength conversion and also give detailed results and performance analysis. Section 6 concludes the paper with a summary of this research and directions for future research.

2. Reconfigurable Cross-Connect Architectures for Multigranular Switching

As explained earlier, the main idea of WBS is to group and route several wavelengths together as a band, and switch the whole band using a single port whenever possible. This reduces the port count of cross-connect switches and results in small-sized switching elements, which are less expensive and easy to control. While waveband assignments dealing with how to determine the routes and assign wavelengths to lightpaths to form wavebands has been a major concern, it is also important to devise node architectures that are flexible (reconfigurable) yet cost-effective. In Part I of this study [2], we proposed and investigated several nodal architectures for multigranular switching. In this paper, we focus on the reconfigurable MG-OXC architecture (see Fig. 1) for dynamic traffic, and we develop heuristics that reduce the blocking probability of new lightpath requests by efficiently using wavelength converters in the network.

As shown in the figure, the MG-OCX includes three switches for wavelength, waveband, and fiber switching as well as a wavelength conversion bank. The wavelength cross-connect (WXC) and band cross-connect (BXC) layers consist of cross connect(s) and multiplexer(s) and/or demultiplexer(s). The WXC layer includes a WXC switch that is used to bypass or add or drop lightpaths at this layer, band-to-wavelength (BTW) demultiplexers, and wavelength-to-band (WTB) multiplexers. The BTW demultiplexers are used to demultiplex bands into wavelengths, while the WTB multiplex-

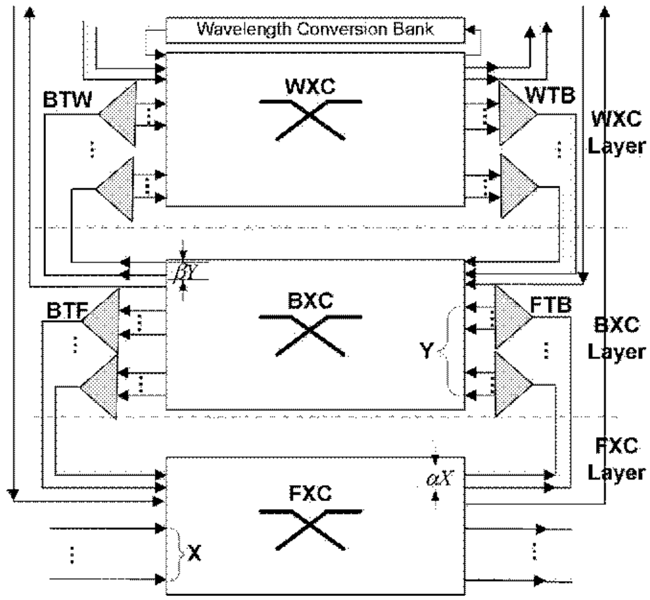

Fig. 1. Reconfigurable multilayer MG-OXC.

ers 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, at the fiber cross-connect (FXC) layer FXCs are used to switch fibers.

Since it is unnecessary to demultiplex all the fibers and/or bands to bands and/or wavelengths and switch them individually [30–32], the MG-OXC has only a predetermined limited port count as in Fig. 1. More specifically, let X denote the number of incoming fibers, Y denote the number of BXC ports from FTB demultiplexers, $\alpha \leqslant 1$ the ratio of fibers (to the total number of fibers) that can be demultiplexed into bands using FTB ports, and similarly, $\beta \leqslant 1$ the ratio of bands that can be demultiplexed to wavelengths using BTW ports. Such MG-OXC architectures only allow $\lceil \alpha X \rceil$ fibers to be demultiplexed into bands, and $\lceil \beta Y \rceil$ of these bands can be demultiplexed into wavelengths simultaneously by appropriately configuring the MG-OXC. In Section 5, we show that even with *limited* reconfiguration (i.e., $\alpha < 1$ and $\beta < 1$), an intelligent algorithm can be deployed to considerably reduce the port count while satisfying dynamic traffic with an acceptable request blocking probability.

Note that for single-fiber systems, it is necessary to set $\alpha = 1$ to allow any fiber to be demultiplexed to bands (otherwise, the blocking probability is too high). However, we can and/or should limit the value of β to be less than 1 by allowing only a limited number of bands (i.e., $\lceil \beta Y \rceil$) to be demultiplexed into wavelengths simultaneously.

3. Wavelength Conversion in Waveband Switching Networks

In WRNs, with wavelength conversion, a lightpath no longer has to occupy the *same* wavelength on all the links that it spans (this is called the *wavelength-continuity constraint*). Prior research on wavelength conversion in WRNs has, in general, confirmed the benefit of wavelength conversion in reducing blocking probability, and to a lesser extent, in reducing the wavelength requirement to carry a given set of traffic demands (this of course is dependent on the traffic and topology). In addition, research has shown that a major benefit can be obtained by using sparse wavelength conversion and/or limited wavelength conversion.

