Waveband Switching in Optical Networks

Xiaojun Cao, Vishal Anand, and Chunming Qiao, State University of New York at Buffalo

ABSTRACT

The rapid advances in dense wavelength-division multiplexing technology with hundreds of wavelengths per fiber and worldwide fiber deployment have brought about a tremendous increase in the size (i.e., number of ports) of photonic cross-connects, as well as in the cost and difficulty associated with controlling such large cross-connects. Waveband Switching (WBS) has attracted attention for its practical importance in reducing the port count, associated control complexity, and cost of photonic cross-connects. In this article we show that WBS is different from traditional wavelength routing, and thus techniques developed for wavelength-routed networks (including, for example, those for traffic grooming) cannot be directly applied to effectively address WBS-related problems. We describe two multigranular OXC architectures for WBS. By using the multilayer MG-OXC in conjunction with intelligent WBS algorithms for both static and dynamic traffic, we show that one can achieve considerable savings in the port count. We also present various WBS schemes and lightpath grouping strategies, and discuss issues related to waveband conversion and failure recovery in WBS networks.

INTRODUCTION

Optical networks using wavelength-division multiplexing (WDM) technology, which divides the enormous fiber bandwidth into a large number of wavelengths (100 or more, each operating at 2.5 Gb/s or higher), is a key solution to keep 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 WDM network is becoming increasingly *critical* and *complicated*. In particular, the rapid advance and use of dense WDM (DWDM) technology has brought about a tremendous increase in the size (e.g., number of ports) of photonic (both optical and electronic) cross-connects, as well as the cost and difficulty associated with controlling and management of such large cross-connects. Hence, despite the remarkable technological advances in building photonic cross-connect systems and associated switch fabrics, the high cost (both capital and operating expenditures) and unproven reliability of huge switches have hindered their deployment.

Recently, the concept of *Waveband Switching* (WBS) has been proposed to reduce this complexity to a reasonable level. The main idea of WBS is to group several wavelengths together as a band and switch the band (optically) using a single port. In this way, not only the size of digital cross-connects (DXCs) (e.g., optical-electronic-optical, OEO, grooming switches) can be reduced because bypass (or express) traffic can now be switched optically, but also the size of optical cross-connects (OXCs) that traditionally switch at the wavelength level can be reduced because of the bundling of lightpaths into bands in WBS networks. In this article we focus on the use of WBS to reduce the size of the multigranular OXC (MG-OXC) [1–6], which is part of the multigranular photonic cross-connect (Fig. 1).

This article is organized as follows. We first compare two principal MG-OXC architectures for WBS, and present various WBS schemes and lightpath grouping strategies. We then explain how WBS differs from wavelength routing. Next, we focus on the design of WBS algorithms for both static and dynamic traffic.

MULTIGRANULAR OPTICAL CROSS-CONNECT ARCHITECTURES

In wavelength-routed networks (WRNs) with ordinary OXCs (i.e., single-granular OXCs) that switch traffic only at the wavelength level, wavelengths either terminate at or transparently pass through a node, each requiring a port. However, in WBS networks several wavelengths are grouped together as a band and switched as a single entity (i.e., using a single port) whenever possible. A band is demultiplexed into individual wavelengths if and only if necessary (e.g., when the band carries at least one lightpath that needs to be dropped or added). WBS networks employ MG-OXC to not only *switch* traffic at multiple levels or granularities such as fiber, band, and wavelength (and DXC to switch traffic at the subwavelength level), but also *add* and *drop* traf-

0163-6804/03/$17.00 © 2003 IEEE

The MG-OXC is a key element for routing high speed WDM data traffic in a Multi-Granular optical network. While reducing its size has been a major concern, it is also important to devise node architectures that are flexible (reconfigurable) yet cost-effective.

