A Study of Waveband Switching With Multilayer Multigranular Optical Cross-Connects

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***Abstract*—Waveband switching (WBS) has only recently attracted attention from the optical networking industry for its practical importance in reducing port count, the associated control complexity, and cost of optical cross-connects (OXCs). However, WBS-related problems of theoretical interest have not been addressed thoroughly by the research community and many issues are still wide open. In particular, WBS is different from 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.**

In this paper, we first develop an integer linear programming (ILP) model, which for a given set of lightpath requests, determines the routes and assigns wavelengths to the lightpaths so as to minimize the number of ports needed. Since the optimal WBS problem of minimizing the port count in WBS networks contains an instance of routing and wavelength assignment (RWA), which is NP-complete, we adopt a powerful waveband assignment strategy and develop an efficient heuristic algorithm called balanced path routing with heavy-traffic first waveband assignment (BPHT). Both the ILP and the heuristic algorithm can handle the case with multiple fibers per link.

We conduct a comprehensive evaluation of the benefits of WBS through detailed analysis and simulations. For small networks, our results indicate that the performance of the BPHT heuristic is close to that achievable by using the ILP model and, hence verifying its near-optimality. We show that for larger networks, BPHT can perform better than its variation called balanced traffic routing with maximum-hop first waveband assignment and much better than another heuristic based on optimal (but waveband oblivious) RWA that minimizes wavelength resources. We also show that WBS using BPHT is even more beneficial in multifiber networks than in single-fiber networks in terms of reducing the port count. Our analytical and simulation results provide valuable insights into the effect of wavelength band granularity, as well as the tradeoffs between the wavelength-hop and the port count required in WBS networks.

***Index Terms*—Waveband switching (WBS), multigranular optical cross-connect (OXC), integer linear programming (ILP), wavelength division multiplexing (WDM), routing and wavelength assignment.**

I. INTRODUCTION

OPTICAL NETWORKS using wavelength-division multiplexing (WDM) have become promising candidates for the Internet backbone. The WDM technology divides the enormous fiber bandwidth into a large number of wavelengths and with current technologies, each fiber can have 100 or more wavelengths (each operating at 2.5 Gb/s or higher). However, such advances in the transmission technology also brings about tremendous increase in the number of ports (which is a major contribution to the overall cost) at optical cross-connects (OXCs), as well as the complexity and difficulty associated with control and management of such large-scale OXCs.

Recently, the concept of waveband switching (WBS) or simply wavebanding has been proposed by several optical networking companies 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 using a single port whenever possible. Systems having a high wavelength count can use a hierarchical or multigranular OXC (MG-OXC) such as the one proposed in [1]–[3]. Merits of the MG-OXC such as small-scale modularity, crosstalk, and complexity reduction were summarized in [1]. The concept of WBS was applied to WDM ring networks in [4] and [5], and a three-layer MG-OXC architecture for mesh network and its application to metro-area networks were described in [2] and [6] while a single-layer architecture was proposed in [7]. In [8], a limited and simple analytical solution was presented, wherein that the authors only considered two-layer architecture for single-fiber ring networks. Research in efficient WBS algorithm design and their performance evaluation, as well as other problems of more theoretical interest has only begun in academia [9], [10].

In this paper, we first propose a MG-OXC architecture (shown in Fig. 1), which is more *flexible* than our previously proposed architecture in [10]. This architecture allows *dynamic* configuration of the add, drop, and bypass ports, while the former architecture only allow *fixed* add, drop and bypass. The rational behind using such a MG-OXC to reduce the port count is that a fiber is demultiplexed into bands if and only if necessary (for example, it carries at least one lightpath which needs to be dropped or added). Similarly, a band is demultiplexed into individual wavelengths if and only if necessary. On the other hand, the MG-OXC with only a wavelength cross-connect (WXC) layer becomes what will be called an *ordinary-OXC* (single-granular).

WBS differs from conventional wavelength routing in several ways, one for example is that each has different objectives. Accordingly, techniques developed for wavelength-routed networks (including for example, those for traffic grooming) cannot be directly applied to effectively address WBS-related problems. More specifically, in networks employing ordinary-OXC, the routing and wavelength assignment (RWA) problem is to find a route for a lightpath and assign a wavelength

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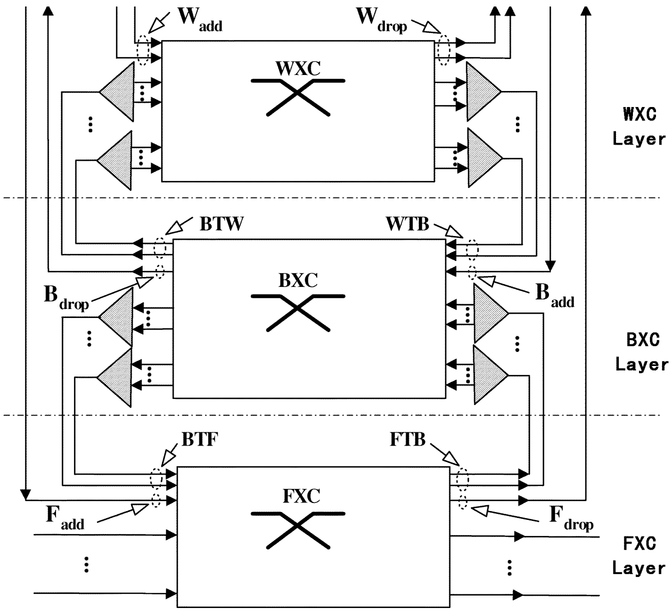

Fig. 1. Architecture of an MG-OXC.

to it. One of the key objectives of the traditional RWA algorithms is to minimize the total number of wavelength-hops (WHs) or the maximum number of wavelengths required to satisfy a given set of lightpath requests, which is known to be NP-complete [11]–[13]. In this paper, we study the optimal WBS problem, with its main objective being to route lightpaths and assign appropriate wavelengths to them so as to minimize the total number of ports required by the MG-OXCs. As to be shown, even though traditional RWA is still an important component of WBS, new waveband assignment algorithms need to be developed in order to effectively achieve the objective.

The above optimal WBS problem is still an open and challenging problem. Recently, an integer linear programming (ILP) model was proposed in [9], but the model is restrictive in that it tries to band or group lightpaths with the same destination only. Further, it requires wavelength conversion capability at WXC layer. In this paper, we adopt a more general, and in fact the most powerful waveband assignment strategy that can group lightpaths with different sources and different destinations.

Since the optimal WBS problem contains an instance of RWA, which is NP-complete, it can be solved for a small problem size (e.g., network size) only. Accordingly, we also develop a heuristic algorithm, called balanced path routing with heavy-traffic first [or balanced path routing with heavy-traffic first waveband assignment (BPHT)], for large problem sizes. We show that for small networks, the proposed BPHT waveband assignment heuristic algorithm can achieve results that are close to the optimal results. For large networks, BPHT can significantly outperform a heuristic based on the optimal RWA algorithm (WBO-RWA) and balanced traffic routing with maximum-hop first waveband assignment (BTMH) (which is a variation of BPHT). We develop an analytical model to calculate the number of ports required in a WBS network. In particular, we analyze the performance of the BPHT heuristic, which is also verified through extensive simulation. Once our algorithm are used to design the MG-OXC nodes (including the multiplexers/demultiplexers and cross-connects), waveband switching can be implemented under the generalized multiprotocol label switching (GMPLS) framework [14]–[17], which addresses corresponding signaling protocols. In particular, a new class of label switched path (LSP), waveband-label switched path (WB-LSP), and specific extension presented in [3] and [18] can be used for LSP signalling along with RSVP-TE or CR-LDP protocols.

