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Framework for waveband switching in multigranular optical networks: part I-multigranular cross-connect architectures

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Framework for waveband switching in multigranular optical networks: part I–multigranular cross-connect architectures [Invited]

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Optical networks using wavelength-division multiplexing (WDM) are the foremost solution to the ever-increasing traffic in the Internet backbone. Rapid advances in WDM technology will enable each fiber to carry hundreds or even a thousand wavelengths (using dense-WDM, or DWDM, and ultra-DWDM) of traffic. This, coupled with worldwide fiber deployment, will bring about a tremendous increase in the size of the optical cross-connects, i.e., the number of ports of the wavelength switching elements. Waveband switching (WBS), wherein wavelengths are grouped into bands and switched as a single entity, can reduce the cost and control complexity of switching nodes by minimizing the port count. This paper presents a detailed study on recent advances and open research issues in WBS networks. In this study, we investigate in detail the architecture for various WBS cross-connects and compare them in terms of the number of ports and complexity and also in terms of how flexible they are in adjusting to dynamic traffic. We outline various techniques for grouping wavelengths into bands for the purpose of WBS and show how traditional wavelength routing is different from waveband routing and why techniques developed for wavelength-routed networks (WRNs) cannot be simply applied to WBS networks. We also outline how traffic grooming of subwavelength traffic can be done in WBS networks. In part II of this study [Cao *et al.*, submitted to J. Opt. Netw.], we study the effect of wavelength conversion on the performance of WBS networks with reconfigurable MG-OXCs. We present an algorithm for waveband grouping in wavelength-convertible networks and evaluate its performance. We also investigate issues related to survivability in WBS networks and show how waveband and wavelength conversion can be used to recover from failures in WBS networks. © 2006 Optical Society of America

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1. Introduction

Internet traffic is growing rapidly as emerging Internet applications such as IPTV, VoIP, P2P, e-business, and e-healthcare provide a wide range of individuals and corporate users with on-demand interactive communication from anywhere. In tandem with consumer needs, large-scale science applications such as high-energy nuclear physics, climate computations, and remote experimentation also require the transport of petabytes of data across the nation. To meet the huge bandwidth demand from this traffic explosion, optical networks using WDM technology [1], which divides the enormous fiber bandwidth into a large number of wavelengths, is the foremost solution.

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With the advances in WDM technology and use of ultradense WDM, one fiber is expected to transmit more than 1000 wavelengths, each operating at 10 Gbits/s or higher [2,3]. Simply augmenting transmission capacity is not the long-term solution to build cost-effective networks. Next-generation optical networks are expected to not only cost-effectively support increasing traffic but also employ switching technologies that are capable of handling this large traffic without a significant increase in complexity or expenditure. However, when the number of wavelengths is large due to DWDM technologies and worldwide fiber deployment, traditional optical cross-connects (OXCs) that switch traffic only at the wavelength granularity become huge (requiring a large number of switching ports), resulting in increased cost and control complexity.

Waveband switching (WBS) in conjunction with multigranular optical cross-connects (MG-OXCs) can be used to reduce the port count and the associated control complexity and cost of OXCs [4–8]. The main idea of WBS is to group and route several wavelengths together as a band and switch the whole band by use of 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 are demultiplexed into individual wavelengths only when some traffic needs to be added/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 this paper (part I of our study), we investigate and evaluate in detail the characteristics of various MG-OXC switches while exploring the challenges of routing and wavelength assignment and traffic grooming in WBS networks. In particular, we present multigranular photonic cross-connect switches for WBS based on three-layer and single-layer architectures. The multigranular photonic cross-connect consists of an MG-OXC and a digital cross-connect (DXC). MG-OXCs can be further classified as single-layer and three-layer MG-OXCs based on the number of switching elements. We provide qualitative and quantitative analysis of the performance of various MG-OXC architectures. Our results indicate that the single-layer architecture is capable of reducing the port count under static traffic conditions even further. However, the single-layer architecture lacks flexibility in terms of dynamically choosing bands to multiplex/demultiplex to switch dynamic traffic. In part II of the study [9] we examine new techniques and the use of wavelength and waveband conversion in WBS networks. We show how wavelength and waveband conversion can be used effectively for WBS network survivability. In particular, we introduce a novel failure recovery scheme based on band segments and propose two new techniques called band swapping and band merging, which use wavelength conversion 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.

This paper is organized as follows. In Section 2, we review some of the related work on WBS. In Section 3 we propose various cross-connect architectures for WBS and compare them in terms of port count and flexibility. Section 4 explains the difference between techniques and objectives for wavelength-routed networks (WRNs) and those for WBS networks. In Section 5 we discuss how traffic grooming for subwavelength traffic can be done in WBS networks. Section 6 concludes the paper with a summary and directions for future research.