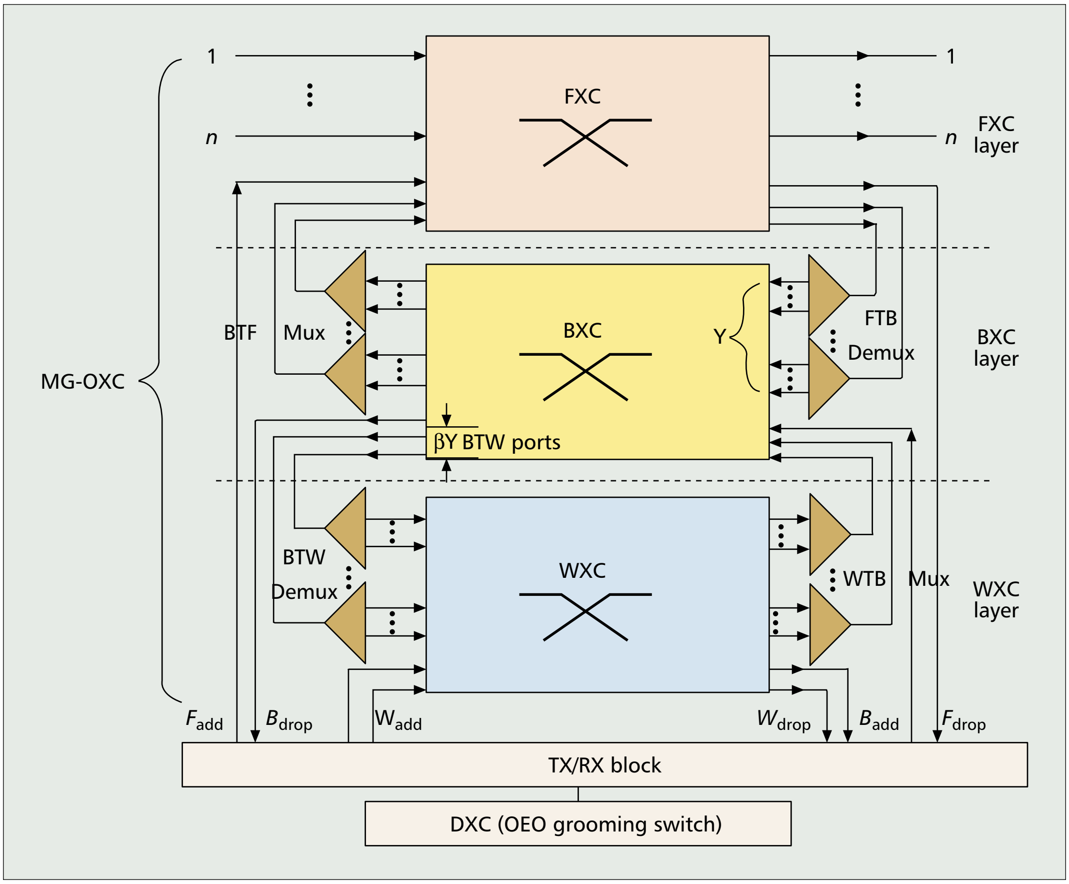


Figure 1. *A multigranular photonic cross-connect consisting of a three-layer MG-OXC and a DXC.*

fic at multiple granularities. Traffic can be transported from one level to another via multiplexers and demultiplexers within the MG-OXC.

THE MULTILAYER MG-OXC

The MG-OXC is a key element for routing high-speed WDM data traffic in a multigranular optical network. While reducing its size has been a major concern, it is also important to devise node architectures that are flexible (reconfigurable) yet cost-effective. Figure 1 shows a typical MG-OXC considered in [2, 6], which includes the fiber cross-connect (FXC), band cross-connect (BXC), and wavelength cross-connect (WXC) layers.

As shown in Fig. 1, the WXC and BXC layers consist of cross-connect(s) and multiplexer(s)/demultiplexer(s). The WXC layer includes a WXC that is used to switch lightpaths. To add/drop wavelengths from the WXC layer, we need W_{add}/W_{drop} ports. In addition, BTW demultiplexers are used to demultiplex bands to wavelengths, and WTB multiplexers are used to multiplex wavelengths to bands. At the BXC layer, the band cross-connect, B_{add} and B_{drop} ports are used for bypass bands, added bands, and dropped bands, respectively (see later sections for the definition of Y and βY). FTB demultiplexers and BTF multiplexers are used to demultiplex fibers to bands and multiplex bands to form fibers, respectively. Similarly, fiber cross-connect/F_{add}/F_{drop} ports are used to switch/add/drop fibers at the FXC layer. In order to reduce the number of ports, the MG-OXC switches a fiber using one port (space switching) at the fiber cross-connect if none of its wavelengths is used to add or drop a lightpath. Otherwise, it will demultiplex the fiber into bands, and switch an entire band using one port at the band cross-connect if none of its wavelengths needs to be added or dropped. In other words, only the band(s) whose wavelengths 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 ordinary OXCs, which need to switch every wavelength individually using one port.

With this architecture, it is possible to dynamically select fibers for multiplexing/demultiplexing from the FXC 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 demultiplexer, any fiber can be demultiplexed into bands. Similarly, at the BXC layer any band can be demultiplexed to wavelengths using a free BTW demultiplexer by appropriately configuring the FXC and BXC and associated demultiplexers.

SINGLE-LAYER MG-OXC

Unlike the previously described multilayer MG-OXC, the one shown in Fig. 2 is a single-layer MG-OXC that has only one common optical switching fabric [4]. This switching matrix includes three *logical* parts corresponding to the FXC, BXC, and WXC, respectively. However, the major differences are the elimination of