Note that even a simple WBS algorithm is not a trivial extension of traditional RWA algorithms. In addition, our research indicates that since the objective of WBS is to minimize the number of ports in MG-OXCs, rather than to minimize WHs as in traditional RWA algorithms, WBS may require more WHs than that needed by optimal RWA to satisfy a given set of lightpath requests. In other words, there is a tradeoff between minimizing the number of WHs versus minimizing the number of ports in WBS networks. Our results indicate that our heuristic BPHT achieves a *large* reduction in the number of required ports *with only a small* increase in WHs.

The ILP formulation, and the BPHT heuristic developed in this paper are applicable to both single and multifiber networks. The study on multifiber networks is motivated by the work in [19]–[22], which has shown that the performance improvement in terms of reduced blocking and better fault tolerance can be obtained by using multifiber networks. Reference [19] showed that doubling the number of fibers per link is akin to doubling the number of wavelengths per link with the additional advantage of simulating a partial wavelength conversion capability. In this paper, we compare the performance of WBS in multifiber and single-fiber networks. We show that by using WBS in multifiber networks, one can achieve even greater savings in port count than in single-fiber networks. To the best of our knowledge, this is the first comprehensive performance evaluation study on optimal WBS and efficient WBS heuristics.

This paper is organized as follows. In Section II, we describe the proposed WBS node architecture and explain how WBS is performed using this flexible MG-OXC. We then classify WBS into several variations or schemes that differ from each other in flexibility, as well as implementation difficulty. The rest of the paper then focuses on a variation that is the *simplest* to implement. Section III presents our ILP model while Section IV presents heuristic algorithms. In Section V, we analyze the performance of BPHT. Numerical results from our ILP model and heuristic algorithms are presented in Section VI. Finally, Section VII concludes the paper with a summary of its major contributions.

II. WAVEBAND SWITCHING (WBS)

In this section, we describe the proposed, flexible MG-OXC architecture shown in Fig. 1, which includes the FXC, BXC, and WXC layers. As shown in the figure, the WXC and BXC layers consist of cross-connect(s) and multiplexer(s)/demultiplexer(s). The WXC layer includes a wavelength cross-connect (WXC) switch that is used to bypass/add/drop lightpaths at this layer, band-to-wavelength (BTW) demultiplexers, and wavelength-to-band (WTB) multiplexers. The BTW demultiplexers are used to demultiplex bands into wavelengths, while the WTB multiplexers are used to multiplex wavelengths into bands. At the BXC layer, the waveband cross-connect (BXC) switch is used

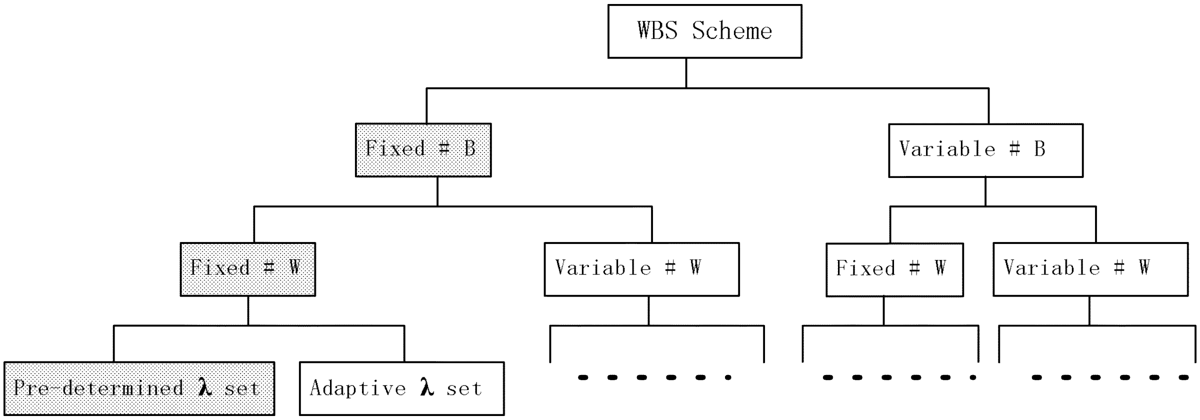

Fig. 2. Classification of the WBS scheme.

to bypass/add/drop wavebands. The BXC layer also includes the fiber-to-band (FTB) demultiplexers and band-to-fiber (BTF) multiplexers. Similarly, fiber cross-connect (FXC) switch is used to bypass/add/drop fibers at the FXC layer.

The MG-OXC architecture proposed in this paper is different and more flexible than that in [10], as it allows for dynamic interconnection or configuration of the MG-OXC. 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. On the other hand, in the earlier proposed architecture, these configurations are fixed, in that only certain fixed fibers (bands) can be demultiplexed. Due to the difference between this new architecture and the one considered in [10], the way to count the number of ports is also different.

More specifically, when counting the number of ports, we will only focus on the *input side* of the MG-OXC.[1] We define the input side of a MG-OXC to consist of locally added traffic and traffic coming into the MG-OXC node from all other nodes (which consists of bypass traffic and locally dropped traffic). 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 is used to add or drop a lightpath. In other words, only the band(s) whose individual 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. For example, assume there are ten fibers, each having 100 wavelengths, and one wavelength needs to be dropped and one to be added at a node. The total number of ports required at the node when using an ordinary-OXC is 1000 for incoming wavelengths (including 999 for bypass and 1 for drop wavelength), plus 1 for add wavelength for a total of 1001. However, if the 100 wavelengths in each fiber are grouped into 20 bands, each having five wavelengths, then using a MG-OXC, only one fiber needs to be demultiplexed into 20 bands (using a 11-port FXC). Then, only one of these 20 bands needs to be demultiplexed into five wavelengths (using a 21-port BXC). Finally, one wavelength is dropped and added (using a 6-port WXC). Accordingly, the MG-OXC has only $11 + 21 + 6 = 38$ ports, an almost 30 times reduction.

We first classify *WBS schemes* into two variations depending on whether the number of bands in a fiber ($\mathcal{B}$) is fixed or variable as in Fig. 2. Each variation is further classified according to whether the number of wavelengths in a band (denoted by $\mathcal{W}$) is fixed or variable. For a given fixed value of $\mathcal{W}$, the set of wavelengths in band can be further classified depending on whether they are predetermined (e.g., consists of consecutively numbered subset of wavelengths) or can be adaptive (dynamically configured).

Hereafter, we concentrate on the simplest of the WBS scheme, where 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 (shown shaded in Fig. 2), though the ILP model and heuristic algorithms developed in this paper can be extended to other WBS variations as well. With the current state of art, wavelength conversion technology is still too immature (and expensive), and hence, in the following, we assume that there is no wavelength conversion in our model. The case with wavelength conversion and other variations of the WBS scheme will be studied in the future.

III. ILP MODEL FOR WBS

This section formulates the WBS scheme using ILP. The ILP model is for multifiber networks, where we use $f > 1$ to label the fibers on a link. For single-fiber networks, f is always one and in fact can be omitted from the formulations.

