

Multi-Layer versus Single-Layer Optical Cross-connect Architectures for Waveband Switching

Xiaojun Cao

Department of Computer Science
and Engineering
State University of New York at Buffalo
Buffalo, New York 14260
Email: xiaojun@ieee.org

Vishal Anand

Department of Computer Science
SUNY College at Brockport
350 New Campus Drive
Brockport NY 14420
Email: vanand@brockport.edu

Chunming Qiao

Department of Computer Science
and Engineering
State University of New York at Buffalo
Buffalo, New York 14260
Email: qiao@computer.org

Abstract—Waveband Switching (WBS) in conjunction with Multi-Granular Optical Cross-connect (MG-OXC) architectures can reduce the cost and complexity of switching nodes. In this paper, we study two MG-OXC architectures: the Single-Layer and the Multi-Layer MG-OXCs, and compare their performances with both off-line (static) and on-line (dynamic) traffic. In the off-line case, we develop feasible near-optimal Integer Linear Programming models (called Off-ILP models) for each of the MG-OXC architectures that aim to reduce the size of the MG-OXC, and compare them with the Balanced Path routing with Heavy-Traffic first waveband assignment (BPHT) heuristic developed for the Multi-Layer MG-OXCs in [4]. The two architectures are then compared in terms of the number of wavelength hops (WH) and MG-OXC ports required to satisfy a given set of traffic demands. In the on-line case, we develop an on-line ILP model called On-ILP, which aims to minimize the number of used ports for each of the MG-OXC architectures, given a fixed number of wavelengths on each link. We also propose a novel efficient heuristic algorithm, called Maximum Overlap Ratio (MOR) to satisfy new requests and compare it with the On-ILP, First-Fit, and Random-Fit algorithms. We compare the two architectures in terms of the blocking probability, weighted (request) acceptance ratio, which serves as an indication of the revenue generated by satisfying the requests. We also study the impact of waveband size in the off-line and on-line cases.

Our results indicate that using WBS with either Single-Layer or Multi-Layer MG-OXCs can reduce the number of ports (hence the size and cost) of the switching nodes compared to using ordinary OXCs (without waveband switching). In particular, in the off-line case, using Single-Layer MG-OXCs provides a greater reduction in size than Multi-Layer MG-OXCs, while in the on-line case, using the Multi-Layer MG-OXC is better.

I. INTRODUCTION

The use of dense Wavelength Division Multiplexing (WDM) technology has significantly increased the available bandwidth in backbone networks. On the other hand, the rapid advances in dense WDM technology with hundreds of wavelengths per fiber and world-wide fiber deployment have brought about a tremendous increase in the cost and size of electronic cross-connects or DXCs (e.g., OEO grooming switches). Optical (photonic) cross-connects (OXCs) that switch bypass traffic all-optically are useful in reducing the cost and size of the

OEO grooming switches. However, when the number of wavelengths is large, traditional OXCs that switch traffic *only* at the wavelength granularity themselves will have a large number of wavelength ports, resulting in increased cost and control complexity. Recently, Waveband Switching (WBS) in conjunction with new Multi-Granular Optical Cross-connects (or MG-OXCs) that can switch traffic at fiber, waveband and wavelength granularities [1]–[9], has been proposed to reduce this cost and complexity. The main idea of WBS is to group several wavelengths together as a band, and switch the band using a single port whenever possible (e.g., as long as it carries only bypass or express traffic), and demultiplex it to switch the individual wavelengths only when some traffic needs to be added/dropped. As the bypass traffic accounts for 60% to 80% of the total traffic in the backbone, 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 number of ports of the MG-OXCs can be reduced by using WBS.

A. Prior Related Work

The concept of WBS based on two stage multiplexing was applied to WDM ring networks in [1], while its merits such as small-scale modularity, cross-talk and complexity reduction were summarized in [2]. A Three-Layer switching fabric consisting of a fiber cross-connect (FXC), a band cross-connect (BXC) and a wavelength cross-connect (WXC) was presented in [3], [10], and the application of such Three-Layer MG-OXC architectures to metro-area networks was briefly demonstrated in [11]. For such Multi-Layer MG-OXCs, limited analytic work for a few specific traffic patterns in rings was done in [12]. Hybrid hierarchical switches (with all-optical waveband switching and OEO traffic grooming) have been studied in [13], [14]. The work in [13] also studied the benefit of using non-uniform waveband hierarchy. The authors of [15], [16] presented MILP-based approaches for the design of a two-layer MG-OXC network using a simple lightpath grouping strategy, which does not take full advantage of the

benefits of wavebanding. However, *no* detailed algorithms or comparisons with other architectures was given. Issues related to multi-granularity optical switching and waveband grouping under the Generalized Multi-Protocol Label Switching (GMPLS) framework, such as signalling protocols and Link Management Protocols, have been partially addressed in [17], [18]. Recently, the authors in [7] proposed a Single-Layer MG-OXC architecture for WBS.

In our prior research [4], the most powerful lightpath grouping strategy, i.e., sub-path grouping for a Three-Layer MG-OXC architecture was adopted. In particular, we provided a general Integer Linear Programming (ILP) model, and an efficient heuristic called Balanced Path routing with Heavy-Traffic first waveband assignment (BPHT) for off-line static traffic in [4]. The ILP model and the BPHT heuristic were also extended to multi-fiber systems in [9], [19]. In [20], we discussed the differences between WBS and traditional Wavelength Routed Networks (WRNs) and provided an overview of the issues related to WBS such as survivability and wavelength/waveband conversion. The work in [20] provided only a qualitative discussion of the Single-Layer MG-OXC architecture but neither presented any specific WBS algorithms in detail nor provided any quantitative comparison results of the two architectures.

B. Overview of this Work

All existing performance evaluation work on WBS has been limited to *only* a specific MG-OXC architecture, and in addition, *only for the off-line case* (where a set of lightpath requests is known a priori). In this work, for the first time, we *quantitatively* compare the performance of the Single-Layer and the Three-Layer MG-OXCs¹ for *both off-line and on-line* (incremental traffic) cases. The Single-Layer and Three-Layer MG-OXC architectures for the on-line case are *different* from the corresponding Single-Layer and the Three-Layer architectures for the off-line case. More specifically, for the on-line case, where new lightpath requests need to be processed one at a time without knowledge of any future requests, we propose *novel reconfigurable* MG-OXC architectures. We also develop an on-line ILP model (On-ILP), which minimizes the used ports and the request blocking probability, given a fixed number of wavelengths and MG-OXC size. We then propose a new *efficient* heuristic algorithm, called Maximum Overlap Ratio (MOR) to carry dynamic incremental traffic and compare the performance of the two architectures using On-ILP, MOR and other heuristics such as First-Fit and Random-Fit.

In the off-line case, we develop a feasible (although near-optimal) off-line ILP model (Off-ILP) as opposed to the optimal ILP model in our earlier work in [9], [19] (which is not feasible for large systems) for each architecture, and compare the two architectures in terms of the number of wavelength hops (WH) and MG-OXC size (port count) required to satisfy a given set of traffic demands. Given the somewhat heuristic

¹From now on, we use the terms Multi-Layer MG-OXC and Three-Layer MG-OXC interchangeably.

nature of the Off-ILP models, we also compare Off-ILP with heuristic BPHT and show that Off-ILP can perform better than BPHT, which is better than other heuristics according to [4].