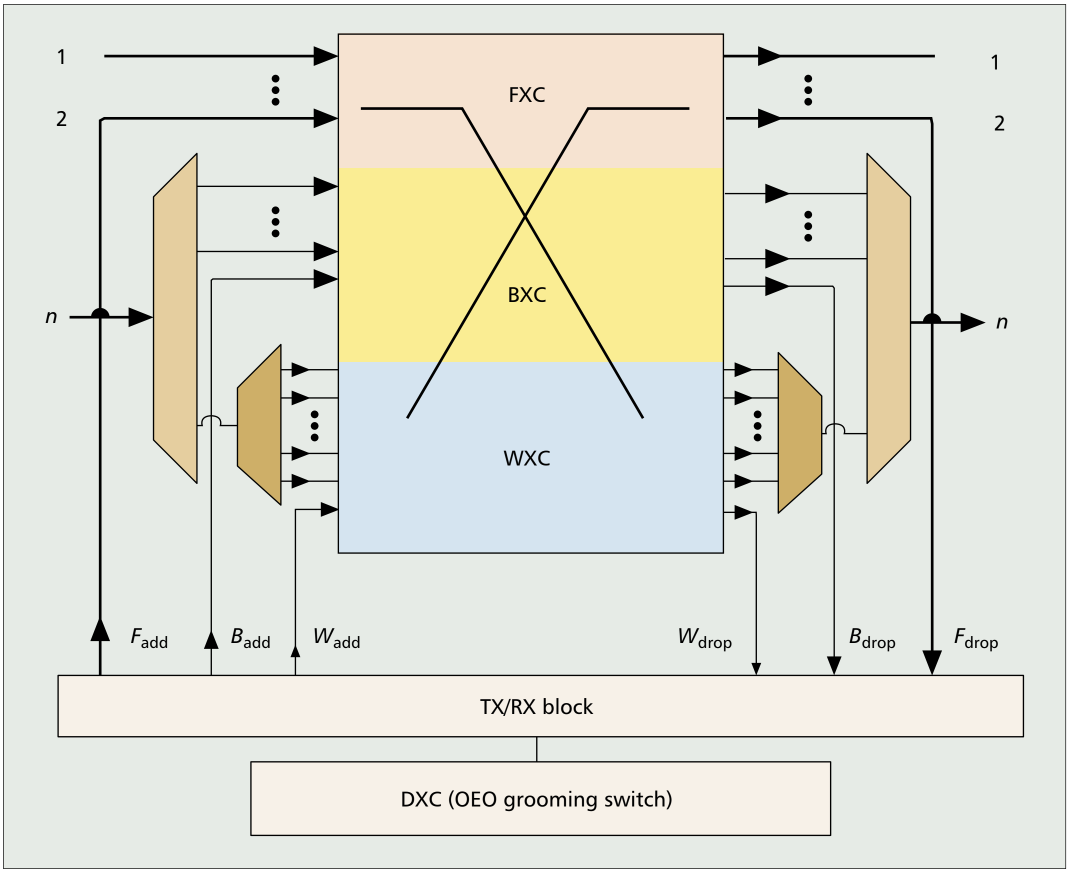


Figure 2. *A multigranular photonic cross-connect consisting of a single-layer MG-OXC and a DXC.*

With WBS, some or most of the wavelength paths (or lightpaths) do not have to pass through individual wavelength filters, thus simplifying the multiplexer and demultiplexer design. In fact, cascading of FTB and BTW demultiplexers has been shown to be effective in reducing cross-talk.

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 lightpaths go through only one switching fabric, whereas in multilayer MG-OXCs, some of them may go through two or three switching fabrics (i.e., FXC, BXC, and WXC).

As a trade-off, some incoming fibers, say, fiber *n* (Fig. 2), are preconfigured as *designated fibers*. Only designated fibers can have some of their bands dropped while the remaining bands bypass the node (i.e., all the bands in nondesignated incoming fibers, e.g., fibers 1 and 2, have to either bypass the node or be dropped). Similarly, within these designated fibers, only designated bands can have some of their wavelengths dropped while the remaining wavelengths bypass the node. In short, this architecture is not as flexible as the multilayer MG-OXC, which may result in inefficient utilization of network resources. More specifically, in WBS networks with single-layer MG-OXCs, an appropriate WBS algorithm needs to make sure that the lightpaths 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 online traffic where global optimization for all lightpath demands is often difficult (if not impossible) to achieve.

AN ILLUSTRATIVE EXAMPLE

We use an example to illustrate the differences between the multi- and single-layer MG-OXCs. When counting the number of ports, we will only focus on the input side of the MG-OXC (due to the symmetry of the MG-OXC architecture), which consists of locally added traffic and traffic coming into the MG-OXC node from all other nodes (i.e., bypass traffic and locally dropped traffic). Assume there are 10 fibers, each having 100 wavelengths, and one wavelength needs to be dropped and one added at a node. The total number of ports required at the node when using an ordinary OXC is 1000 for incoming wavelengths (including 999 for bypass and 1 dropped wavelength), plus 1 added wavelength for a total of 1001. However, if the 100 wavelengths in each fiber are grouped into 20 bands, each having 5 wavelengths, using an MG-OXC as in Fig. 1, only one fiber needs to be demultiplexed into 20 bands (using an 11-port FXC). Hence, only one of these 20 bands needs to be demultiplexed into 5 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).