Although there has been a significant amount of research on the benefit of wavelength conversion in WRNs, very little research has focused on investigating the benefit of wavelength conversion in WBS networks with MG-OXCs. Note that wavelength conversion can ease the wavelength requirement and facilitate waveband assignment, and thus may also reduce the port count (and multiplexers and/or demultiplers) required in MG-OXCs. However, as we can see from Fig. 1, to perform wavelength conversion, it is required that the fiber carrying the wavelength(s) to be converted be demultiplexed into bands and then into wavelengths, thus consuming resources (e.g., ports and multiplexers and/or demultiplexers) in the MG-OXCs. This, in turn, may cause more blocking in networks with limited reconfigurable MG-OXCs (i.e., $\alpha < 1$ and $\beta < 1$).

The following example shows that in WRNs with full wavelength conversion, wavelength assignment is trivial, but in WBS networks one must assign wavelengths judiciously in order to reduce the port count of MG-OXCs. In the following example shown in Fig. 2, assume that there is one fiber on each link with two bands, each having two wavelengths (i.e., $\{\lambda_0, \lambda_1\} \in b_0$, $\{\lambda_2, \lambda_3\} \in b_1$. Also assume wavelength λ_2 is not available on any of the links, and there are three existing lightpaths, one from node 1 to node 5 using λ_0, the second from node 2 to node 4 using λ_3, and the third from node 6 to node 4 using λ_3. Hence, the only wavelengths available on the link from node 4 to node 5 are λ_1 and λ_3.

Assume that a new lightpath from node 6 to node 5 is assigned λ_1 on the link from node 6 to node 4 and node 4 to node 5 as shown in Fig. 2(a). As a result, another new lightpath from node 1 to node 5 must then use λ_1 on links from node 1 to node 4 and then be converted to λ_3 on the link from node 4 to node 5. Alternatively, as shown in Fig. 2(b), one can assign λ_3 to the first new lightpath on the link from node 4 to node 5 and assign λ_1 to the second new lightpath all the way from node 1 to node 5. In a WRN, this alternative does not result in much difference at all as it also requires a wavelength conversion at node 4. However, in a WBS network using MG-OXCs, this alternative will require fewer ports. The reason is that in Fig. 2(b), band b_0 no longer needs to be demultiplexed at node 4. Note that performing a wavelength conversion to the first new lightpath does not increase the port count because even in Fig. 2(a), band b_0 on the fiber from node 6 to node 4 carrying the first new lightpath needs to be demultiplexed into wavelengths so that its λ_1 can be multiplexed with λ_0 on the link from node 4 to node 5.

None of the prior research has studied in detail the benefit of *waveband* conversion (without full wavelength conversion) in WBS networks. Having waveband conversion is similar to, but not identical to having limited wavelength conversion. For example, if one assumes there are two wavelengths in each band (i.e., $\{\lambda_0, \lambda_1\} \in b_0$, $\{\lambda_2, \lambda_3\} \in b_1$, $\{\lambda_4, \lambda_5\} \in b_2, \ldots$). Then with waveband conversion, converting band b_0 to bands b_1 or b_2 is similar to having limited conversion, i.e., λ_0 can only be converted to λ_2 or λ_4, while λ_1 can only be converted to λ_3 and λ_5. On the other hand, the difference is that, with waveband conversion, we are now forced to convert λ_0 to λ_2 and *also* λ_1 to λ_3 at the same time. Moreover, waveband conversion can be accomplished using novel technologies (see Refs. 27 and 28) without having to demultiplex each band into individual wavelengths, which could be a major benefit in terms of reducing the port count of MG-OXCs.

Wavelength conversion capabilities can be incorporated at either all or some of the nodes (the latter is referred to as sparse wavelength conversion). Further, wavelength conversion can be full or limited range (i.e., partial). In the case with limited-ranged wavelength conversion, a wavelength can be converted only to a subset of the wavelengths (e.g., wavelength numbered λ can only be converted to the wavelengths within the range $[\lambda - \delta, \lambda + \delta]$ for some integer δ). In the case with limited number of wavelength converters, the nodal architecture can be share per node or share per link. In this paper, we will focus on the share-per-link architecture, where a dedicated number (say $d \leqslant X$) of wavelength converters are associated with each outgoing link.

For WBS networks, a practical wavelength conversion technology is called intraband wavelength conversion, where a wavelength can only be converted to any other wavelengths within the *same* band. For example, assume that the band size is 3 and wavelengths w_1, w_2, and w_3 are in the same band b_1 and wavelengths w_4, w_5, and w_6

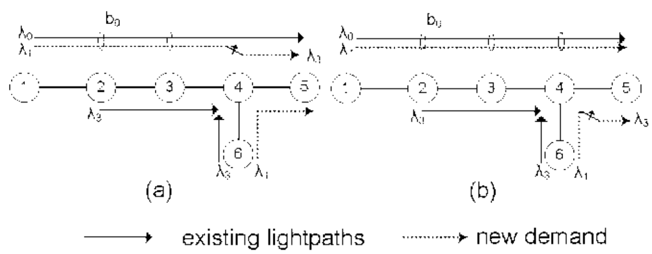

Fig. 2. Wavelength and waveband conversion.

are in the same band b_2. Then wavelength w_3 can be converted only to a wavelength in band b_1 (i.e., w_1 or w_2) whereas wavelength w_4 can be converted only to a wavelength in band b_2 (i.e., w_5 or w_6), which is different from the case with limited-range wavelength conversion. As mentioned earlier, a significant amount of research on the benefit of wavelength conversion in WRNs has been done, but the blocking performance and efficient usage of wavelength converters, especially intraband wavelength converters, in WBS networks are open issues.