A. Notations

I_n	set of input fibers at node n (excluding those for local add);
$\mathcal{I}_{n,m}^f$	input fiber f at node n, connected to node m, so $I_n = \bigcup_{m,f} \mathcal{I}_{n,m}^f$;
O_n	set of output fibers at node n (excluding those for local drop);
$\mathcal{O}_{n,m}^f$	output fiber f at node n, connected to node m. So $O_n = \bigcup_{m,f} \mathcal{O}_{n,m}^f$;

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[1] Due to the symmetry of the MG-OXC architecture, the number of ports on the input side and output side are equal.

A_n	set of local add fibers at node n, including those used at the ports of WXC, BXC, and FXC layer;
D_n;	set of local drop fibers at node n, including those used at the ports of WXC, BXC, and FXC layer;
IA_n	this set includes the set of all incoming fibers (local and nonlocal) at node n;
OD_n;	this set includes the set of all outgoing fibers (local and nonlocal) at node n;
$\pounds_b$	set of wavelengths in band b;
$\mathcal{F}$	number of fibers per link that can be used for each direction;
$\mathcal{K}$	number of wavelengths per fiber;
$\mathcal{B}$	number of wavelength bands per fiber;
$\mathcal{W}$	number of wavelengths per wavelength band ($\mathcal{K} = \mathcal{B} \times \mathcal{W}$);
P	set of node pairs having nonzero traffic demand. Each node pair can be denoted by $p = (p.\mathrm{src}, p.\mathrm{dest})$, where $p.\mathrm{src}$ and $p.\mathrm{dest}$ represent the source and destination nodes of one or more request lightpaths, respectively;
T[p]	traffic matrix whose element t_p is an integer, representing the traffic demand (i.e., number of lightpaths) of the node pair p.

B. ILP Variables

To facilitate presentation and understanding of our ILP model, we define variables to describe the properties of a node (instead of a link as in other ILP formulations for RWA). More specifically, to obtain and represent the detailed information of the routing and wavelength assignment, we introduce the following binary variables to be used in the ILP formulation.

Note that the traffic at a node can be drop traffic, bypass traffic or add traffic. The following four variables: $V_{i,o,p}^{n,w}, W_{i,o}^{n,w}, B_{i,o}^{n,b}$, and $F_{i,o}^{n}$ are used for describing the lightpaths, each of which can represent bypass traffic when $i \in I_n, o \in O_n$; add traffic when $i \in A_n, o \in O_n$ or drop traffic when $i \in I_n, o \in D_n$. An incoming (or outgoing) fiber refers to either an input (or output) fiber from (or to) a neighboring node or a fiber connecting the local node to any add (or drop) port at the WXC, BXC, and FXC layer (as mentioned earlier in Section III.A).

$V_{i,o,p}^{n,w}$	one if node n has a lightpath for node pair $p = (p.\mathrm{src}, p.\mathrm{dest})$ on wavelength w from incoming fiber i to outgoing fiber o and zero otherwise;
$W_{i,o}^{n,w}$	one if node n has a wavelength w bypass/add/drop at the WXC layer from incoming fiber i to outgoing fiber o and zero otherwise;
$B_{i,o}^{n,b}$	one if node n has a waveband b ($b \in [0, 1, \ldots, \mathcal{B} - 1]$) bypass/add/drop at the BXC layer from incoming fiber i to outgoing fiber o and zero otherwise;
$F_{i,o}^{n}$:	one if node n has an incoming fiber i bypass/add/drop to outgoing fiber o at the FXC layer and zero otherwise.

Four additional variables used for describing multiplexing/demultiplexing are also defined.

FTB_i^n	one if input fiber i ($i \in I_n$) needs to be demultiplexed into bands at node n and zero otherwise;
$\mathrm{BTW}_i^{n,b}$	one if band b on input fiber i ($i \in I_n$) needs to be demultiplexed into wavelengths at node n and zero otherwise;
BTF_o^n:	one if a band needs to be multiplexed onto an output fiber o ($o \in O_n$) at node n and zero otherwise;
$\mathrm{WTB}_o^{n,b}$:	one if a wavelength needs to be multiplexed on to band b of an output fiber o ($o \in O_n$) at node n and zero otherwise.

As a consequence of multiplexing/demultiplexing, we need to use multiplexer/demultiplexer port(s) at the respective layers. Fig. 3 shows one such example involving two lightpaths, one for node pair p_1 using λ_1 on input fiber 1 and the other for node pair p_2 using λ_2 to be added locally. Using the MG-OXC, the two lightpaths are grouped together in the same band of the same output fiber (e.g., fiber 2). By definition, we have $V_{i_1,o_2,p_1}^{n,\lambda_1} = V_{a_0,o_2,p_2}^{n,\lambda_2} = 1$. For this, input fiber 1 (containing the lightpath for p_1) has to be demultiplexed into band b_1 (and other bands) using a FTB demultiplexer (hence, $\mathrm{FTB}_{i_1}^n = 1$). Band b_1 then has to be further demultiplexed into λ_1 and other wavelengths (hence, $\mathrm{BTW}_{i_1}^{n,b_1} = 1$) to switch the lightpath for p_1 (hence, $W_{i_1,o_2}^{n,\lambda_1} = 1$). The second lightpath for p_2 is added into band b_1 using a WTB multiplexer (hence, $\mathrm{WTB}_{o_2}^{n,b_1} = 1$). Now that the two lightpaths are in the same band, the band is multiplexed onto a fiber using a BTF multiplexer (hence, $\mathrm{BTF}_{o_2}^n = 1$), and then transmitted onto output fiber 2.

C. Objective Function

Let $\mathrm{WXC}_n, \mathrm{BXC}_n$, and FXC_n be the number of ports at WXC, BXC, and FXC layers at node n, respectively. There are two reasonable objectives. The first is to minimize the total cost associated with the MG-OXC ports in the network, that is

$$\text{minimize} \left[\alpha \times \sum_n \mathrm{WXC}_n + \beta \times \sum_n \mathrm{BXC}_n + \gamma \times \sum_n \mathrm{FXC}_n \right] \quad (1)$$

where α, β, and γ are the coefficients or weights corresponding to the cost of each port at the WXC, BXC, and FXC layer, respectively. When $\alpha = \beta = \gamma = 1$, the objective becomes to minimize the total number of MG-OXC ports in the network, which is the sum of the port count at FXC, BXC, and WXC layers, respectively.