As a comparison, if the single-layer MG-OXC (as shown in Fig. 2) is used, and if the lightpath to be dropped is assigned to an appropriate fiber (i.e., a designated fiber) and an appropriate (designated) band in the fiber, even fewer ports are needed. More specifically, only

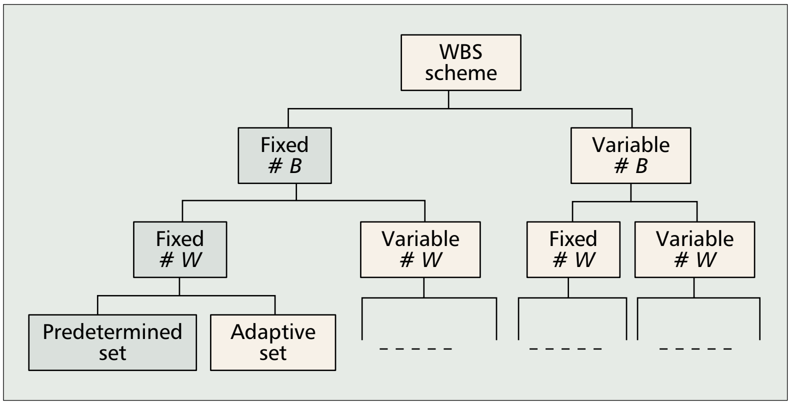


Figure 3. *Classification of the WaveBand Switching scheme.*

one fiber needs to be demultiplexed into 20 bands requiring only 9 ports for the other non-designated fibers. Furthermore, only one of the 20 bands demultiplexed from the designated fiber needs to be further demultiplexed into wavelengths, requiring only 19 ports for the other non-designated bands in the fiber. Finally, six ports are needed for the five wavelengths demultiplexed from the designated band and the add/drop wavelength. Hence, the total number of ports needed is only 9 + 19 + 6 = 34, more than 10 percent less than the multilayer MG-OXC and 96 percent less than the ordinary OXC.

WAVEBAND SWITCHING

In this section we introduce various WBS schemes and lightpath grouping strategies while we summarize the major benefit of using WBS in conjunction with MG-OXCs.

WAVEBAND SWITCHING SCHEMES

We first classify *WBS schemes* into two variations depending on whether the number of bands in a fiber (B) is fixed or variable, as in Fig. 3. 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., consists of consecutively numbered subsets of wavelengths) or can be adaptive (dynamically configured). For example, one variation could be to allow a variable number of wavelengths in a band at different nodes, with these wavelengths being chosen randomly (not necessarily consecutively). Such a variation may result in more flexibility (efficiency) in using MG-OXC than the variation shown shaded; on the other hand, the MG-OXC (especially its BXC) required to implement this variation may be too complex to be feasible with current and near future technology.

Hereafter, we concentrate on the variation shown shaded in Fig. 3, where each fiber has a fixed number of bands and each band has a fixed number as well as a fixed set of wavelengths, although the principles to be discussed can be extended to other WBS variations as well.

LIGHTPATH GROUPING STRATEGY

The following grouping strategies can be used to group lightpaths into wavebands.

- *End-to-end grouping*: grouping the traffic (lightpaths) with same source-destination (s-d) only
- *One-end grouping*: grouping the traffic between the same source (or destination) nodes and different destination (or source) nodes
- *Subpath grouping*: grouping traffic with common subpath (from any source to any destination)

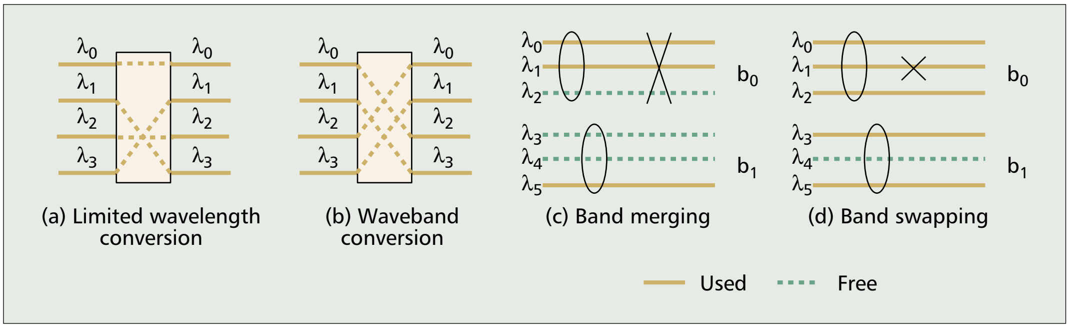
We can see that the third strategy is the most powerful (in terms of being able to maximize the benefits of WBS), although it is also the most complex to use in WBS algorithms.

MAJOR BENEFITS OF WBS NETWORKS

From the previous discussion and performance results (to be shown later), we see that WBS in conjunction with MG-OXCs can bring about tremendous benefits in terms of reducing the size (i.e., number of ports) of OXCs, which in turn reduces the size of the OEO grooming switch, as well as the cost and difficulty associated with controlling them. In addition to reducing the port count (which is a major factor contributing to the overall cost of switching fabrics), the use of bands reduces the number of entities that have to be managed in the system, and enables hierarchical and independent management of the information relevant to bands and wavelengths. This translates into reduced size (footprint) and power consumption, and simplified network management. Moreover, relatively small-scale modular switching matrices are now sufficient to construct large-capacity optical cross-connects, making the system more scalable. With WBS, some or most of the wavelength paths (or lightpaths) do not have to pass through individual wavelength filters, thus simplifying the multiplexer and demultiplexer design as well. In fact, cascading of FTB and BTW demultiplexers has been shown to be effective in reducing crosstalk [1], which is critical in building large-capacity backbone networks. Finally, all of these also result in reduced complexity of controlling the switch matrix, provisioning, and providing protection/restoration.