Our results show that the proposed Off-ILP can significantly reduce the computational complexity, while yielding close to optimal results. The comparison indicates that for the off-line case, the Single-Layer MG-OXC uses 15% fewer ports than the Three-Layer MG-OXC. On the other hand, for the on-line case, the Three-Layer MG-OXC achieves a lower request blocking probability (and a higher weighted acceptance ratio) than the Single-Layer MG-OXC. Further, we show that the proposed MOR algorithm can perform better than First-Fit, Random-Fit and even On-ILP. These results also provide valuable insights into the trade-offs between port counts and blocking probability. In addition, the novel heuristics proposed are especially useful for minimizing the number of used ports in a WDM network, and thus the network operating costs, while achieving a low blocking probability of requests. To the best of our knowledge, this is the first study of WBS algorithms (ILP and heuristics) for on-line traffic, and also the first quantitative comparison of the Three-Layer and Single-Layer MG-OXC architectures.

This paper is organized as follows. Section II describes and compares the Three-Layer and Single-Layer MG-OXC architectures for WBS. In Section III we present our near-optimal off-line ILP and the simulation results, which compare the performance of the Single-Layer and Three-Layer MG-OXC for off-line traffic. In Section IV, we describe the reconfigurable MG-OXC for on-line traffic, and describe our on-line ILP and heuristic algorithms. We then present simulation results that compare the performance of the Single-Layer and Three-Layer MG-OXC for dynamic traffic. Finally, we conclude the paper in Section V, with a summary of its major contributions.

II. MG-OXC ARCHITECTURES

In traditional optical networks, wavelengths terminate at, or transparently pass-through a node using an *ordinary-OXC*. Such ordinary-OXCs switch each individual wavelength using one port. On the other hand, 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. A complementary hardware is MG-OXC that not only can *switch* traffic at multiple levels (or granularities) such as fiber, waveband, and individual wavelength, but also may *add/drop* traffic at multiple levels, as well as *multiplex/demultiplex* traffic from one level to another.

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. Two principle MG-OXC architectures: the Three-Layer and Single-Layer, have been proposed in literature.

A. Three-Layer MG-OXC

Figure 1 shows the Three-Layer MG-OXC consisting of the *FXC*, *BXC* and *WXC* layers, which is similar to but *different* from the architectures studied in [4], [9], in that it is also *applicable to the on-line case* due to its reconfigurability based on the values of α and β (see Section IV for more details and definitions of X , Y , αX and βY). As shown in the figure, the *WXC*, *BXC* layers consist of cross-connect(s) and multiplexer(s)/demultiplexer(s). The *WXC* layer includes a wavelength cross-connect (*WXC*) that is used to switch bypass lightpaths. To add/drop wavelengths from the *WXC* layer, we need W_{add}/W_{drop} ports and multiplexers/demultiplexers. At the *BXC* layer, the waveband cross-connect (*BXC*), B_{add} and B_{drop} ports are used for bypass wavebands, added wavebands and dropped wavebands respectively. In addition, *BTW* ports are used to demultiplex wavebands to *WXC* layer and *WTB* ports are used to multiplex wavelengths from *WXC* layer to bands. Similarly, fiber cross-connect (*FXC*)/ F_{add}/F_{drop} ports are used to switch/add/drop fibers at the *FXC* layer. *FTB* and *BTF* ports are used to demultiplex fibers to wavebands, and multiplex wavebands to fibers, respectively. In order 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 or drop a lightpath. Otherwise, it will demultiplex the fiber into bands, and switch an entire band using one port at the *BXC* 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 the ordinary-OXCs, which needs to switch every wavelength individually using one port.

This architecture allows dynamic selection of fibers for multiplexing/demultiplexing from *FXC* layer to the *BXC* layer, and bands for multiplexing/demultiplexing from *BXC* to the *WXC* layer. For example, at the *FXC* layer, as long as there is a free *FTB* 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, in order to reduce the total port count in the off-line case or to reduce the request blocking probability (and the number of used ports) in the on-line case, efficient WBS algorithms are needed to determine the routing and wavelength (or waveband) assignment for the lightpaths.

B. Single-Layer MG-OXC

Compared to the previously described Three-Layer MG-OXC, the one shown in Figure 2 is a Single-Layer MG-OXC², which has never been detailedly studied in literature. As shown in the figure, this architecture has only *one* common switching

²It is different from the one studied in [7], in that it is *applicable to the on-line case* due to its reconfigurability based on the values of α and β .

fabric, which includes three *logical* divisions corresponding to the *FXC*, *BXC* and *WXC*, respectively.

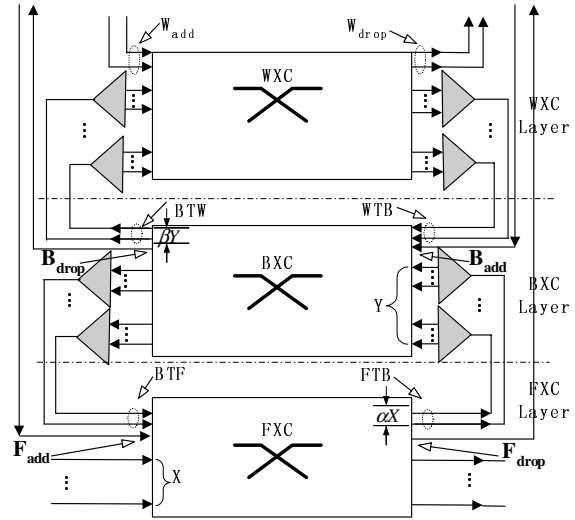


Fig. 1. Three-Layer Multi-Granular optical Cross-connect

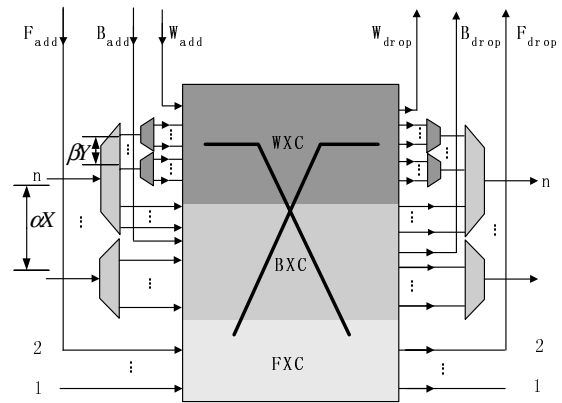


Fig. 2. Single-Layer Multi-Granular optical Cross-connect

However, the major differences (from the Three-Layer MG-OXC) are the elimination of *FTB*/*BTW* demultiplexers and *BTF*/*WTB* multiplexers between the 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 the Three-Layer MG-OXC, some of them may go through as many as three switching fabrics (i.e., *FXC*, *BXC* and *WXC*). As a trade-off, some incoming fibers, e.g., fiber n (see Figure 2), are pre-configured as *designated fibers*. Only these designated fiber(s) can have some of its bands dropped while the remaining bands bypass the node, all other non-designated 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 fiber(s), only designated band(s) can have some of its wavelengths dropped while the remaining bands bypass the node. Thus, the Single-Layer MG-OXC is simple, but not flexible in that it

does not allow lightpaths to be multiplexed/demultiplexed and grouped into bands arbitrarily, which may result in inefficient utilization of network resources. More specifically, in WBS networks with Single-Layer MG-OXC, 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 be always possible if there is only a limited number of designated fibers/bands, especially in the case of on-line traffic where global optimization for all lightpath demands is often difficult (if not impossible) to achieve. For this reason, a network with Three-Layer MG-OXC may in fact require fewer ports and wavelengths in order to satisfy all the on-line lightpath demands, or result in a better blocking performance (i.e., a lower blocking probability) for a given set of on-line lightpath demands with the same number of wavelength and ports.