4. Survivability in MG-OXC Networks

Due to the high bit rate of a single wavelength and large number of wavelengths per fiber, network survivability becomes an important design problem in optical networks. Protection and restoration schemes for failure recovery from a broken fiber link or an OXC node (or, in general, a failed SRLG) have been studied extensively. However, previous research has largely examined recovery from such a failure at either the fiber or wavelength level in WRNs and studied the trade-offs involved in recovery at these two different levels. The remainder of this section introduces multiple techniques for protection and recovery at the band level.

With the introduction of multigranular WBS networks a waveband may fail because of a malfunctioning port at the BXC layer, a broken waveband multiplexer and/or demultiplexers or waveband converter. If the other bands in the same fiber are not affected by the failure, simply recovering the traffic carried by the affected band can be more bandwidth efficient (or more likely to succeed in restoring the traffic) than recovering the traffic carried by the entire fiber (as if the fiber is cut) although the latter is simple and has a faster response and/or restoration time. Even when a fiber is cut, treating the traffic carried by one band as a basic unit for recovery can achieve a useful balance between treating the entire fiber or each individual wavelength as a basic recovery unit. We describe the trade-offs involved in recovery from a fiber link failure at the band level (as opposed to the fiber or wavelength level) and new ways to recover from waveband or wavelength failures in WBS networks.

4.A. Band-Segment-Based Failure Recovery

While recovering at the fiber level is done via link protection and/or restoration, recovering at the wavelength level is often done via path protection where an entire backup lightpath, which is link disjoint from the primary working lightpath, is provisioned from the source. To recover at the band level, it is useful to first define the *band segment* (BS) of a given band b_i to be the portion of fiber route between two MG-OXCs such that b_i is formed (e.g., multiplexed from wavelengths using a WTB) at the first MG-OXC and then demultiplexed into wavelengths at the second MG-OXC (e.g., using a BTW). That is, within a BS, the lightpaths carried in the band are not switched individually. Two examples of *active* (also called primary or working) BS are shown in Fig. 3. The first, denoted by ABS0, goes from node 1 to node 3 via node 2, carrying two active lightpaths, AP0 and AP1 (the former is dropped at node 3). The second, denoted by ABS1, goes from node 3 to node 4 carrying two active lightpaths, AP1 and AP2 (the latter is added at node 3).

Based on the concept of BS, failure recovery can be accomplished in two ways as shown in Figs. 3(a) and 3(b). The first approach is to recover the affected ABS0 as a basic unit using one backup (or alternate) BS, denoted by BBS0 (which includes backup lightpath BP0 and lightpath segment BP1) as shown in Fig. 3(a). The second approach is to recover each individual lightpath and/or lightpath segment carried in

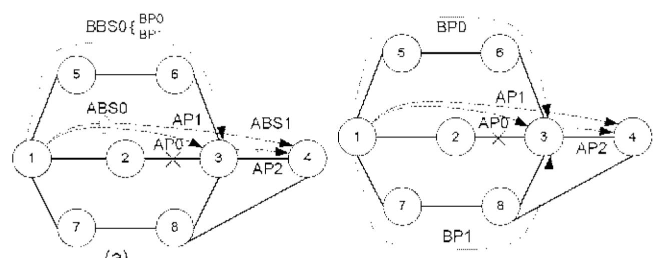

Fig. 3. Recovery schemes using WBS.

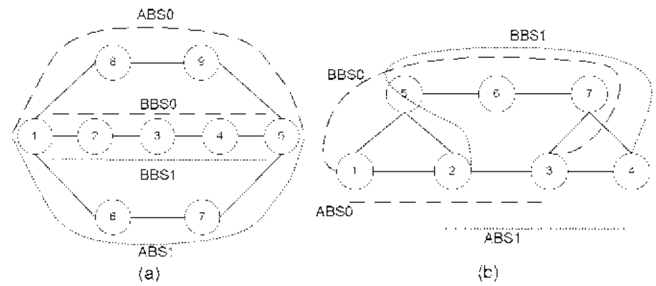

Fig. 4. Backup bandwidth sharing using WBS.

the affected BS as a unit. Note that this is similar but not identical to recovering at the wavelength level without regard to the concept of BS. Wavelength grouping strategies will affect the performance of such BS-based recovery schemes in terms of resource efficiency, recovery speed, and complexity. More specifically, if only the lightpaths with the same source and destination are grouped into a band, it is convenient to protect all the lightpaths in a waveband segment. Otherwise, a lightpath may transit one or more BSs along its route as AP1 does in Fig. 3, which reduces the port count but complicates things like fault localization. Such issues in failure recovery are *unique* to WBS networks, and deserve further research.