WAVEBAND ROUTING VS. WAVELENGTH ROUTING

Although a tremendous amount of work on wavelength-routed networks (WRNs) has been carried out, and wavelength routing is still fundamental to a WBS network, the work on WBS (and MG-OXCs) in terms of the *objective* and *techniques* are quite different from all existing work on WRNs. For example, a common objective in designing (dimensioning) a WRN is to reduce the number of required wavelengths or the number of used wavelength hops (WHs); see [7] for example. However, in WBS networks, the objective is to minimize the number of ports required by the MG-OXCs. As will be shown, minimizing the number of wavelengths or WHs



(a) Limited wavelength conversion (b) Waveband conversion (c) Band merging (d) Band swapping

■ **Figure 4.** *Waveband conversion and failure recovery.*

Having waveband conversion is similar to but not identical to having limited wavelength conversion, and even with full wavelength conversion, efficient WBS algorithms are still necessary to ensure the reduction in port count.

does *not* lead to minimization of the port count of the MG-OXCs in WBS networks [6], and even a simple WBS algorithm is not a trivial extension of the traditional routing and wavelength assignment (RWA) algorithm. In fact, our studies have indicated that when using the traditional optimal RWA algorithm (based on integer linear programming) with a best-effort lightpath grouping heuristic can *backfire* (i.e., result in an increase instead of decrease in the number of ports), and that an ideal WBS algorithm may need to trade a slight increase in number of wavelengths (or WHs) for a much reduced port count. While many optimization problems (e.g., optimal RWA) in WRNs are already NP-complete, some of the optimization problems have more constraints in WBS networks and accordingly are even harder to solve in practice.

Due to the differences in the objectives, techniques developed for WRNs (including, e.g., those for traffic grooming) cannot be directly applied to effectively address WBS-related problems. For example, techniques developed for traffic grooming in WRNs, which are useful mainly for reducing the electronics (e.g., SONET add-drop multiplexers) and/or number of wavelengths required (e.g., [8, 9]), cannot be directly applied to effectively group wavelengths into bands. This is because in WRNs, 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. However, in WBS networks, there is at least *one more constraint*: only the traffic carried by a fixed set of wavelengths (typically consecutive) can be grouped into a band.

WAVELENGTH AND WAVEBAND CONVERSION

Having waveband conversion is similar to but not identical to having limited wavelength conversion, and even with full wavelength conversion, efficient WBS algorithms are still necessary to ensure the reduction in port count. Note that in WRNs with full wavelength conversion, wavelength assignment is trivial. In WBS networks, on the other hand, although wavelength conversion does facilitate wavelength grouping (or banding), but performing wavelength conversion requires each fiber or band to be demultiplexed first into wavelengths, thus potentially increasing the number of ports needed (see an example in [6]). In other words, even if wavelength conversion itself would cost nothing, in order to minimize the port count of MG-OXCs, one can no longer use wavelength conversion *freely* to make up for careless wavelength assignment as is possible in WRNs with full wavelength conversion capability. For this reason, we should also explore the use of *waveband conversion* [10] in WBS networks, which differs from limited wavelength conversion studied in the context of WRNs (e.g., [11]) in that not only a given wavelength in a band b_i can be converted to a corresponding wavelength only in another band b_j, but also all other wavelengths in band b_i have to be converted to their corresponding wavelengths in b_j *at the same time*. For example, if we assume there are two wavelengths in each band (i.e., $\{\lambda_0, \lambda_1\} \in b_0$, $\{\lambda_2, \lambda_3\} \in b_1$, $\{\lambda_4, \lambda_5\} \in b_2$, …). Then with waveband conversion, converting band b_0 to bands b_1 or b_2 is similar to having limited conversion; that is, 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, as shown in Figs. 4a and 4b.

WAVEBAND FAILURE RECOVERY IN MG-OXC NETWORKS

Due to possible failures of the ports and multiplexers/demultiplexers within a MG-OXC, as well as possible failure of waveband converters, one or more wavebands in one or more fibers may be affected, but not the entire fiber or link (cable). Existing protection/restoration approaches deal only with failures of individual wavelengths and fiber/link failure. Hence, new approaches and techniques to provide effective protection and restoration based on the novel concept of *band segment* [6] become interesting, as does the use of waveband conversion and/or wavelength conversion to recover from waveband level failures. For example, in WRNs, one cannot merge the traffic carried by two or more wavelengths without going through OEO conversions (one may consider traffic grooming as a way to merge wavelengths through OEO conversion). However, in WBS networks we may use a new recovery technique that *merges* the critical traffic carried in a band affected by a waveband failure with the traffic carried by an unaffected band, without having to go through any OEO conversions.