In the remainder of the paper, we will develop ILP-based mathematical models and heuristic algorithms for the Three-Layer and Single-Layer MG-OXC networks, and compare the two architectures quantitatively for the off-line and the on-line cases.

Hereafter, we concentrate on one of the WBS schemes in [4], wherein each fiber has a fixed number (\mathcal{B}) bands and each band has a fixed number (\mathcal{W}) as well as a fixed set of wavelengths. Note that the ILP model and heuristic algorithms developed in this paper can be extended to the other WBS schemes (e.g., allowing variable number of bands per fiber) as well. With the current state of the art, wavelength conversion technology is still too immature (and expensive), hence, in this work we assume that there is no wavelength conversion. The case with wavelength conversion and other variations of the WBS scheme will be studied in the future.

III. Off-Line Waveband Switching Algorithms

Given a network (whose parameters include topology, the number of wavelengths in each fiber etc.), and a set of off-line traffic demands (i.e., set of lightpaths), how to satisfy the traffic demands while minimizing the size of MG-OXC is the off-line WBS problem. To achieve optimal results for this problem, we can apply the ILP model in [9], [19]. However, for large networks, since the optimal solution is intractable and in fact NP-complete, the optimal ILP becomes too time consuming and one must look for a near-optimal solution.

A. Off-Line ILP Model for static traffic (Off-ILP)

In this section, we develop a near-optimal solution based on ILP (called Off-ILP) by limiting the number of possible routes for each source-destination pair. Our objective is to be able to apply such an algorithm to medium to large sized networks and obtain better results than existing heuristic algorithms. Note that to limit the number of possible routing, new (different) variables and constraints from those in [9], [19] are needed. Below, we first present the near-optimal ILP model for the Three-Layer MG-OXC and then adapt it to suite the Single-Layer MG-OXC.

Notations: The following parameters are used by the ILP model.

I_n :	Set of input fibers at node n (excluding those for local add);
O_n :	Set of output fibers at node n (excluding those for local drop);
A_n :	Set of local add fibers at node n , including those used at the WXC, BXC and FXC layer;
D_n :	Set of local drop fibers at node n , including those used at the WXC, BXC and FXC layer;
IA_n :	$I_n \cup A_n$. This set includes the set of all incoming fibers (local and non-local) at node n ;
OD_n :	$O_n \cup D_n$. This set includes the set of all outgoing fibers (local and non-local) at node n ;
Λ_b :	Set of wavelengths in band b ;
\mathcal{X} :	Number of wavelengths per fiber;
\mathcal{B} :	Number of wavelength bands per fiber;
\mathcal{W} :	Number of wavelengths per wavelength band ($\mathcal{X} = \mathcal{B} \times \mathcal{W}$);
P :	Set of node pairs having non-zero traffic demand.
$T(p)$:	Traffic matrix whose element t_p is an integer, representing the traffic demand (i.e., number of lightpaths) for the node pair p ;
K :	Maximum number of paths that can be used for routing for a node pair;
$L_{k,p}$:	The set of links along the k^{th} shortest path of the node pair p ($1 \leq k < K$).

ILP Variables: To facilitate the presentation and understanding of our ILP model, we first define variable $V_{k,p}^w$ to help select one of the several shortest-paths.

$V_{k,p}^w$:	1 if a lightpath for the node pair p uses wavelength w along the k^{th} shortest path, and 0 otherwise;
---------------	---------------------------------------------------------------------------------------------------------------

To describe the drop/bypass/add traffic (lightpath) at a node, the following four variables: $S_{i,o}^{n,w}$, $W_{i,o}^{n,w}$, $B_{i,o}^{n,b}$ and $F_{i,o}^n$ are used, where $I_n \cup A_n$ is called incoming fiber and $O_n \cup D_n$ is called outgoing fiber. More specifically, when $i \in I_n, o \in O_n$, these variables represent bypass traffic; add traffic when $i \in A_n, o \in O_n$, and drop traffic when $i \in I_n, o \in D_n$ (note that the case when $i \in A_n, o \in D_n$ does not make sense).

$S_{i,o}^{n,w}$:	1 if at node n , there is a lightpath using wavelength w on an incoming fiber i to outgoing fiber o , and 0 otherwise;
$W_{i,o}^{n,w}$:	1 if node n has a lightpath using wavelength w on an incoming fiber i through the WXC layer onto an outgoing fiber o , and 0 otherwise;
$B_{i,o}^{n,b}$:	1 if node n has a set of lightpaths using waveband b ($b \in [1, 2, \dots, \mathcal{B}]$) on an incoming fiber i through the BXC layer onto an outgoing fiber o , and 0 otherwise;
$F_{i,o}^n$:	1 if node n has a set of lightpaths using an incoming fiber i through the FXC layer onto an outgoing fiber o , and 0 otherwise;

The following four additional variables are also defined for describing the multiplexing/demultiplexing at the FXC, BXC and WXC layers.

FTB_i^n :	1 if input fiber i ($i \in I_n$) needs to be demultiplexed into bands at node n , and 0 otherwise;
$BTW_i^{n,b}$:	1 if band b on input fiber i ($i \in I_n$) needs to be demultiplexed into wavelengths at node n , and 0 otherwise;
$BTFO^n$:	1 if a band needs to be multiplexed onto an output fiber o ($o \in O_n$) at node n , and 0 otherwise;
$WTB_o^{n,b}$:	1 if a wavelength needs to be multiplexed on to band b of an output fiber o ($o \in O_n$) at node n , and 0 otherwise;

Objective Function: There are two reasonable objectives. The first is to minimize the total cost associated with the MG-OXC ports in the network, which is:

$$\min [\tau \times \sum_{n,i,o,w} W_{i,o}^{n,w} + v \times \sum_{n,i,o,b} (B_{i,o}^{n,b} + WTB_o^{n,b} + BTW_i^{n,b}) + \phi \times \sum_{n,i,o} (F_{i,o}^n + BTFO^n + FTB_i^n)] \quad (1)$$

where τ, v and ϕ are the coefficients or weights corresponding to the cost of each port at the WXC, BXC and FXC layers, respectively. When $\tau = v = \phi = 1$, the objective becomes to minimize the total number of MG-OXC ports in the network.

The second objective is to minimize the maximum cost at each node over all nodes. This can be formulated as:

$$\min_n \max_n [\tau \times \sum_{i,o,w} W_{i,o}^{n,w} + v \times \sum_{i,o,b} (B_{i,o}^{n,b} + WTB_{i,o}^{n,b} + BTW_{i,o}^{n,b}) + \phi \times \sum_{i,o} (F_{i,o}^n + BTF_{i,o}^n + FTB_{i,o}^n)] \quad (2)$$

When $\tau = v = \phi = 1$, this becomes equal to minimizing the maximum port count (node size) over all the nodes in the network.