4.B. New Backup Bandwidth Sharing Opportunities

We briefly describe how backup bandwidth sharing can be achieved in the BS-based protection scheme. As shown in Fig. 4(a), when the two active BSs ABS0 and ABS1 (in two different fibers) are node disjoint, their respective backups BBS0 and BBS1 can share bandwidth and still recover *any* single failure (of a fiber link or a node other than node 1 or node 5) in the network.

While the above is similar to shared mesh (path) protection in WRNs, the following example shows unique backup bandwidth sharing opportunities in BS-based protection in WBS networks. As shown in Fig. 4(b), even though ABS0 and ABS1, which can be in the same fiber or two different fibers, are *not* link disjoint, their corresponding BBS0 and BBS1 can still share the bandwidth on links $5\rightarrow 6\rightarrow 7$ as long as only one band, either ABS0 or ABS1, can fail if the two bands are in the same fiber (or if they are in two fibers, as long as only one fiber can fail). In fact, using the novel technique called band merging to be described next, BBS0 and BBS1 may use the same backup BS on links $5\rightarrow 6\rightarrow 7$ even if both ABS0 and ABS1 are affected by the broken link $2\rightarrow 3$.

4.C. Unique Band Swapping and Merging Techniques

We describe how waveband conversion (and wavelength conversion) can be used effectively to recover from failures in WBS networks. For example, assume that a fiber has two bands, b_0 and b_1, each with three wavelengths as shown in Fig. 5(a). Further assume that all wavelengths except λ_4 are used. Now assume that λ_1 in b_0 alone is affected by a wavelength failure. To recover from such a failure using the spare bandwidth on λ_4, one may convert λ_1 to λ_4 at a node prior to the fault, but this requires both bands to be demultiplexed at this node. To avoid demultiplexing of the bands and preserve the wavelength grouping, a new technique called band swapping, which converts band b_0 to b_1 and b_1 to b_0, can be used to recover from the failure.

As another example, assume that λ_0 and λ_1 are used in b_0, so is λ_5 in b_1 as in Fig. 5(b). Further assume that band b_0 is affected by a band failure. Instead of having to reroute the traffic carried by band b_0 using a backup BS along a link-disjoint path,

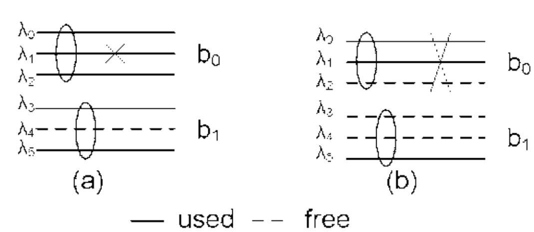

Fig. 5. Band swapping and merging for intralink failure restoration.

one may use a technique, which we call *band* merging, whereby the traffic carried by wavelengths λ_0 and λ_1 can be restored on their corresponding wavelengths in b_1 (i.e., λ_3 and λ_4). Note that the traffic carried on λ_5 should remain intact as a result of band merging as its corresponding wavelength λ_2 in b_0 is inactive. Also, while the band-merging technique can be implemented by simply converting λ_0 and λ_1 to λ_3 and λ_4, it may also be implemented by using a novel device operating under a principle similar to that of waveband conversion, which can avoid demultiplexing bands b_0 and b_1, as required by wavelength conversion.

5. Waveband Assignment in a Convertible Network

As described earlier, issues related to wavelength and waveband conversion, and survivability in the WBS network are challenging and are now gaining more attention. Due to space limitation, in this section, we focus on the WBS network with MG-OXCs as shown in Fig. 1 and study the problem of determining the routes and wavelengths (or, more precisely, wavebands) to lightpaths in WBS networks with wavelength converters.

5.A. Waveband Assignment with Path Graph

We propose a heuristic that reduces the blocking probability of new lightpath requests by efficiently grouping wavelengths into bands and reducing the number of wavelength converters by using the reconfigurable multilayer MG-OXC shown in Fig. 1. We assume that the existing connections are not rearrangeable and develop our heuristic based on the layered-graph approach. For illustration purposes, we assume that fixed routing (shortest path first or constrained shortest path first) is used in WBS networks with intraband wavelength conversion as explained in Section 3. However, we note that our algorithm can be applied to different wavelength conversion and routing schemes.