2. Related Work

Much of the research work on routing and wavelength assignment (RWA) considers only routing at the wavelength level in WRNs [10,11]. Recently, research on multigranular waveband switching networks has received increasing attention [4,7,8,12–17]. Although wavelength routing is still fundamental to a WBS network, the challenging issues in 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) [10,11]. However, as Ref. [8] showed, minimizing the number of wavelengths or wavelength hops does not lead to minimization of the port count of the MG-OXCs (which is one important objective 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 [18], which indicates that new algorithms taking advantage of wavebanding need further exploration.

The authors of Refs. [4,19] discussed how optical bypass can be efficiently realized using wavelength bands in local and metropolitan area ring networks. Merits of the multigranular optical cross-connect such as small scale modularity, crosstalk, and complexity reduction were explained in Refs. [6,20,21], which presented a two-layer switching fabric containing a band cross-connect and a wavelength cross-connect. In Refs. [5,8,12] the authors extended this to a three-layer MG-OXC architecture for mesh networks by adding a new switching layer, i.e., a fiber cross-connect but without wavelength conversion or waveband conversion capabilities. On the other hand, a single-layer cross-connect architecture for WBS was proposed in Refs. [13,22] as opposed to the above three-layer architecture. The work in Ref. [23] extended the single-layer architecture to a photonic cross-connect architecture with cyclic multiplexers and demultiplexers. The authors argued that this single-layer MG-OXC has better optical properties, for example, reduced optical losses for traffic. In addition, the cyclic demultiplexer design allows for demultiplexing of any waveband into wavelengths by use of the same demultiplexer, thus providing increased dynamic functionality at low cost. However, the authors provided no results or analysis that showed that such an MG-OXC can in fact perform WBS efficiently, e.g., with low blocking probability, with high fiber capacity usage, or using few ports. The authors of Refs. [24,25] compared different wavelength grouping strategies, namely, end-to-end waveband switching and same-destination-intermediate waveband switching, in terms of blocking probability and cost savings. They reported that simulation results indicated that end-to-end waveband switching is better for reducing blocking probability, whereas same-destination-intermediate grouping gives superior cost savings. Most of the above work considered only the port cost of the switching fabric, although a few other works such as Ref. [26] also considered the link (fiber) cost.

While Ref. [27] provided limited analytic work for some special traffic patterns in ring networks with multilayer MG-OXCs, the authors of Ref. [14] considered the problem of WBS in star networks. They provided a greedy algorithm for waveband partitioning and showed that it is optimal in that it requires the minimum number of bands subject to using the minimum possible number of wavelengths. The benefits of using nonuniform wavebands were studied in Ref. [28]. The authors divided the problem of efficient WBS into two subproblems, waveband selection and waveband assignment, and derived respective formulations by relating the problems to set partition theory, for instance, the knapsack problem, the k-payment problem, or the change-making problem. They showed that nonuniform wavebands reduce the “aggregation overhead” and can adjust better to a varying traffic scenario. In Ref. [17] the authors compared the effectiveness of uniform versus nonuniform waveband switching to reduce network costs, i.e., switching and fiber capacity costs in star and general topology networks. Minimum-waveband algorithms that allow for small wavelength inefficiencies in return for reducing the number of wavebands down to just the nodal degree are provided to help characterize the optimal performance frontier. To achieve optimal performance, initially the authors allowed any size granularity for the wavebands. They also showed that even by restricting the wavebands to only uniform waveband sizes they could achieve performance that was optimum or close to optimum.

In our previous work on WBS [8,13,18], we proposed a multigranular photonic cross-connect. We distinguish between a multigranular photonic cross-connect and an MG-OXC, in the sense that a multigranular photonic cross-connect has additional optical–electrical–optical (OEO) grooming capabilities when a DXC consisting of a three-layer MG-OXC with a DXC is used. The architecture allows for dynamic selection of fibers for multiplexing/demultiplexing into wavebands and wavebands into wavelengths. We compared this architecture 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 the flexibility to switch dynamic traffic. We developed integer linear programming (ILP) models and heuristic algorithms such as balanced path routing with heavy-traffic first waveband assignment (BPHT). BPHT employs the general wavelength aggregation technique, wherein traffic from "any source to any destination" may be grouped into wavebands, thus maximizing the possibility that various wavelength paths having common subpaths may be accommodated in the same band. Upper and lower bounds on port counts were also calculated through analysis. In Ref. [18], we developed another ILP formulation and extended the BPHT algorithm to multifiber networks. The study of multifiber networks is motivated by previous works that has shown that performance improvement in terms of reduced blocking and better fault tolerance can be obtained by using multifiber networks, with the additional advantage of simulating partial wavelength conversion capability. We showed that WBS can result in further reduction in port count compared with single-fiber networks and thus is even more beneficial in multifiber networks.

Issues related to optical multigranularity and particularly waveband switching under the generalized multiprotocol label switching (GMPLS) framework have been partially addressed in Ref. [29]. A new switching unit called a waveband-label switched path is defined in GMPLS [29] to expand the underlying provisioning capabilities of traffic grooming and wavebanding in optical networks. However, as is illustrated in this work, many open research issues in areas such as nodal architecture, conversion, protection/restoration, and control plane/signaling need further exploration.