Constraints: Equations (3) and (4) ensure that every traffic demand is satisfied, and each is assigned wavelength resources along its route.

$$\sum_{w,k} V_{k,p}^w = t_p \quad \forall p; \quad (3)$$

$$S_{i,o}^{n,w} \geq V_{k,p}^w \quad \forall k, p, w, i, o \in L_{k,p}; \quad (4)$$

For Waveband Switching, we need the following additional constraints.

$$1 \geq F_{i,o}^n + B_{i,o}^{n,b} + W_{i,o}^{n,w} \geq S_{i,o}^{n,w} \quad \forall w \in \Lambda_b, i \in IA_n, o \in OD_n; \quad (5)$$

$$1 \geq F_{i,o}^n + \sum_{o_1 \neq o} S_{i,o_1}^{n,w}, \quad 1 \geq F_{i,o}^n + \sum_{i_1 \neq i} S_{i_1,o}^{n,w} \quad \forall w, i, o; \quad (6)$$

$$1 \geq B_{i,o}^{n,b} + \sum_{o_1 \neq o} S_{i,o_1}^{n,w}, \quad 1 \geq B_{i,o}^{n,b} + \sum_{i_1 \neq i} S_{i_1,o}^{n,w} \quad \forall i, o, w \in \Lambda_b; \quad (7)$$

Constraints (5) – (7) ensure that if a lightpath uses wavelength w belonging to band b of incoming fiber i and outgoing fiber o (i.e., $S_{i,o}^{n,w} = 1$), then at node n ,

- exactly one of FXC, BXC and WXC cross-connect port will be used for switching this lightpath when it is a bypass (i.e., $i \in I_n, o \in O_n$) or
- exactly one of F_{add}, B_{add} and W_{add} port will be used for adding this lightpath when it is added (i.e., $i \in A_n, o \in O_n$) or
- exactly one of F_{drop}, B_{drop} and W_{drop} port will be used for dropping this lightpath when it is dropped (i.e., $i \in I_n, o \in D_n$)

In addition, the constraint below ensures that a wavelength w at node n switched or added at the WXC layer has to pass a WTB multiplexer to the BXC layer. At the same time, every band from a WTB multiplexer has to pass a BTF multiplexer before it can leave node n .

$$BTF_{i,o}^n \geq WTB_{i,o}^{n,b} \geq W_{i,o}^{n,w} \quad \forall w \in \Lambda_b, o \in O_n, i \in IA_n; \quad (8)$$

Similarly, Equation (9) below specifies that a wavelength w switched or dropped at the WXC layer has to come from BXC layer using a BTW demultiplexer, and in addition every band demultiplexed by BTW can only come from a FTB demultiplexer.

$$FTB_{i,o}^n \geq BTW_{i,o}^{n,b} \geq W_{i,o}^{n,w} \quad \forall w \in \Lambda_b, o \in OD_n, i \in I_n; \quad (9)$$

Finally, any bypass or add bands should pass a BTF multiplexer as specified in equation (10) and similarly, any drop

or bypass band can only come from a FTB demultiplexer as specified in Equation (11) .

$$BTF_{i,o}^n \geq B_{i,o}^{n,b} \quad \forall o \in O_n, i \in IA_n; \quad (10)$$

$$FTB_{i,o}^n \geq B_{i,o}^{n,b} \quad \forall o \in OD_n, i \in I_n; \quad (11)$$

Compared to the ILP model in [9], [19], the above K-shortest path based Off-ILP model is more flexible. For example, if we set $K = 1$, the ILP will use *only* one (i.e., the first shortest path) for routing the lightpath between every node pair, and assign wavelengths such that the port count is minimized. However, if we set $K = \infty$, the ILP will search as many routes as the ILP model in [9], [19]. By restricting K , we reduce the search space of the ILP, so that we can get a near-optimal solution in a reasonable time. Our experiments show that the above ILP model can be applied to moderately large network systems, whereas the ILP model in [9], [19] can only be applied to very small network systems.

The above Off-ILP is used to minimize the port count and the number of multiplexers/demultiplexers in a network with Three-Layer MG-OXCs. By ignoring (i.e., not counting) the ports for FTB/BTF and BTW/WTB , we can also apply it to WBS networks with Single-Layer MG-OXCs, and hence, the detailed formulations is omitted.

B. Numerical Results

In this section, we compare the performance of Three-Layer and Single-Layer MG-OXCs using the above Off-ILP model for the off-line case in a 14-node NSF network. We set $\tau = v = \phi = 1$ in the objective equation (1) and use the CPLEX ILP solver to obtain numerical results. To evaluate the performance of each approach, we define the following three *performance-metrics*.

- Total port number ratio :
$$\frac{\text{Total port count when using MG-OXCs}}{\text{Total port count when using ordinary-OXCs}}$$
- Max port number ratio:
$$\frac{\text{Maximum port count (node size) over all MG-OXC nodes}}{\text{Maximum port count (node size) over all ordinary-OXC nodes}}$$
- Used wavelength-hop ratio:
$$\frac{\text{Wavelength-hops required for WBS using MG-OXCs}}{\text{Wavelength-hops required in WRNs using ordinary-OXCs}}$$

Our experiments show that the best performance is achieved by setting K (i.e., the number of possible routes for a node pair) to 3, and increasing K further only increases the computation time. Hence, the following results are obtained using $K = 3$. We also show the performance of the Three-Layer and Single-Layer MG-OXC when the BPHT heuristic developed in [9], [19] is used. The optimal ILP model is not considered here because it is not feasible for the 14-node network and in addition, it has already been shown in [9], [19] that for a small network, its performance can be approximated by BPHT.

Figures 3 to 5 illustrate how the Total port number ratio, Maximum port number ratio and used WH ratio vary with changing waveband granularity (i.e., the number of wavelengths in a band) when the number of wavelengths per fiber is

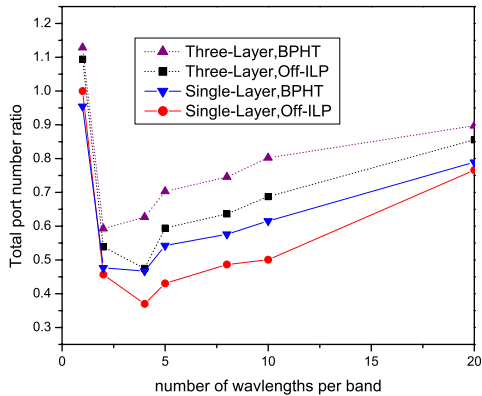


Fig. 3. Total port number ratio: Off-line Traffic

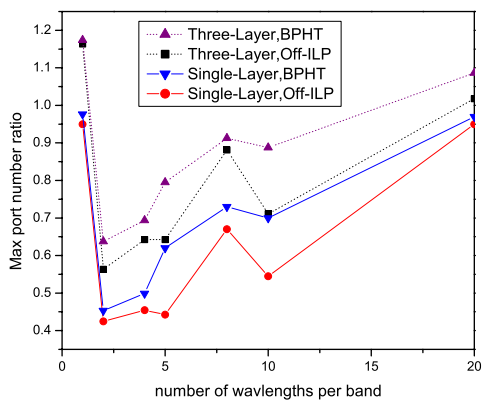


Fig. 4. Max. port number ratio: Off-line Traffic

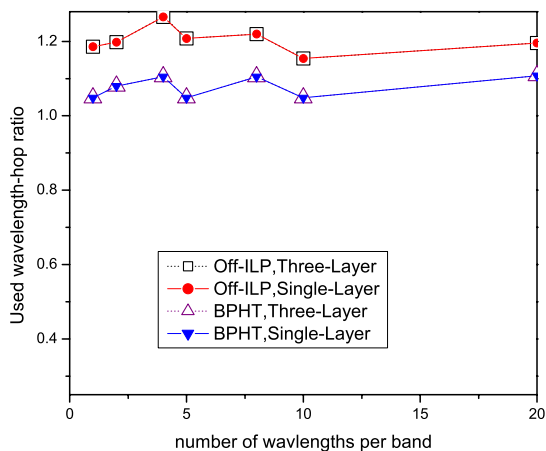


Fig. 5. Used Wavelength-hop ratio: Off-line Traffic

fixed. From the figures, we notice that the total number of ports in the network and the maximum number of ports at a node among all nodes by using Single-Layer MG-OXC is less than that required by using Three-Layer MG-OXC. We also note that the near-optimal ILP model (Off-ILP) proposed above is better than the heuristic BPHT in [9], [19]. Specifically, using Single-Layer MG-OXC requires about 15% fewer ports (either total or maximum) than using Three-Layer MG-OXC (when either the Off-ILP or BPHT is used). This can be explained as follows. When switching a lightpath 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 lightpath is switched only once (using one input and one output port) at every node, resulting in fewer ports.