For lightpath requests equal to or larger than the size of a band, WAPG tries to allocate one or more band paths for the requests and then allocates individual wavelengths for the remaining requests as shown in Algorithm WAPG. For a lightpath request using path l, $s=s_0 \rightarrow s_1 \ldots \rightarrow s_i \rightarrow s_{i+1} \rightarrow \ldots d=s_n$, H is the number of hops along the path, and each link has X wavelengths, partitioned into B bands, each consisting of W wavelengths. Let $\Lambda=\{w_1,w_2,\ldots,w_\lambda,\ldots,w_X\}$ be the set of wavelengths, and b be the index of waveband set $\mathcal{L}=\{1,2,\ldots\lceil X/B\rceil\}$ on each link. Accordingly we note that wavelength $1\leqslant\lambda\leqslant X$ belongs to band $b=\lceil\lambda/B\rceil$. We model a given path l using X layers of the path graph (one for each wavelength). The nodes in each layer of the path graph correspond to the nodes in the network topology. For a given path graph (λ), the links between the nodes in the same layer correspond to the existence of that wavelength between the physical nodes while the links between different layers imply the existence of wavelength converters at the physical nodes.

Following is the description of the waveband assignment with path graph (WAPG) algorithm for efficient WBS using wavelength conversion. The first five lines of the WAPG algorithm create the path graphs. Once the path graph is created, the next step is to assign appropriate weights to each link in the graph so that we can use the Dijkstra algorithm on the path graph to assign appropriate wavelengths for the request. Based on the observation that FirstFit wavelength assignment facilitates grouping wavelengths into bands and hence helps in reducing the blocking probability [31,33], we set the weight of the links in each wavelength layer to be the index number of the wavelength (see line 13 of the Algorithm). To reduce weights (or costs), Dijkstra's algorithm will prefer using the lower indexed wavelength as much as possible. In addition, to minimize the usage of the wavelength converters, we set the weight of links between different path-graph layers (i.e., the cost of using a wavelength converter) to be $X\times H$ (as in line 6 of the Algorithm). Note that, by setting the weight in this way, we implicitly try to assign wavelengths in group (consecutively) while utilizing a minimal number of wavelength converters.

WAPG Algorithm

if $H>1$ **then**
for each node s_i on the path l, each wavelength w_λ **do**
Create logical node s_i^λ in the path graph.
if there are intraband wavelength converters from λ to λ' at the node **then**
Create logical link between node s_i^λ and $s_i^{\lambda'}$ in the path graph.
Set the weight of the logical link $s_i^\lambda \rightarrow s_i^{\lambda'}$ as $w(s_i^\lambda, s_i^{\lambda'}) = X \times H$.
end if
end for

for each link $s_i \rightarrow s_{i+1}$ on the path l, each wavelength w_λ **do**
if wavelength w_λ is available on link $s_i \rightarrow s_{i+1}$ **then**
Create logical link between node s_i^λ and s_{i+1}^λ in the path graph.
Set the weight of the logical link $s_i^\lambda \rightarrow s_{i+1}^\lambda$ as $w(s_i^\lambda, s_{i+1}^\lambda) = \lambda$.
end if
end for

Create logical node s, d and links $s \rightarrow s_0^\lambda$, $s_n^\lambda \rightarrow d$.
Set the weight of the logical links $s \rightarrow s_0^\lambda$ and $s_n^\lambda \rightarrow d$ as 0.
Use Dijkstra algorithm and search proper wavelengths to accommodate the new request.

else
Use FirstFit algorithm to accommodate the new request.
end if

The request will be blocked if neither wavelength continuous lightpath (using the same wavelength all along path l) nor non-wavelength-continuous lightpath (with help of wavelength converters) can be found. One can see that the algorithm optimally minimizes the number of used wavelength converters for online traffic while keeping wavelength grouping in consideration. One of the variations of the above algorithm is to set $w(s_i^\lambda, s_{i+1}^\lambda)=1$ and $w(s_i^\lambda, s_i^{\lambda'})=H$, which tries to minimize the number of wavelength converters with arbitrary wavelength assignment.

WAPG can be effectively applied to the case with sparse wavelength conversion, full wavelength conversion (FWC), or limited-range wavelength conversion (LWC) as well. In the case with FWC at every node, there will be links from one layer to all other layers representing the FWC. On the other hand, in the case with sparse wavelength conversion only at the selected node, there are some links between different layers, whereas in the case with LWC, only limited links between different layers exist at every node. It is obvious that in the case without wavelength conversion, no links exist between different layers, in which our algorithm works exactly as the FirstFit algorithm. We compare WAPG with FirstFit and RandomFit algorithms. The FirstFit algorithm tries to use the first available wavelength-continuous path. On the other hand, if such a wavelength-continuous path is not found, it then assigns the first available wavelength to the first link of the path, for example, λ_i. On the next link, only if λ_i is not available, the first available wavelength, for example, λ_j $(i \neq j)$ is chosen, and a wavelength converter is employed to convert wavelength λ_i to λ_j, this process is continued until a wavelength has been assigned to all the links along the path. Similarly, the RandomFit algorithm randomly allocates wavelengths to satisfy the new connection request.