3. Cross-Connect Architectures for Multigranular Switching

As explained above, 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 light paths to form wavebands have been a major concern, it is also important to devise node architectures that are flexible (reconfigurable) yet cost-effective. As a part of the multigranular photonic cross-connect, the MG-OXC is a key element for routing high-speed WDM traffic in a multigranular optical network. The challenge is how to design MG-OXCs to cut down the overall cost of the system by not only reducing the number of ports but also decreasing/simplifying other components such as multiplexers/demultiplexers and transmitters/receivers, as well as increasing bandwidth utilization (or reducing the number of wavelengths needed). In this section, we will propose and compare several node architectures for multigranular switching.

3.A. Three-Layer Multigranular Photonic Cross-Connect Architecture

Figure 1 shows the architecture of a three-layer multigranular photonic cross-connect. The photonic cross-connect includes a three-layer MG-OXC and a DXC that allows for OEO grooming of sub-lambda traffic. In addition to three switches for wavelength, waveband, and fiber switching, the three-layer MG-OXC also has wavelength and waveband conversion banks. The wavelength cross-connect (WXC) and band cross-connect (BXC) layers consist of cross-connect(s) and multiplexer(s)/demultiplexer(s). The WXC layer includes a wavelength cross-connect switch that is used to bypass/add/drop light paths 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 multiplexers are used to multiplex wavelengths into bands. At the BXC layer, the waveband cross-connect is used to switch wavebands. The BXC layer also includes the fiber-to-band (FTB) demultiplexers and band-to-fiber (BTF) multiplexers. Similarly, at the fiber cross-connects (FXCs) layer, FXCs are used to switch fibers. FXCs, BXCs, and WXCs may be implemented using technologies based on all-optical transparent switches such as 2-D and 3-D microelectromechanical systems or arrayed waveguide gratings [30–32]. Furthermore, bandpass and tunable filter technologies using acousto-optic, thermo-optic polymers can be employed to multiplex/demultiplex bands/wavelengths from respective fibers/bands [33].

This architecture allows dynamic selection of fibers for multiplexing/demultiplexing from FXC layer to the BXC layer and bands for multiplexing/demultiplexing from the BXC to the WXC layer. For example, at the FXC layer, as long as there is a free FTB

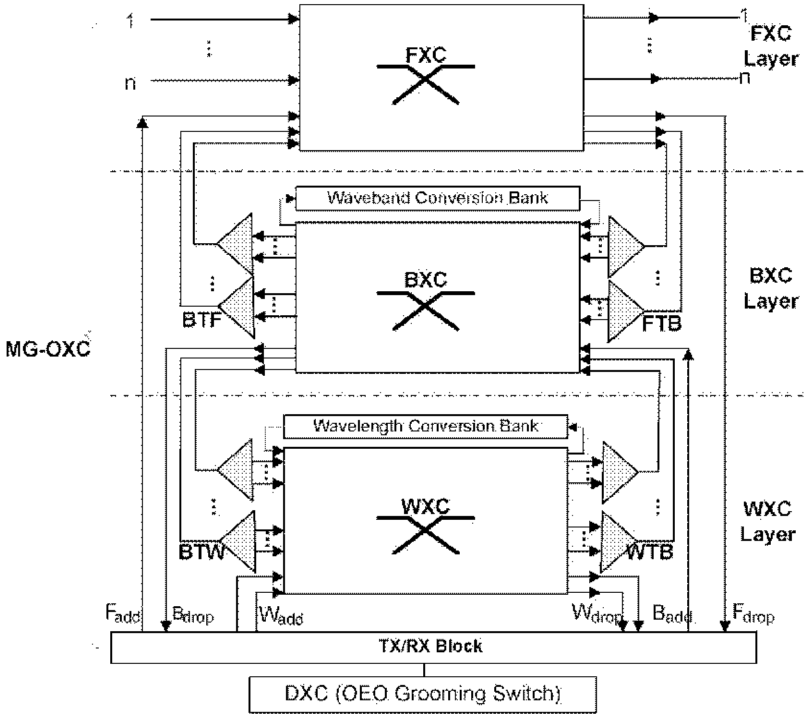

Fig. 1. Three-layer multi-granular photonic cross-connect.

port, any fiber can be demultiplexed into bands. Similarly, at the BXC layer any band can be demultiplexed to wavelengths using a free BTW port by appropriately configuring the FXC, BXC cross-connects, and associated demultiplexers. Nevertheless, to reduce the total port count in the static traffic off-line case or to reduce the request blocking probability (and the number of used ports) in the dynamic traffic online case, efficient WBS algorithms are needed to determine the routing and wavelength (or waveband) assignment for the light paths.