The above figures (e.g., Figure 3) also indicate that with an appropriate wavelength granularity ($\mathcal{W} \simeq 4$), using the Off-ILP model for WBS (with Single-Layer and Three-Layer MG-OXC) can achieve more than 50% reduction in the number of ports when compared to using ordinary OXC.

From Figure 5, we can see that the number of used WHs is the same when using Single-Layer and Three-Layer MG-OXC in a WBS network. The wavelength-hop ratio does not change much with the waveband granularity and exceeds 1 by a *small percentage*, which means that using MG-OXC increases WHs (when compared to the case using ordinary OXC); a price paid for the reduction in the total number of ports. This trade-off between port count and WHs 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 WHs (even though minimizing WHs in ordinary-OXC networks is equivalent to minimizing the number of ports). Such a trade-off between the required number of WHs and ports was also discussed for Three-Layer MG-OXC networks in [4], [9], [19].

IV. On-Line Waveband Switching Algorithms

The off-line problem studied so far is meaningful when building a green-field WBS network. Another challenging problem, which has never been studied before is how to design WBS algorithms for the on-line case, given an existing MG-OXC architecture and network. In this section, we describe a reconfigurable MG-OXC architecture and on-line WBS algorithms to handle incremental traffic, i.e., establish new/additional lightpaths while existing connections stay indefinitely.

The Three-Layer MG-OXC architecture we consider for dynamic traffic is similar to the MG-OXC in Figure 1. However, unlike in the off-line case, where the MG-OXC can have as many port as needed to guarantee that all the demands

are satisfied, here, the MG-OXC has only a predetermined limited port count. More specifically, let X denote the number of incoming fibers, Y the number of BXC ports from FTB demultiplexers, $\alpha \leq 1$ the ratio of fibers (to the total number of fibers) that can be demultiplexed into bands using FTB ports, and similarly, $\beta \leq 1$ the ratio of bands that can be demultiplexed to wavelengths using BTW ports. The proposed Three-Layer MG-OXC architecture is reconfigurable (and hence flexible) in that *any* $\lceil \alpha X \rceil$ fibers can be demultiplexed into bands and *any* $\lceil \beta Y \rceil$ of these bands can be demultiplexed into wavelengths simultaneously by appropriately configuring the MG-OXC. We show that even with *limited* reconfiguration (i.e., $\alpha < 1$ and $\beta < 1$), we can use an intelligent algorithm (e.g., the proposed MOR for routing and wavelength/waveband assignment) to considerably reduce the port count required to satisfy dynamic incremental traffic with an acceptable request blocking probability.

The total number of ports at such a reconfigurable, Three-Layer MG-OXC node n can be calculated as in Equation (12).

$$MG-OXC_n = \lceil (1+\alpha) \times X + (1+\beta) \times Y + \beta \times Y \times W + W_{add/drop} \rceil \quad (12)$$

Note that when $\alpha = 1, \beta = 1$, there is no limitation on the number of fibers/bands that can be multiplexed/ demultiplexed, and hence, the blocking of a lightpath request can only come from the limited number of wavelengths as in an ordinary-OXC network. If we consider single-fiber systems and let δ be the degree of node n , we have $X = \delta, Y = \lceil \alpha \times X \times B \rceil$. For an ordinary-OXC that only switches individual wavelengths, the number of ports at node n is $OXC_n = \lceil \delta \times B \times W + W_{add/drop} \rceil$. Accordingly, if we ignore the $W_{add/drop}$ ports (which are common to both the Three-Layer reconfigurable MG-OXC and ordinary-OXC), Equation (13) gives the ratio of the port count in a Three-Layer MG-OXC to the port count in an ordinary-OXC, denoted by T_3 .

$$\begin{aligned} T_3 &= \frac{\lceil (1+\alpha) \times \delta + (1+\beta) \times \alpha \times \delta \times B + \alpha \times \beta \times \delta \times B \times W \rceil}{\lceil \delta \times B \times W \rceil} \\ &\simeq \beta \times \alpha + \frac{(1+\beta) \times \alpha}{W} \end{aligned} \quad (13)$$

Similarly, Equation (14) gives the ratio of the port count in a Single-Layer MG-OXC to the port count in an ordinary-OXC, denoted by T_1 .

$$T_1 \simeq \beta \times \alpha + \frac{(1-\beta) \times \alpha}{W} \quad (14)$$

The difference between T_3 and T_1 is due to the fact that there are *no* FTB/BTF and BTW/WTB ports in the Single-Layer MG-OXC architecture, which are present in the Three-Layer MG-OXC architecture. From Equations (13) and (14), we see that, in order to reduce the port count by using MG-OXCs instead of ordinary-OXCs, the values of α and β need to be constrained so as to ensure that $T_3 < 1$ and $T_1 < 1$. 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.

Below, we propose on-line ILP formulations and heuristics algorithms based on K-shortest paths for networks with either Three-Layer or Single-Layer architectures, and then compare the two architectures.

A. On-Line ILP model for dynamic traffic (On-ILP)

In this section, we extend the Off-ILP model in Section III-A to accommodate new lightpaths assuming that existing connections stay indefinitely and are non-rearrangeable. Equations (15) and (16) are the additional constraints for Three-Layer MG-OXC architecture, which constrain the total number of bands that can be demultiplexed/multiplexed using the BTW/WTB ports³.

$$\sum_{o,b} WTB_o^{n,b} \leq \lceil \delta \times \beta \rceil \quad \forall n \quad (15)$$

$$\sum_{i,b} BTW_i^{n,b} \leq \lceil \delta \times \beta \rceil \quad \forall n \quad (16)$$

In the Single-Layer MG-OXC architecture, the choice of the designated bands (i.e., which bands can be demultiplexed into wavelengths) is critical. Since the traffic carried by a designated band at one node may bypass at another node, we cannot set the same band(s) as the designated bands for every node in the network. Therefore, the subset of designated bands at each node will be randomly selected in this study. We use the following two additional parameters denoting the setting of designated band(s) and associated multiplexers/demultiplexers at every node.

$$\begin{aligned} EBTW_i^{n,b}: & \quad 1 \text{ if band } b \text{ on input fiber } i \text{ (} i \in I_n \text{) can be demultiplexed into} \\ & \quad \text{wavelengths at node } n, \text{ and } 0 \text{ otherwise;} \\ EWTB_o^{n,b}: & \quad 1 \text{ if wavelengths can be multiplexed on to band } b \text{ of an output fiber} \\ & \quad o \text{ (} o \in O_n \text{) at node } n, \text{ and } 0 \text{ otherwise;} \end{aligned}$$

The probability that the above variables will be set to 1 (i.e., a band b is assigned as a designated band) is equal to β . Similarly, Equations (17) and (18) constrain the number of designated bands at a node in the Single-Layer MG-OXC.

$$WTB_o^{n,b} \leq EWTB_o^{n,b} \quad \forall o, n, b \quad (17)$$

$$BTW_i^{n,b} \leq EBTW_i^{n,b} \quad \forall i, n, b \quad (18)$$

Similar to the Off-ILP, the On-ILP searches only a limited number (K) of routes to decrease the computational complexity. On the other hand, unlike the Off-ILP, which can reduce the port count by considering *all* the lightpath requests, the On-ILP can *only* reduce the additional ports by appropriately routing the new lightpath request (as reconfiguration of existing lightpaths is not allowed).