For example, assume that a fiber has two bands, b_0 and b_1, each with three wavelengths such that λ_0 and λ_1 are used in b_0; so is λ_5 in b_1, *Given a network (whose parameters include topology, the nodal MG-OXC architecture, the number of wavelengths in each fiber, etc.), and a set of static traffic demands, how to satisfy the traffic demands while minimizing the number of required ports is the static offline WBS problem.*

Scenarios	OXC	WBO-RWA					BPHT				
		FXC	BXC	WXC	Total	WH	FXC	BXC	WXC	Total	WH
$B = 6, W = 20$	4042	84	504	3968	4556	2765	84	387	2436	2907	2792
$B = 15, W = 8$	4042	84	1224	3319	4627	2765	84	707	1218	2009	2790
$B = 20, W = 6$	4042	84	1575	3045	4704	2765	84	869	1042	1995	2796

Table 1. *Total number of ports in the NSF network.*

as in Fig. 4c. 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 band along a link-disjoint path, one may use a technique 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, respectively). 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. The band-merging technique can be implemented by simply converting λ_0 and λ_1 to λ_3 and λ_4, respectively; 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.

As another example (Fig. 4d), assume that all wavelengths except λ_4 are used, and 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.

PERFORMANCE OF WBS NETWORKS

In this section, we present numerical results of our heuristics for static and dynamic traffic for the multilayer MG-OXC networks. These results are obtained by using the corresponding WBS algorithms developed for static and dynamic traffic patterns, respectively, assuming that there is no wavelength conversion.

STATIC TRAFFIC

Given a network (whose parameters include topology, the nodal MG-OXC architecture as in Fig. 1, the number of wavelengths in each fiber, etc.), and a set of static traffic demands (i.e., set of lightpaths), how to satisfy the traffic demands while minimizing the number of required ports is the static offline WBS problem. To achieve optimal results for this problem, an ILP model was developed in [6]. However, for large networks the optimal solution is not feasible as solving the ILP becomes too time-consuming, and hence we employ heuristic algorithms for WBS to achieve near-optimal results. One such heuristic algorithm is called Balanced Path Routing with Heavy Traffic (BPHT) first waveband assignment, which tries to maximize the reduction in the MG-OXC size by using intelligent wavebanding [6]. To study the relationship between WBS and traditional RWA, a heuristic algorithm, which is completely oblivious to the existence of wavebands, called WBO-RWA that uses the ILP formulations developed for traditional RWA (to minimize the total number of used WHs) [6], and then tries to group the assigned lightpaths into bands is also considered.

Table 1 shows in detail the number of ports used by each of the algorithms for a random traffic pattern, and for varying numbers of band per fiber (i.e., B) and band size (i.e., W) in the NSF network. Note that the total number of wavelengths in a fiber is fixed in all the cases; hence, the second column (OXC) (i.e., the number of ports in an ordinary OXC) does not vary. Similarly, note that the WH column in WBO-RWA remains the same as the ILP for traditional optimal RWA tries to only minimize the WH and is not affected by the values of B and W. Columns FXC, BXC, and WXC represent the total number of ports at different layers. With increasing B, the ports of BXC layer increase; the ports of a WXC layer decrease; and the number of ports at the FXC layer remains the same.

From the table, we see that the performance of BPHT is much better than that of WBO-RWA, and in particular, BPHT can save about 50 percent of the total ports than using just ordinary OXCs. In addition, in the process of trying to reduce the total number of ports, BPHT uses more WHs than the ILP solution for RWA (i.e., WBO-RWA). This can be explained as follows: sometimes, to reduce port count, a longer path that utilizes a wavelength in a band may be chosen even though a shorter path (that cannot be packed into a band) exists. In other words, minimizing the number of ports at the MG-OXC does not necessarily imply minimizing the number of WHs (even though minimizing WHs in ordinary OXC networks is equivalent to minimizing the number of ports). In fact, there is a trade-off between the required number of WHs and ports.

Heuristic WBO-RWA, on the other hand, requires more ports at the MG-OXC than using ordinary OXCs, indicating that WBO-RWA is ill suited for networks with MG-OXCs. The reason for this is the use of a large number of multiplexer/demultiplexer ports, which also indicates that techniques developed for traditional RWA and grooming cannot be directly applied to WBS networks efficiently.

DYNAMIC TRAFFIC

How to minimize the number of ports required for a given set of static traffic demand is meaningful when building a greenfield WBS network. A more challenging problem is how to design WBS algorithms and MG-OXC architectures for dynamic traffic. As an example, we consider the use of a multilayer reconfigurable MG-OXC architecture (Fig. 1) and an efficient WBS algorithm called Maximum Overlap Ratio (MOR) to accommodate incremental traffic, wherein requests for new/additional lightpaths arrive one after the other, while existing connections stay indefinitely.