We illustrate the savings in port count that may be achieved by using such a MG-OXC architecture over a traditional single-granular architecture by using an example. Since the above architecture is symmetric in terms of port count at the input side (left) and the output side (right), we focus only on the input side of the MG-OXC. We define the input side of a MG-OXC to consist of locally added traffic and traffic coming into the MG-OXC node from all other nodes, which consists of bypass traffic and locally dropped traffic. To reduce the number of ports, the MG-OXC switches a fiber using one port (space switching) at the FXC cross-connect if none of its wavelengths is used to add/drop a light path. Otherwise, it will demultiplex the fiber into bands and switch an entire band by use of one port at the BXC cross-connect if none of its wavelengths is used to add/drop a light path. In other words, only the band(s) whose individual wavelength(s) need to be added or dropped will be demultiplexed, and only the wavelengths in those bands that carry bypass traffic need to be switched using the WXC. This is in contrast to the ordinary OXCs, which need to switch every wavelength individually using one port. By ordinary OXC, we refer to traditional single-granular cross-connet architecture which can only switch traffic at the wavelength level. For example, assume there are ten fibers, each having 100 wavelengths, and one wavelength needs to be dropped and one to be added at a node. The total number of ports required at the node when one is using an ordinary OXC is 1000 for incoming wavelengths (including 999 for bypass and 1 for drop wavelength), plus 1 for add wavelength for a total of 1001. However, if the 100 wavelengths in each fiber are grouped into 20 bands, each having five wavelengths, then using a MG-OXC, only one fiber needs to be demultiplexed into 20 bands (using an 11-port FXC). Then, only one of these 20 bands needs to be demultiplexed into five wavelengths (using a 21-port BXC). Finally, one wavelength is dropped and added (using a 6-port WXC). Accordingly, the MG-OXC has only 11+21+6=38 ports, an almost 30 times reduction.

3.B. Single-Layer Multigranular Photonic Cross-Connect Architecture

Compared with the node architecture above, Fig. 2 shows a single-layer photonic cross-connect consisting of a single-layer MG-OXC with only one common switching fabric and a DXC. The single-layer switching matrix includes three logical parts corresponding to FXC, BXC, and WXC. The major differences are the elimination of FTB/BTW demultiplexers and BTF/WTB multiplexers between different layers, which results in a simpler architecture to implement, configure, and control. Another advantage of this single-layer MG-OXC is better signal quality, because all light paths that do not require wavelength or waveband conversion go through one switching fabric (except those requiring conversion), whereas in the multilayer MG-OXCs, some of them may go through 2 to 3 switching fabrics (i.e., FXC, BXC, and WXC). As a tradeoff, some incoming fibers, e.g., fiber *n*, are preconfigured as "designated fibers." Only designated fibers can have some of their bands dropped, while the remaining bands bypass the node, all other nondesignated incoming fibers (e.g., fibers 1 and 2) have to have all the bands either bypass the node entirely or be dropped entirely. Similarly, within these designated fibers, only designated bands can have some of their wavelengths dropped, while the remaining bands bypass the node.

Since the single-layer architecture described above has many advantages but suffers from lack of flexibility [18,22], we extend this architecture to make it more flexible as shown in Fig. 3. The extended single-layer architecture aims to achieve a balance between the first two cross-connect architectures. Like the second one (Fig. 2), it is also a single-layer architecture, so there are neither FTB/BTW demultiplexers nor BTF/WTB multiplexers for connecting different layers. It has some "designated" fibers and "designated" bands within these fibers, so it is not as flexible as the first (Fig. 1) MG-OXC. On the other hand, what makes it different (and more powerful) than the second architecture is that this MG-OXC does use a few FTB/BTW demultiplexers and BTF/WTB multiplexers so that even a "nondesignated" fibers (bands) can drop specific bands (wavelengths) without subjecting the other bands in the same fiber (or wavelengths in the same band) to OEO conversions or further optical processing/switching.

We use the same example as the one above to illustrate the differences between the multilayer and single-layer cross-connects. Recall that to add/drop one wavelength at a node with 10 incoming/outgoing fibers, each having 100 wavelengths, the three-layer MG-OXC needs only 38 ports (while an ordinary OXC needs 1001 ports). However, if any of the two single-layer MG-OXCs is used, and if the light path to be dropped is assigned to an appropriate fiber (i.e., a designated fiber) and an appropriate (designated) band in the fiber, then even fewer ports are needed. More specifically, only one fiber needs to be demultiplexed into 20 bands, so only 9 ports are needed for