5.B. Performance Evaluation

In this subsection, we conduct extensive simulations to compare the performance of WAPG with FirstFit and RandomFit under different network scenarios. We assume that the traffic is uniformly distributed to all node pairs in the USANet topology with 46 nodes and 76 links. The lightpath requests arrive according to a Poisson process,

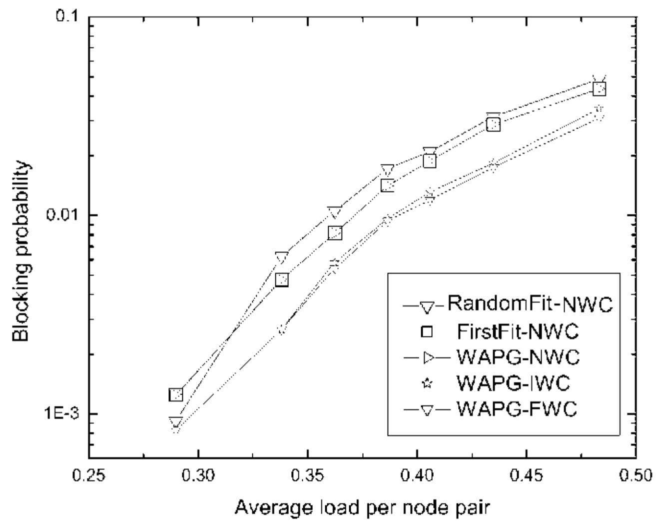

Fig. 6. Blocking probability of various conversion schemes.

and the holding time is exponentially distributed. We also assume that every link has one bidirectional fiber, each fiber has 20 bands, and each band has four wavelengths. Thus the total number of wavelengths on a link is set to $X=80$. Due to the dynamic nature of the traffic (i.e., connections are established and released dynamically), it does not make sense to compare different algorithms in terms of port count reduction or to assess the benefits of wavelength conversion in reducing the port count. Instead, we will use blocking probability and the maximum number of used wavelength converters at any given time as the performance metrics.

5.B.1. Performance when $\beta=1$

In WBS networks using the reconfigurable multilayer MG-OXC architecture with $\beta=1$, there is no limitation on the number of bands that can be demultiplexed into wavelength using BTW ports, which means blocking comes only from the limitation on the number of wavelengths [31]. We compare the performance of the WAPG algorithm with FirstFit and RandomFit wavelength assignment algorithms in the above USANet with or without wavelength converters. We use NWC, IWC, FWC, and LWC to denote the case without any wavelength converters, with maximum number of intraband wavelength converters, with maximum number of full wavelength converters, and with limited number of full wavelength converters.

Figure 6 shows the blocking probability of the network versus the traffic load for different algorithms with different wavelength conversion schemes, while Fig. 7 depicts the performance in terms of the number of used wavelength converters. The

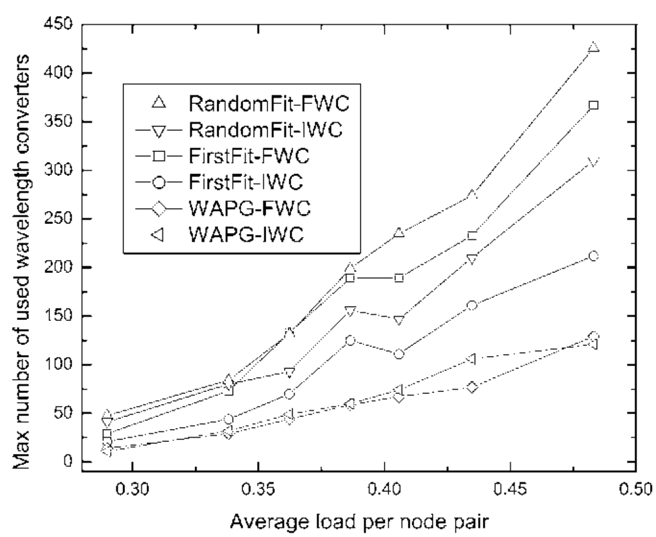

Fig. 7. Maximum number of used wavelength converters ($\beta=1$).

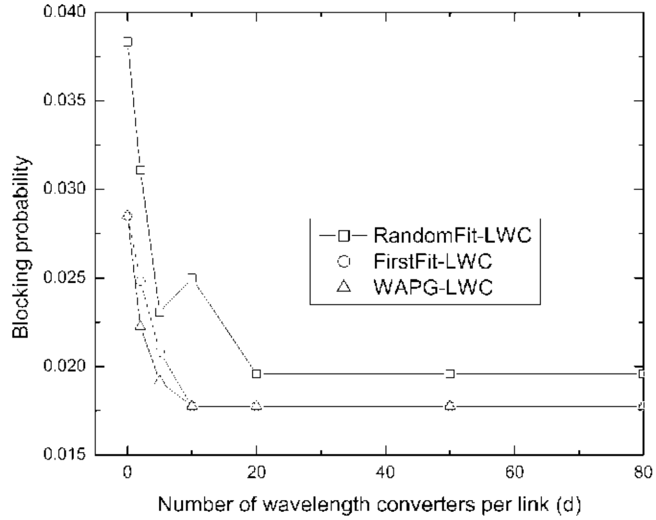

Fig. 8. Blocking performance with LWC (load=0.386).