B. On-line heuristic algorithms for dynamic traffic

We now propose a novel Maximum Overlap Ratio (MOR) algorithm⁴, whose objective is to minimize the request blocking probability by performing efficient routing and wavelength (and waveband) assignment in WBS networks for on-line traffic.

Given that there is no wavelength or waveband conversion in the MG-OXCs, we model a WBS network (for example Figure 6(a)) using \mathcal{B} *band-graphs* (one for each band) as in Figure 6(b). The nodes in each band-graph correspond to the nodes

³Since we have set $\alpha = 1$, there is no constraint on the number of FTB/BTF ports.

⁴This algorithm was briefly mentioned in [20] for only the Three-Layer MG-OXC, without any detailed description and algorithm.

in the physical network topology, while the links between the nodes correspond to the existence of that band between the nodes. For a new lightpath demand for a node pair p , we first find up to K -shortest paths (denoted by $R_1^b, R_2^b, \dots, R_K^b$) in each band-graph b , such that each path R_k^b has at least one free wavelength that can be used to establish the lightpath. We then determine the weight denoted by Q_k^b of the k^{th} ($1 \leq k \leq K$) shortest path in band b .

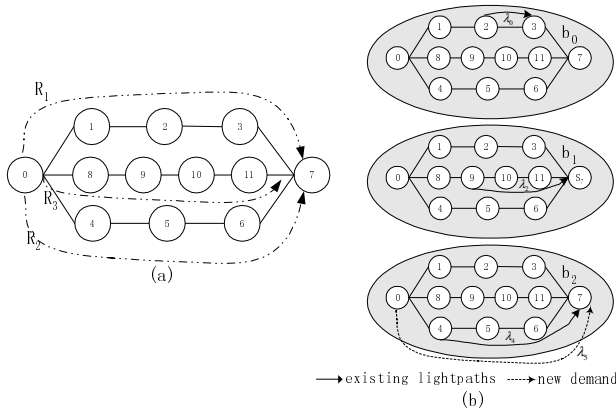


Fig. 6. Determining the weight of each of the K -shortest paths using band graphs

Intuitively, in order to satisfy a new lightpath demand with as few additional ports as possible, it is better to route a new lightpath along a path R_k^b that has maximum number of links in common with all the existing lightpaths established in band b . On the other hand, to avoid the wastage of wavelength resources (WHs), it is better to route along a shortest possible path. To achieve a balance, we set Q_k^b to be L/H , where H is the number of hops (in path R_k^b) and L is the sum of overlap length (number of links in common with all existing lightpaths) in band b . Algorithm MOR chooses a path R_k^b that has the maximum weight Q_k^b , to route the new lightpath and assigns the first available wavelength along R_k^b to the lightpath.

For example, suppose each fiber has three bands b_0, b_1 and b_2 , and each band has two wavelengths: $(\lambda_0, \lambda_1) \in b_0, (\lambda_2, \lambda_3) \in b_1, (\lambda_4, \lambda_5) \in b_2$ as shown in Figure 6(b). Now assume a new request for a lightpath from node 0 to node 7 arrives, for which three paths $R_1^{b_i}, R_2^{b_i}$ and $R_3^{b_i}$ are available in each band b_i , where $i = \{1, 2, 3\}$, as shown in Figure 6(a). The maximum weight is $Q_{k_2}^{b_2} = 3/4$ (note that $Q_{k_1}^{b_0} = 1/4$ and $Q_{k_3}^{b_1} = 3/5$), hence the new lightpath will use λ_5 in band b_2 on path $0 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7$, as indicated by the dashed line in Figure 6(b). Such grouping of lightpaths allows the use of the already existing (in use) ports at node S_4, S_5 and S_6 , leaving more unused ports for future requests.

One of the variations of MOR is to maximize L (the overlap length) only, by setting Q_k^b equal to L instead of L/H . We have compared MOR and its variations and found that maximizing the L/H ratio performs the best, and hence will show only the results obtained from MOR hereafter.

C. Numerical results

In this section, we study the performance of various on-line WBS algorithms, and compare the performance of networks using Three-Layer and Single-Layer MG-OXC. The network topology considered is same as the 14-node NSF network. Since different algorithms tend to satisfy (or block) different set of connection requests, it is not sufficient to use blocking probability only as the performance metric, as it may not be fair to state that an algorithm which blocks a long request is necessarily better than another which blocks two short requests.

Hence, to facilitate a fair comparison of the algorithms, we also use an algorithm-independent performance metric called *weighted acceptance ratio*. Specifically, given a lightpath request l from s to d , let H_l denote the number of hops along the (first) shortest path from s to d and θ_l indicate whether this request is satisfied or not (i.e., $\theta_l = 1$ when request l is satisfied, and $\theta_l = 0$ when the request l is blocked/rejected). Then, the weighted acceptance ratio is defined to be.

$$\text{Weighted Acceptance Ratio} = \frac{\sum H_l \times \theta_l}{\sum H_l} \quad (19)$$

Figures 7 to 12 illustrate how the request blocking probability, weighted acceptance ratio and the used WHs vary with changing β (i.e., the ratio of bands that can be demultiplexed/multiplexed shown in Figures 1 and 2) when the number of wavelengths per band is fixed at $\mathcal{W} = 5$, and the number of bands per fiber is $\mathcal{B} = 16$ (and hence the total number of wavelengths per fiber is 80). We set the number of shortest paths to be considered, $K = 3$ for MOR, On-ILP and heuristics Random-Fit and First-Fit. The heuristic Random-Fit routes the new lightpath request along the shortest possible path assigning it a random wavelength⁵ (in a random band). Heuristic First-Fit, on the other hand, routes the new lightpath request along the shortest possible path assigning it the first available wavelength.

1) *Three-Layer MG-OXC*: From Figures 7 and 8, we note that when $\beta \simeq 0.55$ (i.e., in Equation 13, $T_3 \simeq 0.85$), MOR achieves the *lowest* blocking probability. Increasing β to greater than 0.55 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 arising from the constraint on port counts. In other words, no more than 55% of the bands need to be demultiplexed into wavelengths (and increasing β further will only unnecessarily increase the port count). In fact we need to keep $\beta < 0.8$ in order to take advantage of Three-Layer MG-OXC (i.e., to ensure $T_3 \leq 1$). One of the practical implications of this result is that one may want to build-in about $\beta = 55\%$ (but not more) BTW ports, and use them when needed (i.e., as new connection requests arrive).

⁵As mentioned earlier, [20] presented results for Three-layer MG-OXC only without any algorithms. In addition, the Random-Fit algorithm studied here is quite different, in that only the wavelength assignment for a new lightpath request is random.

When $\beta = 55\%$, the ratio of the port count in a Three-Layer MG-OXC to the port count in an ordinary-OXC is $T_3 \approx 0.85$, which indicates we can achieve a 15% savings in the number of ports when using Three-Layer MG-OXCs instead of ordinary-OXCs.

We can also see that in a WBS network for a given value of β , MOR is better than On-ILP, and much better than Random-Fit in terms of reducing the request blocking probability or increasing weighted acceptance ratio. Although it has been shown [21]–[23] that in WRNs, Random-Fit performs almost as well as First-Fit, the same is not true in WBS networks. Figures 7 and 8 show that Random-Fit is ill-suited for WBS networks. The reason for the poor performance of Random-Fit in WBS networks is that, unlike First-Fit it does not take waveband grouping into consideration. First-Fit, on the other hand, is very likely to assign wavelengths to lightpaths sequentially, which helps in wavebanding and thus reducing the number of used ports and blocking probability. Since the objective of On-ILP is to minimize the number of additional ports for each new request, it cannot minimize the overall port counts by performing a global optimization over all lightpath requests. In other words, the On-ILP is short-sighted in that it will assign paths and wavelengths to the initial set of traffic demands so as to minimize the port count in the beginning. However, this initial greedy path and wavelength assignment, hurts its performance, when it has to assign more ports to future traffic demands, hence increasing its blocking probability. From Figure 9 one can see that On-ILP also uses more wavelength-hops compared to other algorithms.