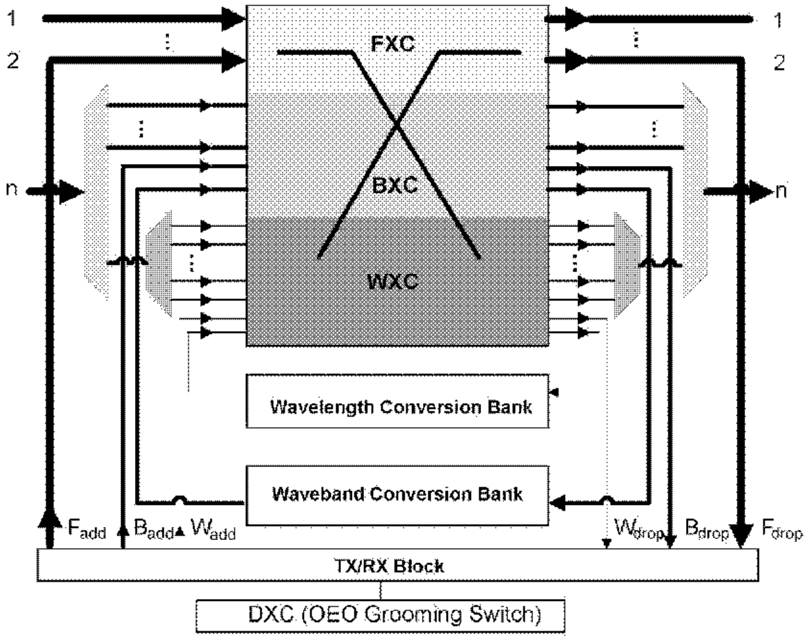

Fig. 2. Single-layer multi-granular photonic cross-connect.

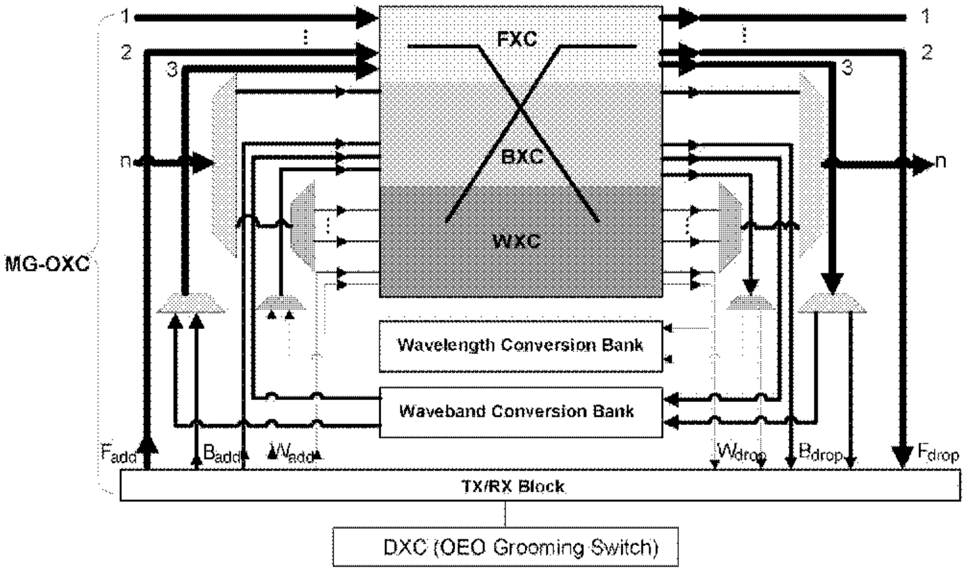

Fig. 3. Extended single-layer multi-granular photonic cross-connect.

other nondesignated fibers. In addition, only 1 of 20 bands demultiplexed from the designated fiber needs to be further demultiplexed into wavelengths, thus only 19 ports are needed for the nondesignated bands in the fiber. Finally, 6 ports are needed for the 5 wavelengths demultiplexed from the designated band and for the add/drop wavelength. Hence, the total number of ports needed is only $9+19+6=34$, more than 10% less than the three-layer MG-OXC.

Note that an MG-OXC, especially a single-layer MG-OXC, can reduce the port count only when an efficient WBS algorithm is used. For example, in WBS networks with single-layer MG-OXCs, an appropriate WBS algorithm needs to make sure that the light paths to be dropped at a single-layer MG-OXC will be assigned wavelengths that belong to a designated fiber/band. Clearly, this may not always be possible given a limited number of designated fibers/bands, especially in the case of on-line traffic, where global optimization for all light-path demands is often difficult (if not impossible) to achieve. For this reason, multilayer MG-OXCs may in fact require fewer ports and wavelengths to satisfy all the light-path demands or result in a better blocking performance (i.e., a lower blocking probability) for a given set of light-path demands with a comparable amount of resource.

3.C. Reconfigurability in MG-OXC

Since it is unnecessary to demultiplex all the fibers/bands to bands/wavelengths and switch them individually [18,25,28], another challenge is how to design efficient reconfigurable architectures for the on-line dynamic traffic case.

The cross-connect architectures that we consider for dynamic traffic are similar to the MG-OXC in Figs. 1 and 2. However, unlike previous architectures, where the three-layer MG-OXC can have as many ports as needed to guarantee that all the demands are satisfied, here the MG-OXC has only a predetermined limited port count as in Figs. 4 and 5. More specifically, let X denote the number of incoming fibers, Y 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 allow only $\lceil \alpha X \rceil$ fibers that can 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 part II, [9] 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/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.