simulation results in Fig. 6 show that a network with IWCs can achieve almost the same performance as that with FWCs. Since we are employing a fixed routing scheme, the blocking performance of WAPG and FirstFit in the case without wavelength converters is identical, which is slightly better than that of RandomFit. The blocking performance of all three algorithms in the case with FWCs is identical. Although not shown, we note that WAPG performs slightly better than the other two in the cases with IWC or LWCs. From Fig. 7, we note that WAPG performs significantly better than the FirstFit algorithm and much better than the RandomFit algorithm in terms of reducing the number of used wavelength converters. Due to the space limitation, simulation results for networks with limited number of wavelength converters, networks with sparse wavelength converters, or networks with LWCs are not reported here. We note that the WAPG is significantly better than FirstFit and RandomFit.

5.B.2. Performance with Limited Number of Wavelength Converters when $\beta=1$

Let $1 \leq d \leq X$ be the number of wavelength converters per link in the network. Figures 8 and 9 show simulation results with limited number of (full) wavelength converters. Figure 8 indicates that it is unnecessary to equip every node with maximum number of FWCs. Specifically, our study shows for the USAnet network with an average load per node pair of 0.386, $d=10$ wavelength converters per link are enough to achieve the same blocking performance as with full unlimited wavelength converters. Hence, WAPG and FirstFit have identical blocking performance when d is bigger than 10 as in the case with maximum number of FWCs (i.e., 80 wavelength converters per link).

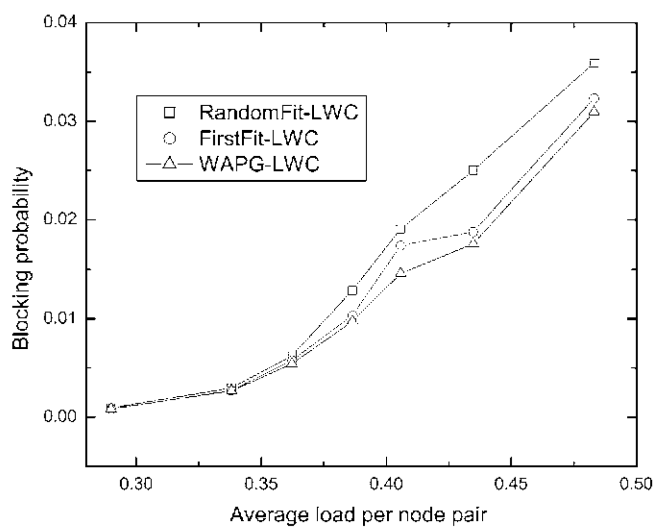

Fig. 9. Blocking performance with LWC ($d=10$).

However, in a network with a limited number of wavelength converters (e.g., $d \leq 10$), how to efficiently use the wavelength converters becomes more important. Figure 9 shows simulation results when each link has only ten wavelength converters. Once again, we can see that WAPG achieves the best performance and the performance differences between WAPG and the other two algorithms, FirstFit and RandomFit, are relatively larger than that in networks with FWC or IWCs. Due to the space limitation, simulation results for networks with sparse wavelength converters or networks with LWCs are not reported here. We note that WAPG is significantly better than FirstFit and RandomFit.

5.B.3. Performance when $\beta = 0.75$

Due to the space limitation, we present results of WAPG in WBS networks with a limited number, $d = 10$, of FWCs (per link) hereafter to show the advantage of using an intelligent WBS algorithm such as WAPG over using a trivial WBS algorithm like RandomFit and FirstFit. Unlike in case 1 above where each MG-OXC has a maximum number of BTW–WTB ports (i.e., $\beta = 1$), in this subsection, we set the ratio of bands that can be demultiplexed to wavelengths using BTW ports to be $\beta = 0.75$. Such a limited number of BTW ports may also cause request blocking if wavelength grouping into bands is not considered properly.

Figure 10 shows the blocking probabilities of the heuristics, and Fig. 11 shows the maximum number of used wavelength converters. When compared with Fig. 6, we see that the difference between the blocking performance of three algorithms is much more significant when $\beta < 1$ than when $\beta = 1$. In particular, RandomFit is ill-suited for networks with MG-OXCs as it assigns wavelength randomly and consumes a large number of wavelength converters as shown in Fig. 11, which results in inefficient use of the limited number of ports in MG-OXCs and high blocking probability. More specifically, the inefficient use of the limited ports comes from two aspects. One is that the random wavelength assignment does not take waveband grouping into consideration. The other is that wavelength conversion can happen only at the WXC layer, which means the fiber carrying the wavelength(s) has to be demultiplexed into bands and then into wavelengths, thus consuming resources (e.g., ports and multiplexers and/or demultiplexers) in the MG-OXCs, and resulting in poor blocking performance.