Unlike the static MG-OXC architecture, which has to have the maximum number of ports to guarantee that all the demands are satisfied, the reconfigurable MG-OXC requires only a limited port count. More specifically, if Y denotes the number of BXC ports from FTB demultiplexers, $\beta \leq 1$, the ratio of bands that can be demultiplexed to wavelengths (by using the BTW ports), this MG-OXC architecture is reconfigurable (and hence flexible) in that any βY bands can be demultiplexed into wavelengths simultaneously by appropriately configuring the MG-OXC. We show that even with *limited* reconfiguration (i.e., $\beta < 1$) and by using MOR, one can considerably reduce the port count required to satisfy dynamic incremental traffic with acceptable blocking probability.

The MOR algorithm performs efficient routing and wavelength (and waveband) assignment by modeling a WBS network as a band graph with B layers (one for each band). The algorithm finds up to K-shortest paths for a s-d pair in each layer of the *band graph* and tries to satisfy a lightpath by using a path in a band layer that maximizes the ratio of the overlap length (i.e., the number of common links with existing lightpaths in that band) to the total path length in hops.

Figure 5 shows the comparison of the blocking probability of the MOR algorithm with that of the traditional Random-Fit and First-Fit wavelength assignment algorithms, assuming that each new connection request has a random source and destination for the NSF network. We can see that the algorithm MOR is better than First-Fit, and much better than Random-Fit in terms of reducing the port number and blocking probability in WBS networks. In particular, we note that with MOR, increasing β to greater than 0.45 does not help in reducing the blocking probability any further because now blocking occurs *only* due to limited wavelength resources and not due to limited reconfiguration flexibility (e.g., ports). In fact, when $\beta = 0.45$, MOR achieves the *lowest* blocking probability and *greatest* reduction in port count. More specifically, only 2205 MG-OXC ports are required, compared to 3360 ports when using ordinary OXCs, which indicates we can achieve a 35 percent savings in the number of ports when using MG-OXCs instead of ordinary OXCs. Since increasing β further does not help in reducing the blocking, but, on the other hand, only unnecessarily increases the port count further, one may want to build in about 45 percent (but not more) BTW ports in a reconfigurable multilayer MG-OXC, and activate them when needed.

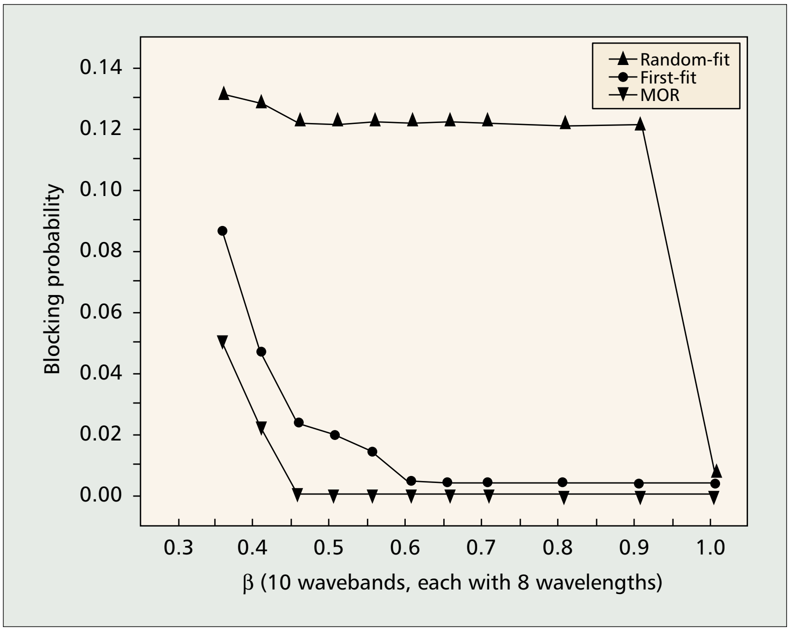


Figure 5. *Blocking probability vs. reconfiguration ratio for a multilayer MG-OXC.*

CONCLUSION

It is well known that optical cross-connects can reduce the size, and the cost and control complexity of electronic (e.g., OEO grooming switches) cross-connects. Waveband Switching is a key technique to reduce the cost and complexity associated with current optical networks with large photonic cross-connects (both electrical and optical cross-connects). Since techniques developed for wavelength-routed networks cannot be efficiently applied to WBS networks, new techniques are necessary to efficiently address WBS-related issues such as lightpath routing, wavelength assignment, lightpath grouping, waveband conversion, and failure recovery. In this article we have provided a comprehensive overview of the issues associated with WBS. In particular, we have classified the WBS schemes into several variations and described two multigranular OXC (MG-OXC) architectures for WBS: single-layer and multilayer.

We show that WBS networks using MG-OXCs can have a much lower port count when compared to traditional wavelength routed networks using ordinary OXCs. For example, for static traffic, a WBS heuristic algorithm called Balanced Path Routing with Heavy-Traffic (BPHT) uses about 50 percent fewer total ports than using just ordinary OXCs. For dynamic traffic, another heuristic algorithm called Maximum Overlap Ratio (MOR) can achieve about 35 percent savings in the number of ports. In addition, we show that 45 percent band-to-wavelength (BTW) ports are sufficient to maintain a low blocking probability using a reconfigurable MG-OXC. However, some of the issues such as the comparison of the single-layer and multilayer MG-OXC architectures, the impact of waveband conversion and survivability in WBS networks need further investigation.