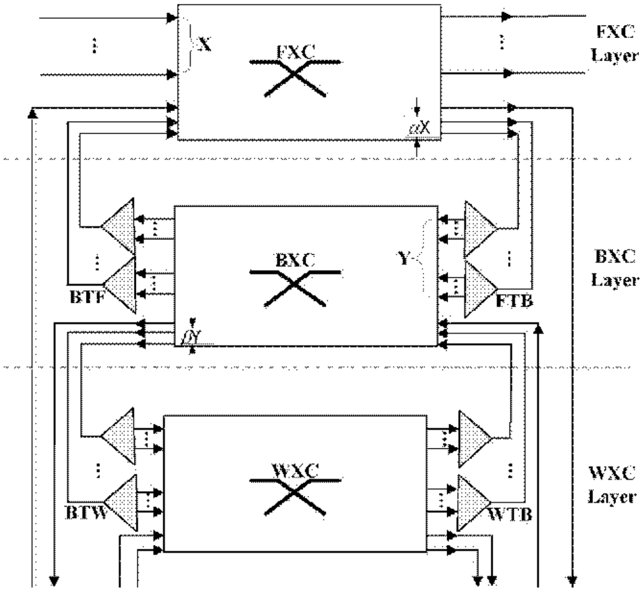

Fig. 4. Reconfigurable multilayer MG-OXC.

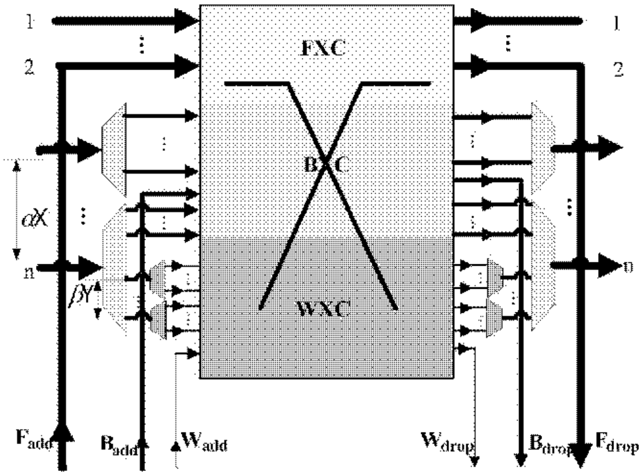

Fig. 5. Reconfigurable single-layer MG-OXC.

4. Waveband Switching

WBS schemes can be classified into two variations, depending on whether the number of bands in a fiber (B) is fixed or variable. Each variation is further classified according to whether the number of wavelengths in a band (denoted by W) is fixed or variable. For a given fixed value of W, the set of wavelengths in a band can be further classified, depending on whether they are predetermined (e.g., whether they consist of consecutively numbered subset of wavelengths) or can be adaptive (dynamically configured).

Further, depending on how the wavelengths are grouped into bands, one can have different wavelength grouping strategies such as (1) *end-to-end grouping*, or grouping the traffic (light paths) with same source–destination (s–d) only; (2) *one-end-grouping*, or grouping the traffic between the same source (or destination) nodes and different destination (or source) nodes; and (3) *subpath grouping*, or grouping traffic with a common subpath (from any source to any destination). While most existing work assumes either strategy 1 or 2, our preliminary work used strategy 3. Strategy 3 is the most powerful in terms of maximizing the benefits of WBS by increasing the grouping of wavelengths, although it is also the most complex to use in WBS algorithms.

4.A. Waveband Switching: an Example

We now illustrate how WBS is done using an example with the three-layer MG-OXC. Figure 6 shows two light paths, one bypassing the node using λ_0 on input fiber 1 and the other originating from the node using λ_1 that is to be added locally. Using the MG-OXC, the two light paths are to be grouped together in the same band of the same output fiber (e.g., fiber 2). For this, input fiber 1 (containing the bypassing light path) has to be demultiplexed into band b_0 (and other bands) by use of a FTB demultiplexer. Band b_0 then has to be further demultiplexed into λ_0 and other wavelengths to switch the bypassing light path. The light path originating from the node is added into band b_0 by use of a WTB multiplexer. Now that the two light paths are in the same band, the band is multiplexed onto a fiber by use of a BTF multiplexer and then transmitted onto output fiber 2.

4.B. Routing and Wavelength Assignment in WBS Networks

As expected, the new paradigm promises opportunities on the one hand and also presents new challenges on the other. The major challenging problems in WBS with MG-OXCs to be addressed are how to determine the routes and assign wavelengths (or more precisely wavebands) to light paths and how to design MG-OXCs to cut down the overall cost/complexity of the system by not only reducing the number of ports but also decreasing/simplifying other components such as multiplexers/demultiplexers and transmitters/receivers, as well as increasing bandwidth utilization (or reducing the number of wavelengths needed). This is challenging because a multilayer MG-OXC consisting of a fiber, band, and wavelength cross-connect introduces overhead in terms of additional ports needed at each layer solely for interconnecting the layers. Accordingly, using an MG-OXC in a naive way may result in requiring more ports (and complexity) than using an ordinary OXC, especially when a sufficiently large number of incoming fibers and wavebands need to be demultiplexed into wavelengths for switch and add/drop purposes.