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

$$\text{minimize} \max_n (\alpha \times \mathrm{WXC}_n + \beta \times \mathrm{BXC}_n + \gamma \times \mathrm{FXC}_n). \quad (2)$$

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

D. Constraints

1) For Routing and Wavelength Assignment: The following constraints on traffic flows, wavelength-capacity and wavelength-continuity are similar to those in the traditional RWA

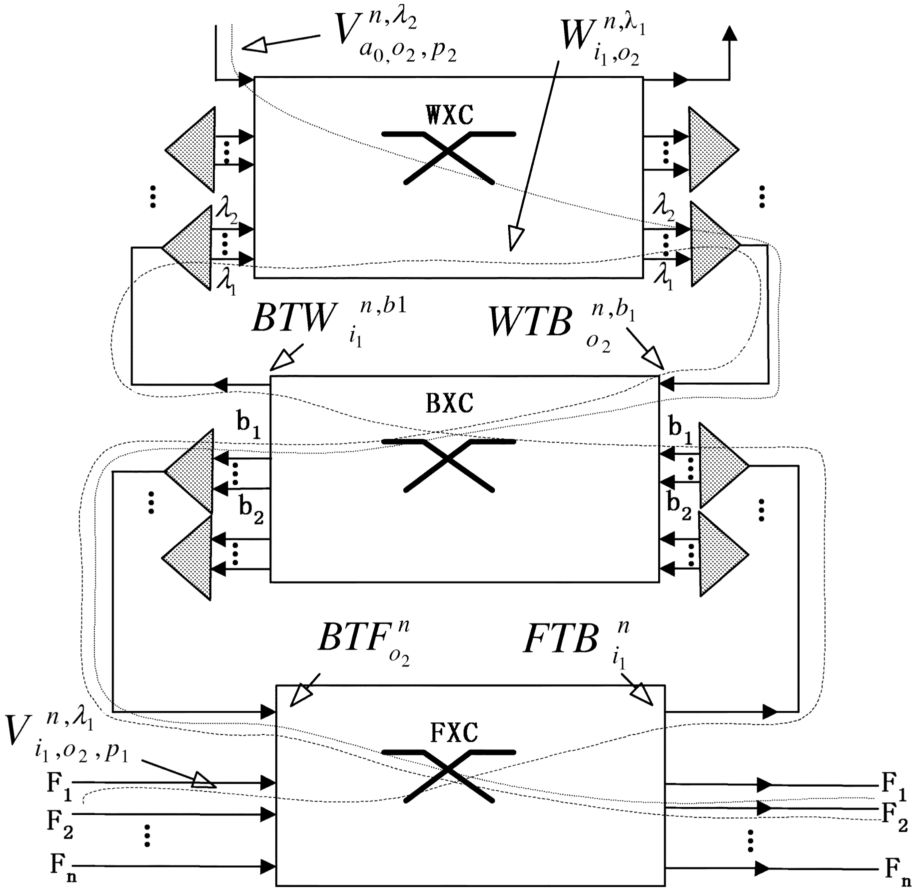

Fig. 3. Waveband at node n.

ILP formulations. Equation (3) is the traffic flow constraint, (4) and (5) are the wavelength capacity constraint, and (6) is the wavelength continuity constraint (as shown at the bottom of the page).

2) For Waveband Switching: We need the following additional constraints:

$$\begin{aligned} 1 &\geq F^{n}_{i,o} + B^{n,b}_{i,o} + W^{n,w}_{i,o} \\ &\geq \sum_{p} V^{n,w}_{i,o,p} \quad \forall w \in \pounds_b, \quad i \in IA_n, \quad o \in OD_n \end{aligned} \tag{7}$$

$$\begin{aligned} &1 \geq F^{n}_{i,o} + \sum_{p,o_1 \neq o} V^{n,w}_{i,o_1,p} \\ &1 \geq F^{n}_{i,o} + \sum_{p,i_1 \neq i} V^{n,w}_{i_1,o,p} \quad \forall w, i, o \end{aligned} \tag{8}$$

$$\begin{aligned} &1 \geq B^{n,b}_{i,o} + \sum_{p,o_1 \neq o} V^{n,w}_{i,o_1,p} \\ &1 \geq B^{n,b}_{i,o} + \sum_{p,i_1 \neq i} V^{n,w}_{i_1,o,p} \quad \forall i, o, w \in \pounds_b. \end{aligned} \tag{9}$$

$$\begin{cases} \sum\limits_{i \in A_n, o \in O_n} V^{n,w}_{i,o,p} = \sum\limits_{i \in I_n, o \in D_n} V^{n,w}_{i,o,p} = 0, & n \neq p.\text{src}, p.\text{dest} \quad \forall w (\text{i}) \\ \sum\limits_{w, i \in A_n, o \in O_n} V^{n,w}_{i,o,p} = t_p, & n = p.\text{src}, \quad (\text{ii}) \quad \forall p \\ \sum\limits_{w, i \in I_n, o \in D_n} V^{n,w}_{i,o,p} = t_p, & n = p.\text{dest}, \quad (\text{iii}) \quad \forall p \end{cases} \tag{3}$$

$$\sum_{p, o \in OD_n} V^{n,w}_{i,o,p} \leq 1 \quad \forall w, i \in I_n \tag{4}$$

$$\sum_{p, i \in IA_n} V^{n,w}_{i,o,p} \leq 1 \quad \forall w, o \in O_n \tag{5}$$

$$\sum_{i \in IA_m, o \in \mathcal{O}^{f}_{m,n}} V^{m,w}_{i,o,p} - \sum_{i \in \mathcal{I}^{f}_{n,m}, o \in OD_n} V^{n,w}_{i,o,p} = 0 \qquad \forall m, n, p, w, f; \tag{6}$$

Equations (7)–(9) ensure that if a lightpath uses wavelength w belonging to band b of incoming fiber i and outgoing fiber o (i.e., $\sum_p V_{i,o,p}^{n,w} = 1$), 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., $i \in I_n, o \in O_n$);

— exactly one of $F_{\text{add}}, B_{\text{add}}$, and W_{add} port will be used for adding this lightpath, when it is added (i.e., $i \in A_n, o \in O_n$);

— exactly one of $F_{\text{drop}}, B_{\text{drop}}$, and W_{drop} port will be used for dropping this lightpath, when it is dropped (i.e., $i \in I_n, o \in D_n$).

$$\text{BTF}_o^n \geq \text{WTB}_o^{n,b} \geq W_{i,o}^{n,w} \quad \forall w \in \pounds_b, \quad o \in O_n, \quad i \in IA_n. \tag{10}$$

The above constraint 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. Similarly, (11) 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.

$$\text{FTB}_i^n \geq \text{BTW}_i^{n,b} \geq W_{i,o}^{n,w} \quad \forall w \in \pounds_b, \quad o \in OD_n, \quad i \in I_n. \tag{11}$$

Finally, any bypass or add bands should pass a BTF multiplexer as specified in (12) and similarly, any drop or bypass band can only come from a FTB demultiplexer as specified in (13)

$$\text{BTF}_o^n \geq B_{i,o}^{n,b} \quad \forall o \in O_n, \quad i \in IA_n \tag{12}$$

$$\text{FTB}_i^n \geq B_{i,o}^{n,b} \quad \forall o \in OD_n, \quad i \in I_n. \tag{13}$$

3) For Port Numbers: The following constraints specify the minimum number of ports required at each layer of the MG-OXC:

$$\text{WXC}_n = \sum_{i \in IA_n, o \in OD_n, w} W_{i,o}^{n,w} \quad \forall n \tag{14}$$

$$\text{BXC}_n = \sum_{i \in IA_n, o \in OD_n, b} B_{i,o}^{n,b} + \sum_{o \in O_n, b} \text{WTB}_o^{n,b} + \sum_{i \in I_n, b} \text{BTW}_i^{n,b} \quad \forall n \tag{15}$$

$$\text{FXC}_n = \sum_{i \in IA_n, o \in OD_n} F_{i,o}^n + \sum_{o \in O_n} \text{BTF}_o^n + \sum_{i \in I_n} \text{FTB}_i^n \quad \forall n. \tag{16}$$

For the WXC layer, the number of input-side ports include the ports for lightpaths coming in from other nodes and locally added lightpaths as specified in (14). The number of input-side ports needed at the BXC layer is the sum of the number of wavebands $B_{i,o}^{n,b}$ (BXC cross-connect and add/drop/bypass bands) and the number of wavebands from the WTB/BTW multiplexers/demultiplexers as in (15). Similarly, (16) can be used to determine the number of ports at the FXC layer.