On the other hand, FirstFit is very likely to assign wavelengths to lightpaths sequentially, which helps in wavebanding and thus reduces the number of used ports and blocking probability, but it does not minimize the number of wavelength converters in case they are needed. In fact, FirstFit still consumes a significant number of wavelength converters as shown in Fig. 11, which in turn consumes ports and hurts its blocking performance. Since the WAPG algorithm tries to use a minimal number of wavelength converters while assigning wavelengths sequentially, it performs better than FirstFit and much better than RandomFit, and it is especially useful when both the number of ports and the number of wavelength converters are limited.

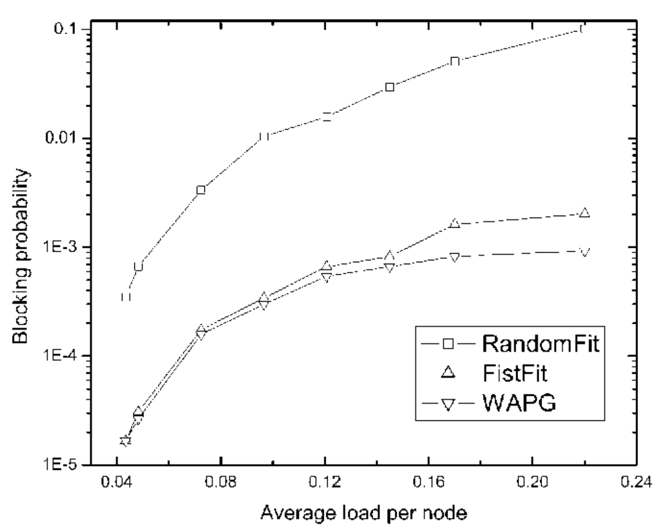

Fig. 10. Blocking performance ($\beta = 0.75$).

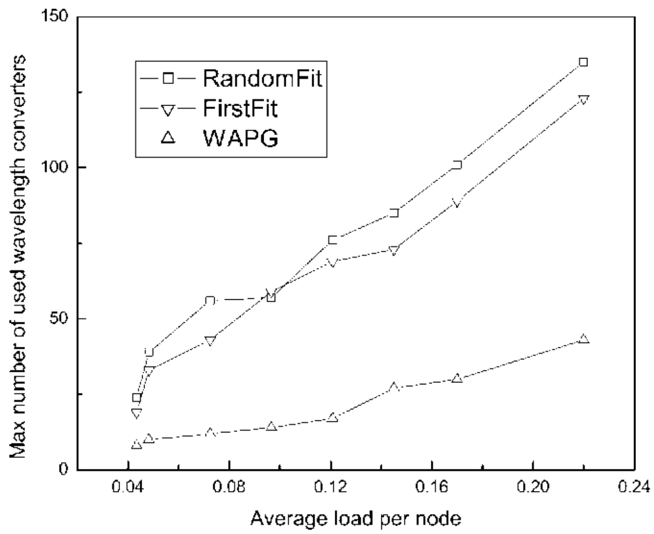

Fig. 11. Maximum number of used wavelength converters (β=0.75).

6. Conclusion and Future Work

In Part II of our study on waveband switching (WBS), we concentrate our research on issues related to wavelength and waveband conversion and failure recovery schemes in WBS networks. Wave-band switching enables the grouping of wavelengths into bands and the subsequent switching and managing of bands instead of individual wavelengths, thus reducing the cost and complexity associated with optical cross-connect switches. We study the effect of using various conversion techniques, namely, wavelength and waveband conversion in WBS networks. We develop an efficient heuristic algorithm called waveband assignment with path-graph (WAPG) algorithm, which tries to use a minimal number of wavelength converters and group wavelengths to band efficiently, thus achieving good blocking performance. The WAPG algorithm has been applied to the case with full wavelength conversion, intraband wavelength conversion (IWC) and limited wavelength conversion (LWC) to accommodate fully dynamic traffic. Through extensive simulations, we have shown that WAPG is significantly better in terms of minimizing the number of used wavelength converters and outperforms RandomFit and FirstFit in terms of blocking probability. We then study the problem of failure recovery in WBS networks and introduce novel techniques based on band segments and explore techniques for backup bandwidth sharing and introduce band swapping and merging. We also show how wavelength conversion can be used effectively to ensure survivability.

Some of the issues, such as comparison of the IWC and LWC, the impact of the placement of sparse wavelength converters and other dynamic and adaptive routing algorithms in the WBS networks, need further investigation. Furthermore, failure recovery in the WBS networks has only recently received attention. Recovery schemes based on path, link, or a hybrid scheme using a mix of the two and techniques based on backup band sharing that effectively use bandwidth and ports also need to be investigated. Recovery schemes wherein the backup bandwidth can be of various granularity, for example, at band granularity, half the band granularity, or at wavelength granularity may provide additional flexibility. This additional flexibility may come at the cost of increased port count and/or wavelength resources; such trade-offs and corresponding algorithms and MG-OXC architectures need further study.

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