Since techniques developed for wavelength-routed networks cannot be efficiently applied to WBS networks, new techniques are necessary to efficiently address WBS-related issues.

REFERENCES

[1] K. Harada *et al.*, "Hierarchical Optical Path Cross-connect Systems for Large Scale WDM Networks," *Proc. OFC,* 1999, pp. WM55–3.

[2] L. Noirie, M. Vigoureux, and E. Dotaro, "Impact of Intermediate Grouping on the Dimensioning of Multigranularity Optical Networks," *Proc. OFC*, 2001, pp. TuG3–3.

[3] O. Gerstel, R. Ramaswami, and W. Wang, "Making Use of A Two Stage Multiplexing Scheme in a WDM Network," *Proc. OFC*, 2000, pp. ThD1–3.

[4] R. Lingampalli and P. Vengalam, "Effect of Wavelength and Waveband Grooming on All-Optical Networks with Single Layer Photonic Switching," *Proc. OFC*, 2002, pp. ThP4.

[5] M. Lee *et al.*, "Design of Hierarchical Crossconnect WDM Networks Employing A Two-Stage Multiplexing Scheme of Waveband and Wavelength," *IEEE JSAC*, vol. 20, no. 1, Jan. 2002, pp. 166–71.

[6] X. Cao *et al.*, "Efficient Design of Waveband Switched Optical Networks," *Opt. Net. Mag.*, 2003 (an earlier version appeared in *OptiComm '02*, pp. 198–210).

[7] B. Mukherjee *et al.*, " Some Principles for Designing a Wide-area Optical Network," *IEEE/ACM Trans. Net.*, vol. 4, Oct. 1996, pp. 684–96.

[8] X. Zhang and C. Qiao, "An Effective and Comprehensive Approach for Traffic Grooming and Wavelength Assignment in SONET/WDM Rings," *IEEE/ACM Trans. Net.*, vol. 8, no. 5, Oct. 2000, pp. 608–17.

[9] O. Gerstel, P. Lin, and G. Sasaki, " Wavelength Assignment in a WDM Ring to Minimize the Cost of Embedded SONET Rings," *Proc. INFOCOM '98*, 1998, pp. 94–101.

[10] H. E. Escobar and L. R. Marshall, "All-optical Wavelength Band Conversion Enables New Scalable and Efficient Optical Network Architectures," *Proc. OFC*, 2002, pp. WH2.

[11] D. E. J. Yates, J. Lacey, and M. Summerfield, "Limited-range Wavelength Translation in All-Optical Networks," *Proc. INFOCOM'96*, 1996, pp. 954–61.

BIOGRAPHIES

XIAOJUN CAO (xcao2@buffalo.edu) received his B.S. degree from Tsinghua University, China, and his M.S. degree from the Chinese Academy of Sciences. He is currently pursuing a Ph.D. degree in the Department of Computer Science and Engineering, State University of New York at Buffalo. His current research interests include algorithms, performance evaluation, and optimization for optical networks as well as network architecture and modeling.

VISHAL ANAND (vanand@cse.buffalo.edu) received his M.S. and B.E. degrees in computer science and engineering from the State University of New York at Buffalo and the University of Madras, India, in 1999 and 1996. Currently, he is completing his Ph.D. at Buffalo, with a concentration in optical telecommunication networks. He has worked as a research scientist at Bell Laboratories, Lucent Technologies and Telcordia Technologies (ex-Bellcore), where he investigated issues relating to traffic routing and survivability in optical networks. He is the winner of the North America OPNET Scholarship from OPNET Tech., Inc., and the Outstanding Ph.D. Student award at Buffalo. His research interests are related to broadband communication networks (IP, ATM, SONET, WDM) and optical burst switching, and include network planning, modeling, internetworking, QoS, and network protocols.

CHUNMING QIAO (qiao@computer.org) is an associate professor at the State University of New York at Buffalo. He has over 12 years of academic and industrial experience in optical networks. He has published more than one hundred papers in leading technical journals and conference proceedings, and is recognized for his pioneering research on optical Internet and, in particular, the optical burst switching (OBS) paradigm. His work on integrated cellular and ad hoc networking systems (iCAR) is also internationally acclaimed. He was the IEEE Communication Society's Editor-at-Large for optical networking and computing until recently when he became an Area Editor of *IEEE Communications Magazine* for the new *Optical Communications Supplement*. He is also an editor of several other journals and magazines including *IEEE/ACM Transactions on Networking*, as well as a guest editor for *IEEE JSAC* and other publications. He has chaired and co-chaired many conferences and workshops on optical communications and networking, including Opticomm 2002. He is also the founder and chair of the Technical Group on Optical Networks sponsored by SPIE, and a vice chair of the IEEE Technical Committee on Gigabit Networking.