In short, our ILP model (and heuristics to be described next) considers the design of MG-OXC nodes (i.e., the number of ports allocated at each of the layers) with the objective to minimize either the total port count or the maximum port count over all MG-OXC nodes in the network given a set of traffic demands to be satisfied on a given network topology, wherein each link in the network may have single or multiple fibers.

Note that if we eliminate the FXC and BXC layers (i.e., set corresponding variables to 0) from the MG-OXC, the above ILP formulation with Objective (1) will minimize the total number of ports, which is equivalent to minimizing WHs using ILP for optimal RWA. As such ILP formulations developed can only be solved for small systems with a few nodes and a few wavelengths on each fiber, we need to develop efficient heuristic-based solutions for large systems.

IV. HEURISTIC ALGORITHMS FOR WBS

In this section, we describe the heuristic algorithms we developed for WBS. There are several waveband assignment strategies in WBS networks, including: 1) grouping the lightpaths with the same source-destination pair only; 2) grouping the lightpaths from the same source only; 3) grouping the lightpaths with same destination only; and 4) grouping the lightpaths with common intermediate links (from any source to any destination). The authors in [9] only considered the Strategy 3, while our ILP formulation covers the fourth strategy, which is the most general and flexible, and can be used in single and multifiber networks. Below, we describe a heuristic that takes into consideration lightpath routing, as well as waveband assignment Strategy 4 in multifiber networks.

A. *Waveband Oblivious Optimal RWA (WBO-RWA)*

To study the relationship between WBS and traditional RWA, we use ILP formulations for RWA [12] that minimize the total number of used WHs and then group the assigned wavelengths into bands, and calculate the number of required ports. Note that the heuristic is completely oblivious to the existence of wavebands. From now on, we refer WBO-RWA as getting wavelength assignment from the optimal RWA ILP formulation and then grouping them.

B. *BPHT*

Intuitively, to maintain *wavelength-continuity* in wavelength routed optical networks without wavelength conversion, it is better to assign wavelengths to longer paths (in terms of hops) first. Further, to reduce the number of ports in MG-OXC, it is better to assign paths that have maximum number of links in common, wavelengths in the same fiber (and band), thus increasing the probability of switching the whole fiber (and band) by just using a single FXC (and BXC) port. The following is our three-stage heuristic algorithm called balanced path routing with heavy-traffic first waveband assignment (BPHT) first waveband assignment, which tries to maximize the reduction in the MG-OXC size using the above ideas.

1) Stage 1: Balanced Path Routing: In this stage, we use the following steps to achieve load balanced routing.

- Find K-shortest routes for every node pair (s,d) with nonzero traffic demand as in [23], and order them from the shortest to the longest (in terms of hop number) as $P^1_{s,d}, P^2_{s,d}, \ldots, P^k_{s,d}$. Let the number of hops of the shortest route be $H_{s,d}$ (i.e., number of hops in path $P^1_{s,d}$).
- Define the load on every link l to be the number of routes already using link l (initially, this is zero). Let C be the maximum link load over all the links.
- Use C to achieve load balanced routing, starting with the node pair (s,d) with the largest $H_{s,d}$ (over all node pairs), to determine the route for each node pair. More specifically, for the K-shortest routes $P^i_{s,d}$ of the selected node pair (s,d), where $i = 1, 2, \ldots, k$, we compute the C and pick one of the routes that minimizes C. If more than one routes, say $P^i_{s,d}$ and $P^j_{s,d}$, have the same minimum C, the shortest one (i.e., $P^i_{s,d}$, if $i < j$) will be used as the route for (s,d). That is, all the lightpaths from s to d will take this route. After the route for (s,d) is chosen, the process continues to choose one route for each of the remaining node pairs, starting with the one having the largest number of hops along the shortest path, until every node pair with nonzero traffic demand is assigned a route.

2) Stage 2: Wavelength Assignment: Based on the observation that bypass traffic, which goes through two or more hops accounts for 60%–80% of the total traffic in the backbone, we assign the wavelengths to those bypass lightpaths first. At the same time, we also want to give preference to the lightpaths that overlap with many other (shorter) lightpaths in order to maximize the advantage of wavebanding.

The following steps are used to assign wavelengths to all the lightpath demands once the routing is done in Stage 1. To maximize the benefit of WBS in multifiber networks, we introduce a new waveband assignment algorithm, called waveband assignment for multifiber WBS [WA-MF-WBS, see Step d) below].

a) For every node pair (s,d), whose route is determined as $s = s_0 \rightarrow s_1 \rightarrow s_2 \ldots s_{n-1} \rightarrow s_n = d$ in Stage 1, define a set Q^s_d, which includes all node pairs (s_i, s_j), whose route is $s_i, s_{i+1}, \ldots, s_j$, as determined in Stage 1, where $0 \le i \le n-2$, and $i+2 \le j \le n$. Note that it is possible that the route chosen for (s_i, s_j) in Stage 1 is not a subpath of the route chosen for (s,d), in which case, (s_i, s_j) will not belong to Q^s_d.

b) Calculate the weight for each set Q^s_d as $W_{sd} = \sum_{p \in Q^s_d} h_p \times t_p$, where $p = (s_i, s_j) \in Q^s_d, h_p$ is the number of hops and t_p is the required number of lightpaths from s_i to s_j;

c) Find the set Q^s_d with the largest W_{sd}.[2]

d) Call set Q^s_d as $\mathcal{L}$, and assign wavelengths to $\mathcal{L}$ as follows.

    i) Suppose that the longest path in $\mathcal{L}$ is as follows: $s_0 \rightarrow s_1 \rightarrow s_2 \ldots s_{n-1} \rightarrow s_n$. Let $s = s_0$ and $d = s_n$ (which is the case initially based on the definition of Q^s_d). Assign wavelengths to the requested lightpaths for the node pair (s,d) by trying to group them into the same fiber, and within each fiber, into the same band(s). More specifically, for each fiber, let $0 \le w \le \mathcal{K} - 1$ and $0 \le b \le \mathcal{B} - 1$ be the index of wavelength and band, respectively, starting from which, an available wavelength and band will be searched in order to fulfill new lightpath requests; In addition, let $1 \le f \le \mathcal{F}$ be the index of the fiber currently under consideration (i.e., whose wavelengths may be used for new lightpaths). Initially, $f = 1$ and $w = b = 0$ for all fibers. The following algorithm WA-MF-WBS assigns wavelengths to the lightpaths for a specified node pair p for multifiber[3] WBS networks.

```
Algorithm: WA-MF-WBS
  while $t_p > \mathcal{W}$ do
    Find a fiber starting from index $f$ that has as many free
      bands as possible (say $a \le \lfloor t_p/\mathcal{W} \rfloor$){
    Call the found fiber $g$, where $g$ may or may not be the
      same as $f$;
    Assign the bands in fiber $g$ to the $a \cdot \mathcal{W}$ lightpaths for $p$;
    $t_p = t_p - a \cdot \mathcal{W}$;
    Set $f = g$, and update $w$ and $b$ for fiber $g$ accordingly;
    }
  end while
  while $t_p > 0$ do
    Find a fiber $(g)$, starting from index $f$, that has at least
      one free wavelength;
    Assign a free wavelength $(x)$, starting from index $w$, to a
      lightpath for $p$, where $x$ is most likely to be $w$;
    $t_p = t_p - 1$;
    Set $f = g$, and $w = x + 1$. Also, update $b$ for fiber $g$
      accordingly;
  end while
```

    ii) Use WA-MF-WBS to assign wavelengths to the requested lightpaths for (s, s_j) starting with the largest j (i.e., $j = n-1, n-2, \ldots, 2$).