Although a tremendous amount of work on WRN has been carried out and wavelength routing is still fundamental to a WBS network, the proposed work on WBS (and MG-OXCs) in terms of the objective and techniques are quite different from all existing work on WRN. 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) [10,11,34,35]. However, minimizing the number of wavelengths or wavelength hops does not necessarily lead to the minimization of the port count of the MG-OXCs in WBS networks. In fact, studies have indicated that when using the optimal RWA algorithm (based on ILP formulations) with a best-effort wavelength grouping heuris-

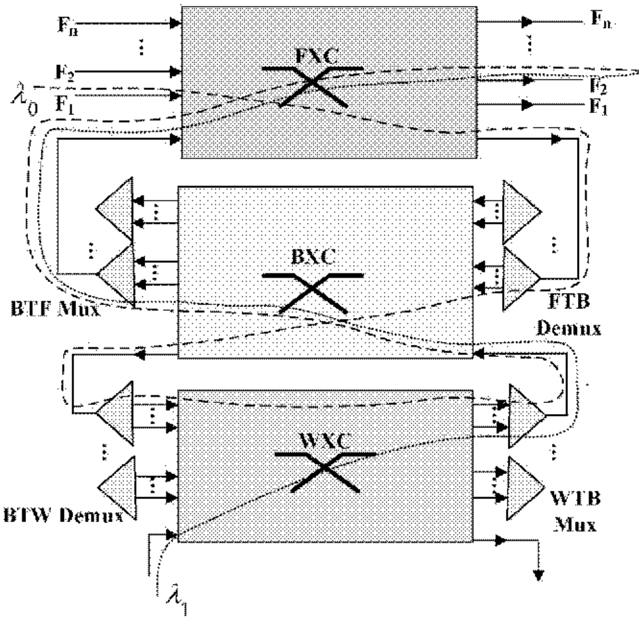

Fig. 6. Waveband at node n.

tic can increase the number of ports needed [8]. Figure 7 shows the performance of three- and single-layer MG-OXCs when employing an ILP model with the objective of minimizing port count under static traffic conditions. Detailed formulation and explanation of the ILP can be found in Ref. [18]. The total port number ratio **T** and used wavelength-hop ratio **W** are defined as

- Total port number ratio: T=total port count when using MG-OXCs/total port count when using ordinary OXCs,
- Used wavelength-hop ratio: W=wavelength hops required for WBS using MG-OXCs/wavelength hops required in WRNs using ordinary OXCs.

The results indicate that using single-layer MG-OXCs requires fewer ports than using three-layer MG-OXCs. This is because when one is switching a light path through the WXC layer of a three-layer MG-OXC, a fiber must be demultiplexed to extract its corresponding bands, which in turn must be demultiplexed to extract the respective wavelengths, and finally multiple wavelengths have to be multiplexed into a band and multiple bands into an outgoing fiber, requiring ports (switch and multiplexers/demultiplexers) at each layer. On the other hand, in a single-layer MG-OXC, every light path is switched only once (using one input and one output port) at every node, resulting in fewer ports. From Fig. 7, we can see that the number of wavelength hops used is the same when we are using single- and three-layer MG-OXCs. The wavelength-hop ratio does not change much with the waveband granularity and exceeds 1 by a small percentage, which means that using MG-OXCs increases wavelength hops (when compared with the case of using ordinary OXCs), a price paid for the reduction in the total number of ports. This trade-off between port count and wavelength hops can be explained as follows. Sometimes, to reduce port count, a longer route that requires fewer "additional" ports may be chosen instead of a shorter route that requires more "additional" ports. In other words, minimizing the number of ports at MG-OXC does not necessarily imply minimizing the number of wavelength hops (even though minimizing wavelength hops in ordinary OXC networks is equivalent to minimizing the number of ports). This indicates that an ideal WBS algorithm may need to trade a slight increase in the number of wavelengths (or wavelength hops) for a much reduced port count. Such a trade-off between the required number of wavelength hops and ports was also discussed for three-layer MG-OXC networks in Refs. [8,36]. While many optimization problems in WRN are already NP-complete, some of the optimization problems in WBS have more constraints and are harder to solve. In particular, in the on-line case where the network topology and the nodal architecture are given, the challenge is how to route and assign wavebands while minimizing the blocking probability or maximizing the throughput for dynamic traffic demands. Several variations in which the traffic demand may be incremental or fluctuating, the existing connections may or may not be rearrangeable, and the network may be upgraded are also possible. Analyzing or optimally solving the on-line problems is difficult (if not impossible), as the future