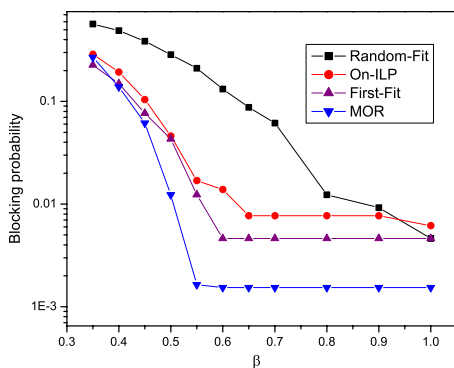


Fig. 7. Blocking Probability in Three-Layer MG-OXCs

2) *Single-Layer MG-OXC*: The fact that in Single-Layer MG-OXCs the designated bands are allocated randomly at different nodes reduces the chance of wavebanding and hence increases the blocking probability considerably. For example, it may happen that a node has no additional designated bands available to add/drop traffic even though there are enough resources (e.g., ports or wavelengths) at the intermediate nodes/links. Hence, the blocking probability of the Single-Layer MG-OXC network is higher than that of the Three-Layer MG-OXC network.

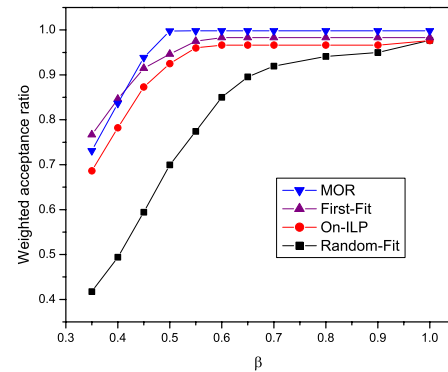


Fig. 8. Weighted acceptance ratio in Three-Layer MG-OXCs

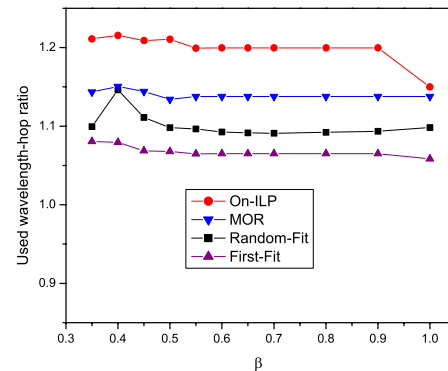


Fig. 9. Used Wavelength-hop ratio in Three-Layer MG-OXCs

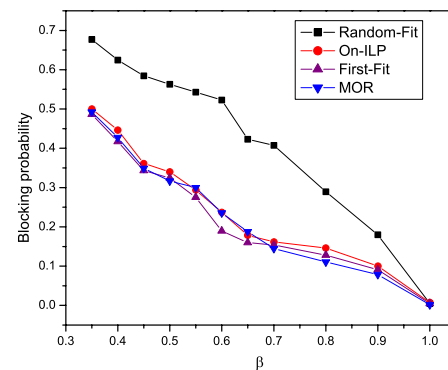


Fig. 10. Blocking Probability in Single-Layer MG-OXCs

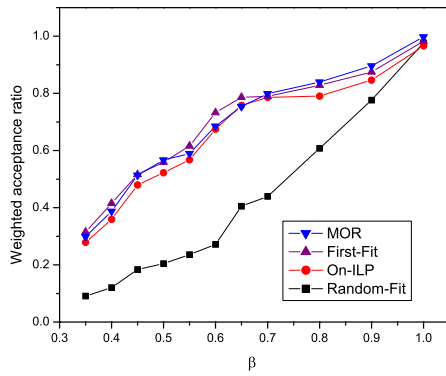


Fig. 11. Weighted acceptance ratio in Single-Layer MG-OXC

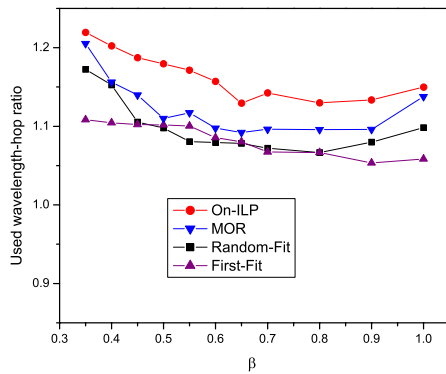


Fig. 12. Used Wavelength-hop ratio in Single-Layer MG-OXC

Figures 10 and 11 shows the request blocking probability and weighted acceptance ratio of Single-Layer MG-OXC. Compared to Figures 7 and 8, we notice that the blocking probability of the Three-Layer MG-OXC network is much lower (up to 10 times) than that of the Single-Layer MG-OXC network when both are equipped with the same number of ports. For example, when the ratio $T_3 = T_1 = 0.8$ (by setting $\beta = 0.5$ for Three-Layer MG-OXC in Figure 7 and $\beta = 0.75$ for Single-Layer MG-OXC in Figure 10, respectively), the blocking probability of the Three-Layer MG-OXC network is less than 0.01 (when using MOR) while that of the Single-Layer MG-OXC network is about 0.1, which indicates that Three-Layer MG-OXC are more suitable for dynamic traffic.

As in the case of using Three-Layer MG-OXC (see Figure 9), there is also a trade-off between the used ports and WHs when using Single-Layer MG-OXC as shown in Figure 12. However, unlike in the networks using Three-Layer MG-OXC, in networks using Single-Layer MG-OXC, First-Fit seems to perform the best with MOR being a close second when $\beta < 0.7$.

3) *Effect of Waveband Granularity*: Our results show that, in networks using Three-Layer MG-OXC, the lowest blocking probability may be achieved when a waveband contains 2

to 8 wavelengths, depending on the traffic and the value of β . Due to space limitation, we only show the effect of the waveband granularity (i.e., number of wavelength in a band) on the blocking probability in networks using Three-Layer MG-OXC when $\beta = 0.55$ (which is the most desirable value of β). We can see from Figure 13 that with an appropriate waveband granularity ($\mathcal{W} \simeq 5$), using MOR achieves the lowest blocking performance. The existence of an optimal band granularity \mathcal{W} is because for a given traffic pattern and WBS algorithm such as MOR, increasing \mathcal{W} to a certain value helps in reducing the number of ports at both the BXC and WXC layers that are used to accommodate a given set of requests due to increased wavebanding, thus freeing up other ports for future requests. This helps reduce the blocking probability. On the other hand, increasing \mathcal{W} further will make it difficult to effectively group wavelengths into bands. Large \mathcal{W} causes more wavelengths in the bands to go unused, or more bands to be demultiplexed into wavelengths (implying that more ports at the BXC and WXC layers will be used), thus resulting in a higher blocking probability.