    iii) Use WA-MF-WBS to assign wavelengths to the requested lightpaths for (s_i, d) starting with the smallest i (i.e., $i = 1, 2, \ldots, n-2$).

    iv) If there are still node pairs $(s_i, s_j) \in Q^s_d$ that have not been considered, repeat from Step d) by treating s_i with the smallest i as s, and s_j with the largest j as d. Otherwise, go to Step e).

e) Recompute the weight for those node pairs whose routes use any part of the route used by node pair (s,d). For each fiber, readjust b and w to be the "next" waveband and the first wavelength in the next waveband, respectively, so as to prevent the lightpaths of the next node pair set (e.g., $Q^{s'}_{d'}$) from using the same bands as the lightpaths of Q^s_d (thus reducing the need to demultiplex and multiplex the

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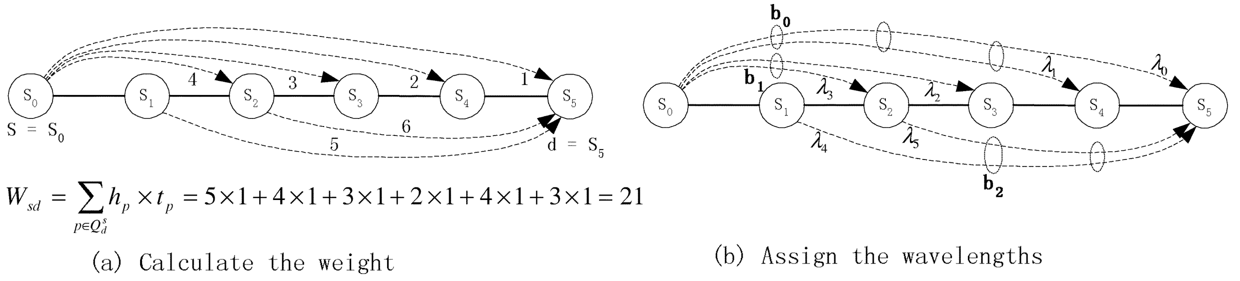
[2] Note that, by starting with set Q^s_d with the largest W_{sd}, we implicitly try and assign wavelengths to the pairs which have maximum number of lightpath requests (i.e., *heavy traffic*) first.

[3] Algorithm WA-MF-WBS is also used to obtain the results for single-fiber networks, as in Section VI.



(a) Calculate the weight (b) Assign the wavelengths

Fig. 4. Example illustrating the Steps b) and d) in Stage 2 of BPHT.

lightpaths belonging to these two sets when they merge and diverge). More specifically, set $b = (b+1) \bmod \mathcal{B}$, and $w = b \times \mathcal{W}$, and then go to Step c). Repeat until all the bypass (multihop) lightpath demands are satisfied.

For example, suppose that the lightpaths numbered from one to six are routed as in Fig. 4(a) (i.e., using links $s_0 \rightarrow s_1 \rightarrow s_2 \rightarrow s_3 \rightarrow s_4 \rightarrow s_5$) as dictated by the load balancing routing algorithm. Accordingly, the node pair set $Q_{s_5}^{s_0}$ consists of the six node pairs, $(s_0, s_5), (s_0, s_4), (s_0, s_3), (s_0, s_2), (s_1, s_5)$, and (s_2, s_5), and the weight of the node pair set is 21 as shown. Hence, now wavelengths will be assigned to the lightpaths in this set as Fig. 4(b) according to Step d).

f) Finally, assign wavelengths to lightpaths between two nodes separated by only one hop, starting with the node pair having the largest lightpath demand.

3) Stage 3: Waveband Switching (WBS): Once the wavelength assignment is done, WBS can be performed in a fairly straight-forward way. Basically, we switch as many fibers using FXCs as possible; and then as many wavebands using BXCs as possible. The remaining lightpaths are then individually switched at the WXC layer. The total number of ports used at a given node can then be determined as discussed at the end of Section III.D. (For example, in Fig. 4(b), assuming that the band size is two, then we can group the assigned wavelengths into bands as shown).

Ideally, BPHT will group traffic from the same source to the same destination, and most of the traffic that has common intermediate links. One of the variations of BPHT (in Stage 1) is to balance the amount of traffic (in terms of the actual number of lightpaths instead of just one route for each node pair) on every link. Another variation is to assign wavelengths to lightpaths with the largest hop count or those for node pairs with the largest weighted traffic demand (i.e., $h_p \times t_p$) first (assuming e.g., shortest-path routing) in Stage 2. We call the heuristic that varies from BPHT at both Stages 1 and 2 in such a manner, balanced traffic routing with maximum-hop first waveband assignment (BTMH). In our experiments, we have compared heuristics based on the above variations and found that the overall performance of BPHT is the best. Due to space limitation, we will only compare the results of BPHT, with that of WBO-RWA and BTMH.

V. PERFORMANCE ANALYSIS

In this section, we present an analytical method for obtaining the total number of ports in a MG-OXC network using our best heuristic algorithm BPHT. We first consider the case when the traffic demand per node pair is not a multiple of the waveband granularity and then extend it to the case when the demand is a multiple of the waveband granularity. We then calculate the generalized upper and lower bounds on the number of ports.

To simplify the analysis of the performance of BPHT, we assume a random network with N nodes and $2L$ unidirectional links and a uniform traffic model where the traffic demand of every node pair p is t (i.e., $t_p = t$). Let $\delta = (2L)/(N)$ be the average node degree, $H(p)$ be the shortest path length for node pair p, and accordingly $G = \lceil (\sum_{p \in P} t \times H(p))/(2L) \rceil$ be the average number of lightpaths on a link. Note that the minimum amount of total traffic going into the input-side of all the nodes is $\mathrm{MP} = \sum_{p \in P} t \times H(p) + N(N-1) \times t$, where $N(N-1) \times t$ is total number of added lightpaths. Further, note that MP is also equal to the minimum number of ports in ordinary-OXC networks.

Given that the proposed heuristic BPHT uses load balanced routing, it is reasonable to assume that all added (or dropped, bypass) traffic, measured in terms of the number of lightpaths, is evenly distributed among *all* the output (or input) links. This implies that the number of dropped (D) or added (A) lightpaths on a link at a node is $A = D = \lceil ((N-1) \times t)/(\delta) \rceil$ and the number of bypassing lightpaths on a link is $I = G - D$.

1) Case 1: Traffic Demand (t) Is Not a Multiple of the Waveband Granularity ($\mathcal{W}$): If the traffic demand (t) is not a multiple of the waveband granularity, each of the three layers contributes to the total port count of the MG-OXC. Below, we calculate the ports at each of the layers at a node n starting at the FXC layer.