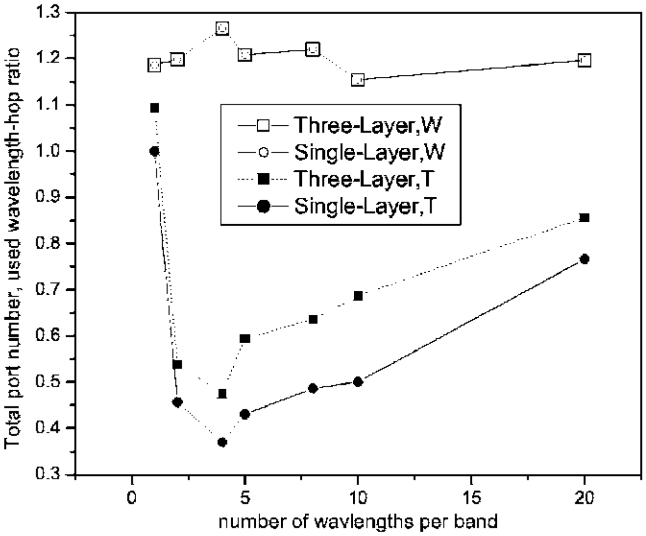

Fig. 7. Total port number ratio and wavelength-hop ratio used.

traffic demands are not known *a priori*. In part II of this study, presented in Ref. [9], we will explore some of the issues related to how to group wavelengths to band efficiently while minimizing the number of wavelength under dynamic traffic patterns.

5. Waveband Switching with Traffic Grooming

Another challenge we face in designing WBS networks is how to efficiently integrate waveband switching with traffic grooming and dynamic provisioning of high-speed channels or end-to-end connections. Techniques developed for traffic grooming in WRN, which are useful mainly for reducing the electronics (e.g., SONET add/drop multiplexers) and/or number of wavelengths required (see, for example, Refs. [37,38]), cannot be directly applied to effectively grouping wavelengths into wavebands. This is because in WRN one can multiplex just about any set of lower bit rate (i.e., subwavelength) traffic such as STS-1s into a wavelength, subject only to the constraint that the total bit rate does not exceed that of the wavelength [39–41]. However, when one considers wavebanding, there is at least one more constraint: only the traffic carried by a fixed set of wavelengths (typically consecutive) may be grouped into a band. Innovative solutions that solve the waveband switching and traffic grooming problem in an integrated fashion can reduce the port count of MG-OXC and size of DXC. Such solutions need to build upon and advance the knowledge and techniques for WRNs.

The multiprotocol lambda switching (MPλS) and GMPLS control plane can provide IP-based optical control plane for cross-connects in an automatic switched optical network (ASON) [29,42–44]. Since a new switching unit called waveband-label switched path (WE-LSP) is defined in GMPLS [29,45], focused efforts are needed to investigate the underlying provisioning capabilities with traffic grooming and wavebanding as well as control plane/signaling issues related to GMPLS/ASON. To meet the requirements of terabits per second thoughput from distributed large-science applications one potential solution is to run parallel fast TCP over WB-LSPs (or multiple LSPs offered by traffic grooming, or both).

The advances of bit rate per wavelength/fiber bring about a significant mismatch between the transmission capacity of wavelength/fiber and the switching/forwarding capability of electronic routers. To overcome the electronic bottleneck and support services at subwavelength level, traffic grooming is construed as a bypass mechanism by which low-rate circuits are appropriately aggregated and assigned to wavelengths. While much work on traffic grooming has been done in the context of design and optimization for SONET ring networks, a few recent studies have started to focus on grooming with OXC in a mesh network (see, for example, Refs. [37,38,46]). However, with introduction of wavebanding as in Figs. 1–3, where all-optical MG-OXCs are combined with an OEO grooming switch, how to efficiently integrate multiplexing/demultiplexing in fiber, band, wavelength, and subwavelength is an open and very important question. Another dynamic issue is provisioning of high-speed (end-to-end) connections in a heterogeneous optical network where nodes are equipped with different switching abilities; for example, some nodes are only OXCs, some are only MG-OXCs, and some have MG-OXC and OEO grooming switch jointly.

6. Conclusion and Future Work

To respond to the surge in Internet traffic, a large number of fibers and wavelengths have been deployed. Although this increases the bandwidth and traffic carrying capacity of optical networks, it also brings about a large increase in the size or the number of ports and the control complexity in cross-connect switches. In part I of this study, we have investigated the problem of waveband switching (WBS), which 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 have provided a systematic study and comparison of various cross-connect switch architectures. In particular, the architectures are compared based on their complexity, port counts, and ability to carry dynamic traffic. We also study issues related to wavelength routing and traffic grooming in WBS networks. In part II of this study [9], we will study the effect of using various conversion techniques, namely, wavelength and waveband conversion in WBS networks. We will also study the problem of failure recovery in WBS networks.

Issues relating to hybrid optical network design, wherein some of the cross-connects are multigranular (maybe a combination of single and multilayer) and others are traditional wavelength-routing OXCs, and the use of photonic cross-connects for grooming subwavelength traffic in WBS networks are still open and require further research. Algorithms for routing traffic at different granularities starting from subwavelengths, individual wavelengths to nonuniform/variable/adaptive band sizes are also largely unexplored.

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