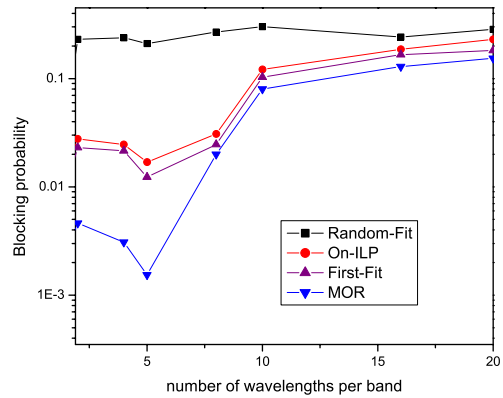


Fig. 13. Blocking Probability in Three-Layer MG-OXC

Our other results, though not included here, show that in networks using Single-Layer MG-OXC, the blocking probability increases with the band granularity, and there is no optimal band size \mathcal{W} . This is because the designated bands are allocated randomly at different nodes and thus increasing \mathcal{W} will not help much in reducing the number of used ports, but will only increase the blocking probability due to the under-utilization of the wavelengths in bands or ineffective grouping of the wavelengths.

V. CONCLUSION

Waveband Switching (WBS) in conjunction with Three-Layer and Single-Layer Multi-Granular Optical cross-connect (or MG-OXC) architectures has been proposed to reduce the increasing costs and complexity in optical networks. In this paper we have for the first time, conducted a comprehensive and quantitative performance comparison of the two architectures for both off-line and on-line traffic. For the off-line

case, we have provided feasible (though near-optimal) Integer Linear Programming models, which is shown to be better than existing heuristics, and thus is a preferred choice for medium to large sized networks. We have also shown that for off-line traffic using Single-Layer MG-OXC is better than using Three-Layer MG-OXC in that the former results in smaller OXC, and thus lowers capital (CAPEX) and operating (OPEX) expenditures. For the on-line case with dynamic incremental traffic, we have for the first time, proposed on-line ILP (On-ILP) models as well as a heuristic called Maximum Overlap Ratio (MOR), which is shown to be better than On-ILP and other heuristic algorithms. We have also shown that using Three-Layer MG-OXC is better than using Single-Layer MG-OXC in that the former results in a lower request blocking probability and a higher weighted acceptance ratio, given the same number of ports and traffic load.

In addition, our study has shown that waveband granularity (\mathcal{W}) and the percentage of bands (β) that can be demultiplexed into wavelengths can greatly affect the performance of WBS networks. Our studies indicate that the optimal value of \mathcal{W} is 4 for off-line traffic for both the Single-Layer and Three-Layer MG-OXC, and for on-line traffic the optimal values of \mathcal{W} and β are 5 and 0.55, respectively, for the Three-Layer MG-OXC. Our results are useful in providing insights into the trade-offs between wavelength-hop usage and OXC sizes in both off-line and on-line cases, when either Three-Layer or Single-Layer MG-OXC are used.

REFERENCES

- [1] O. Gerstel, R. Ramaswami, and W. Wang, "Making use of a two stage multiplexing scheme in a WDM network," in *Proceedings - OFC*, 2000, p. ThD1.
- [2] K. Harada, K. Shimizu, T. Kudou, and T. Ozeki, "Hierarchical optical path cross-connect systems for large scale WDM networks," in *Proceedings - OFC*, 1999, p. WM55.
- [3] L. Noirie, M. Vigoureux, and E. Dotaro, "Impact of intermediate grouping on the dimensioning of multi-granularity optical networks," in *Proceedings - OFC*, 2001, p. TuG3.
- [4] X. Cao, Y. Xiong, V. Anand, and C. Qiao, "Wavelength band switching in multi-granular all-optical networks," in *SPIE's Proc. vol. 4874, OptiComm'02, Boston Massachusetts*, 2002, pp. 198–210.
- [5] M. Lee, J. Yu, Y. Kim, and J. Park, "WDM network design with waveband and wavelength multiplexing scheme," in *Cleo/Pacific Lim*, Jul. 2001, pp. 567–568.
- [6] E. Ciaramella, "Introducing wavelength granularity to reduce the complexity of optical cross connects," *IEEE Photonics Technology Letters*, vol. 12, no. 6, pp. 699–701, Jun. 2000.
- [7] R. Lingampalli and P. Vengalam, "Effect of wavelength and waveband grooming on all-optical networks with single layer photonic switching," in *Proceedings - OFC*, 2002, p. ThP4.
- [8] Pin-Han Ho and H. T. Mouftah, "Routing and wavelength assignment with multi-granularity traffic in optical networks," *IEEE Journal of Lightwave Technology*, vol. 20, no. 8, Aug. 2002.
- [9] X. Cao, V. Anand, Y. Xiong, and C. Qiao, "Performance evaluation of wavelength band switching in multi-fiber all-optical networks," in *Proceedings of INFOCOM '03*, 2003, vol. III, pp. 2251 – 2261.
- [10] L. Noirie, C. Blaizot, and E. Dotaro, "Multi-granularity optical cross-connect," in *ECOC*, 2000.
- [11] L. Noirie, F. Dorgeuille, and A. Bisson, "32 × 10 gbit/s DWDM metropolitan network demonstration with 10 waveband- ADMs and 155 km teralight metro fiber," in *Proceedings - OFC*, 2002, p. ThH4.
- [12] R. Izmailov, S. Ganguly, T. Wang, Y. Suemura, Y. Maeno, and S. Araki, "Hybrid hierarchical optical networks," *IEEE Communications Magazine*, vol. 40, no. 11, pp. 88–94, Nov. 2002.
- [13] R. Izmailov, S. Ganguly, V. Kleptsyn, and A. Varsou, "Non-uniform waveband hierarchy in hybrid optical networks," in *Proceedings of INFOCOM '03*, 2003, vol. II.
- [14] S. Yao and B. Mukherjee, "Design of hybrid waveband-switched networks with oeo traffic grooming," in *Proceedings - OFC*, 2003, p. WH3.
- [15] M. Lee, J. Yu, Y. Kim, C. Kang, and J. Park, "Design of hierarchical crossconnect WDM networks employing a two-stage multiplexing scheme of waveband and wavelength," *IEEE JSAC*, vol. 20, no. 1, pp. 166–171, Jan. 2002.
- [16] G. Huiban, S. Perennes, and M. Syska, "Traffic grooming in WDM networks with multi-layer switches," in *IEEE International Conference on Communications (ICC'02), New York*, 2002.
- [17] R. Douville et al., "Extensions to generalized MPLS in support of waveband switching," *draft-douville-ccamp-gmpls-waveband-extensions-03.txt*, Feb. 2003.
- [18] E. Dotaro et al., "Optical multi-granularity architectural framework," *draft-dotaro-ipo-multi-granularity-02.txt*, Aug. 2002.
- [19] X. Cao, V. Anand, Y. Xiong, and C. Qiao, "A study of waveband switching with multi-layer multi-granular optical cross-connects," *IEEE JSAC*, vol. 21, no. 7, pp. 1081–1095, Sep. 2003.
- [20] X. Cao, V. Anand, and C. Qiao, "Waveband switching in optical networks," *IEEE Communications Magazine*, vol. 41, no. 4, pp. 105–112, Apr. 2003.
- [21] I. Chlamtac, A. Ganz and G. Karmia, "Lightpath communications: An approach to High Bandwidth Optical WAN's," *IEEE Tran. on Comm.*, vol. 40, no. 2, pp. 1171–1182, Jul. 1992.
- [22] M. Kovacevic and A. Acampora, "Benefits of wavelength translation in all-optical clear-channel networks," *IEEE JSAC*, vol. 14, no. 5, pp. 868–880, Jun. 1996.
- [23] A. Mokhtar and Murat Azizoglu, "Adaptive Wavelength Routing in All-Optical Networks," *IEEE/ACM Tran. on Networking*, vol. 6, no. 2, pp. 197–206, Apr. 1998.