We note that, for a given link, $F_a = F_d = \lfloor D/\mathcal{K} \rfloor$ is the number of full fibers that can be added or dropped. On the other hand, $F_b = \lfloor I/\mathcal{K} \rfloor$ is the number of full fibers that will bypass. The remaining number of lightpaths on the link is, thus, $\lambda_{\mathrm{FTB}} = G - F_d \times \mathcal{K} - F_b \times \mathcal{K}$. Hence, $\mathrm{FTB} = \lceil \lambda_{\mathrm{FTB}}/\mathcal{K} \rceil$ is the number of FXC layer ports needed for FTB demultiplexers. Due to the symmetry in added and dropped traffic (i.e., uniform traffic), we have $\mathrm{FTB} = \mathrm{BTF}$ (and $F_a = F_d$, as above).

Accordingly, at the FXC layer of node n (having δ links), the number of required ports include $F_i = \lceil G/\mathcal{K} \rceil$ ports for input fibers (from other nodes), F_a ports for locally added fibers and BTF ports for lightpaths from BTF multiplexers on each connected link. Thus, we have

$$\mathrm{FXC}_n = [F_i + F_a + \mathrm{BTF}] \times \delta. \quad (17)$$

From the analysis, we know that there are $D' = D - F_d \times \mathcal{K}$ remaining lightpaths (per link) that need to be dropped (through the BXC and WXC layers) and $I' = I - F_b \times \mathcal{K}$ remaining bypass lightpaths. Hence, $B_d = \lfloor D'/\mathcal{W} \rfloor$ is the number of ports for bands to be dropped locally, $B_b = \lfloor I'/\mathcal{W} \rfloor$ is the number bypass bands and $\mathrm{BTW} = \lceil \lambda_{\mathrm{BTW}}/\mathcal{W} \rceil$ is the number of ports for BTW demultiplexers where $\lambda_{\mathrm{BTW}} = \lambda_{\mathrm{FTB}} - (B_d + B_b) \times \mathcal{W}$.

Similarly, the number of ports required at the BXC layer of node n includes $B_i = \lceil (I' + D')/(\mathcal{W}) \rceil$ ports for input bands, B_a $(=B_d)$ ports for locally added bands and WTB $(=\mathrm{BTW})$ ports for bands from WTB multiplexers on each connected link. Thus, we have

$$\mathrm{BXC}_n = [B_i + B_a + \mathrm{WTB}] \times \delta. \tag{18}$$

Finally, for the entire network, the remaining $\mathrm{MP} - (F_b + F_d + F_a) \times \mathcal{K} \times \delta \times N - (B_b + B_d + B_a) \times \mathcal{W} \times \delta \times N$ lightpaths will go through the WXC layer. Hence, the number of ports required at the WXC layer is

$$\begin{aligned} \mathrm{WXC} = \mathrm{MP} &- (F_b + F_d + F_a) \times \mathcal{K} \times \delta \times N \\ &- (B_b + B_d + B_a) \times \mathcal{W} \times \delta \times N \end{aligned} \tag{19}$$

Therefore, from (17)–(19), we can obtain the total number of ports in the entire network as

$$\mathrm{Total} = (\mathrm{FXC}_n + \mathrm{BXC}_n) \times N + \mathrm{WXC}. \tag{20}$$

2) Case 2: Traffic Demand (t) Is a Multiple of the Waveband Granularity $(\mathcal{W})$: If the traffic demand per node pair is a multiple of $\mathcal{W}$, the MG-OXC will add/drop/bypass bands, not individual wavelengths in order to reduce the number of ports. Thus, all traffic is switched using the FXC and BXC layers only, and the WXC layer is not needed. Accordingly, at the BXC layer, this is similar to having an ordinary OXC, wherein each port switches a band of wavelengths. Hence, in this case, we obtain the total number of ports at the input-side as follows.

Equation (17) gives us the number of ports required at FXC layer at each node. After switching at the FXC layer, the number of remaining lightpaths going through the BXC layer is $\mathrm{MP} - (F_b + F_d + F_a) \times \mathcal{K} \times \delta \times N$. Thus, we have

$$\mathrm{Total} = \mathrm{FXC}_n \times N + \frac{\mathrm{MP} - (F_b + F_d + F_a) \times \mathcal{K} \times \delta \times N}{\mathcal{W}}. \tag{21}$$

3) Upper and Lower Bounds: Note that, in the best case, all the $G + A$ lightpaths can be added/switched *only* at the FXC layer (i.e., no need for WXC/BXC), and hence the lower bound on the number of ports needed at *each* node is $(\lceil A/\mathcal{K} \rceil + \lceil G/\mathcal{K} \rceil) \times \delta$ FXC ports. On the other hand, in the worst case, all these lightpaths will have to be added/switched at the WXC layer, and thus the maximum WXC_n is $(G+A) \times \delta$. At the FXC layer, the maximum number of ports needed at each node should also be bounded by $(G+A) \times \delta$. In addition, in the worst case, all the input fibers may go through the FTB demultiplexers. Thus, $\mathrm{BTF} = \mathrm{FTB} \leq \mathcal{F} \times \delta$, and then, $\mathrm{FXC}_n \leq \mathcal{F} \times \delta \times 2$. In other words, the maximum FXC_n is $\min[(G+A) \times \delta, \mathcal{F} \times \delta \times 2]$. Similarly, the maximum BXC_n is $\min[(G+A) \times \delta, \mathcal{F} \times \mathcal{B} \times \delta \times 2]$. Thus, the bounds for the total number of ports in the network are as follows:

$$\text{Lower Bound} = \left(\left\lceil \frac{A}{\mathcal{K}} \right\rceil + \left\lceil \frac{G}{\mathcal{K}} \right\rceil \right) \times \delta \times N \tag{22}$$

$$\begin{aligned} \text{Upper Bound} = \{ &\min[(A+G) \times \delta, \mathcal{F} \times \delta \times 2] \\ &+ \min[(A+G) \times \delta, \mathcal{F} \times \mathcal{B} \times \delta \times 2] \\ &+ \delta \times (A+G) \} \times N. \end{aligned} \tag{23}$$

While the upper bound is loose, it is useful in light of the fact that in some cases, using MG-OXCs (and naive WBS algorithms) may result in an increase in the port count due to the overhead (e.g., additional multiplexer/demultiplexer ports) in interconnecting different layers within an MG-OXC.

VI. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we focus on simulation to compare WBS algorithms based on the ILP model, WBO-RWA, BPHT and its variation BTMH. We will first present the results for ILP, WBO-RWA, and BPHT for a random six-node network, as our experiments show that the optimal WBS based on ILP formulation is feasible only for such a small network. We then compare the heuristic algorithms BPHT, BTMH, and WBO-RWA only, for larger networks such as the NSF network.

We define the following three *performance-metrics*. Each metric is a function of a WBS algorithm.

- **Total port number ratio T(a)**

$$\frac{\mathrm{Total}(\mathrm{FXC}_n + \mathrm{BXC}_n + \mathrm{WXC}_n) \text{ used by WBS algorithm } 'a'}{\mathrm{Total}\ (\mathrm{OXC}_n) \text{ of ordinary-OXC}}.$$

- **Max port number ratio M(a)**

$$\frac{\max(\mathrm{FXC}_n + \mathrm{BXC}_n + \mathrm{WXC}_n) \text{ used by WBS algorithm } 'a'}{\max(\mathrm{OXC}_n) \text{ of ordinary-OXC}}.$$

- **Used wavelength-hop ratio W(a)**

$$\frac{\text{wavelength-hops used by WBS algorithm } 'a'}{\text{wavelength-hops used by optimal RWA without WBS}}.$$

Note that by definition $\mathrm{W(WBO-RWA)} = 1$. The results presented below are obtained via extensive simulation, and each point is the averaged result over a large number of simulation runs with different random traffic patterns.

A. Six-Node Network

For the six-node network, a traffic matrix is randomly generated, such that the number of lightpaths requested by a (s, d) pair is in the range of zero to four. When using ILP formulation, we set $\alpha = \beta = \gamma = 1$ in the objective equation (1) and use the ILP solver, CPLEX to obtain optimal results.

For three different representative random traffic patterns where the total lightpaths (i.e., $\sum t_p$) is 25, 31, and 53, respectively, Table I shows the number of ports and performance ratios for optimal WBS (based on ILP), WBO-RWA and BPHT. As the basis for the comparison, the last row (OXC) indicates the minimum total number of ports required when

TABLE I
RESULTS FOR THE SIX-NODE NETWORK ($\mathcal{F} = 2, \mathcal{B} = 2, \mathcal{W} = 2$)

	Optimal WBS			**WBO-RWA**			**BPHT**		
$\sum t_p$	25	31	53	25	31	53	25	31	53
T(a)	0.48	0.42	0.51	1.23	0.84	1.26	0.54	0.43	0.56
M(a)	0.69	0.50	0.73	1.44	1.19	1.50	0.63	0.50	0.69
W(a)	1.02	1.02	1.01	1.00	1.00	1.00	1.00	1.02	1.02
OXC	71	($\sum t_p = 25$);		83	($\sum t_p = 31$);		142		($\sum t_p = 53$)

ordinary-OXCs without WBS are used. The rows T(a), M(a), and W(a) represent the respective performance ratios.

From the table, we see that the performance of BPHT is close to that of the ILP model (optimal WBS) and much better than that of WBO-RWA. We note that the average saving when using WBS is 53% for optimal WBS and 49% for BPHT (comparing with the total ports required when using ordinary-OXCs). In addition, in the process of trying to reduce the total number of ports, both our ILP solution and heuristic, BPHT have $\mathrm{W(a)} > 1$, that is, use more wavelength-hop (WH) 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 MG-OXC does not necessarily imply minimizing the number of WHs (even though minimizing WHs in networks without MG-OXC is equivalent to minimizing the number of ports). In fact, there is a tradeoff between the required number of WHs and ports.

Due to space limitation the results for single fiber are not shown here, however, we note that in multifiber networks there is a slight improvement in the performance in terms of T(a), M(a), and W(a) (over single-fiber networks), which we attribute to the inherent partial wavelength conversion capability. Additional results for BPHT and WBO-RWA in single and multiple fiber networks will be shown in Sections VI-C and D.

For a large network such as the NSF network, the ILP becomes intractable, hence, we will only study the previously described heuristic algorithms in the following sections.

B. NSF Network—Uniform Traffic

In this section, we focus on the validation of our analysis of BPHT (Section V). Fig. 5 shows the number of ports obtained from our analysis with simulation results for the NSF network assuming uniform traffic and two fibers per link. Curve "analysis" is from (20) and (21), curve "lower bound" is from (22) and curve "upper bound" is from (23). The figure illustrate how T(a) changes with the traffic intensity t_p (traffic demand per node pair), assuming that each of the two fibers has 30 bands, and each band has 4 wavelengths (so the total number of wavelengths, is $\mathcal{F} \times \mathcal{B} \times \mathcal{W} = 240$).

We see that when using heuristic algorithm BPHT, the number of MG-OXC ports drops significantly when t_p is a multiple of $\mathcal{W} = 4$ (e.g., t_p is 4, 8, 12, 16, etc.), the number of wavelengths in a band, and is very close to the analytical value. This can be explained as in Fig. 6(a), when the traffic demand (number of lightpaths) per node pair is a multiple of the number of wavelengths in a band (i.e., $\mathcal{W}$), using algorithm BPHT will enable MG-OXCs to add/drop/bypass traffic at the band granularity, rather than the wavelength granularity. This is similar to having an ordinary-OXC, wherein each port switches a band of wavelengths, thus reducing the number of ports. Further, note that when t_p is such that $\mathrm{Mod}(t_p, 4) = 2$ (e.g., t_p is 2, 6, 10, 14, etc.), the performance of BPHT is again close to its analytical value, this is due to the high probability of grouping bypass traffic as in Fig. 6(b).

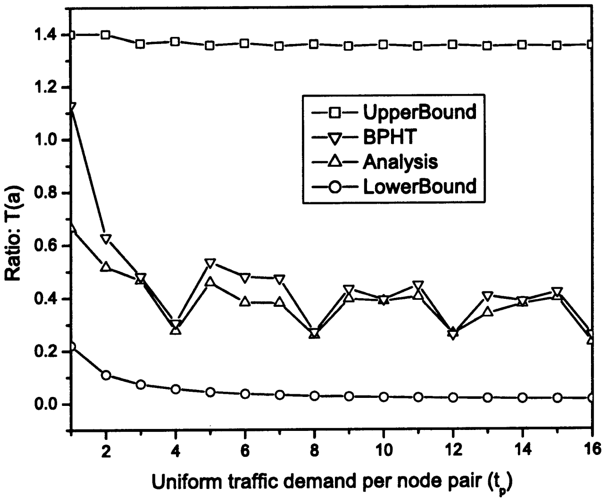
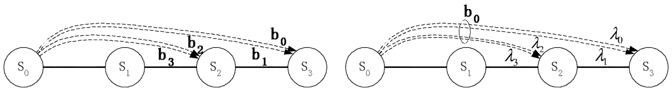


Fig. 5. $T(a)$ in NSF network.



(a)Uniform traffic (t_p=8) (b)Uniform traffic (t_p=2)

Fig. 6. Example of band grouping by BPHT ($\mathcal{W} = 4$).

We can also see that the performance analysis is accurate, as verified by our simulation results, especially at the points where the traffic demand is a multiple of the waveband granularity. At other points, the assumption in the analysis such as every add/drop traffic is evenly distributed on all the output links causes the deviation in the performance of BPHT from the analytical results. Note that similar results and trend is observed for the single-fiber ($\mathcal{F} = 1$) case.

C. NSF Network—Nonuniform Traffic: Single-Fiber Case

In this subsection, we focus on the comparison between WBO-RWA, BPHT and its variation BTMH, again using the NSF network but assuming nonuniform traffic.

Figs. 7–9 illustrate how the ratios $T(a), M(a)$, and $W(a)$ vary with changing waveband granularity (i.e., number of wavelengths in a band), but a fixed number of wavelengths per fiber (i.e., $\mathcal{K} = 120$). 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 BPHT is less than those using BTMH and much less than those using WBO-RWA.

Fig. 10 shows why assigning wavelengths to lightpaths with heavy traffic first is better than based on maximum hop first, and hence BPHT outperforms BTMH (using the first-fit wavelength assignment algorithm). In the example, it is assumed that there are two bands, one consisting of λ_0 and λ_1, the other consisting of λ_2 and λ_3, and four lightpaths, $S_0 \rightarrow D_1, S_0 \rightarrow D_2, S_0 \rightarrow$

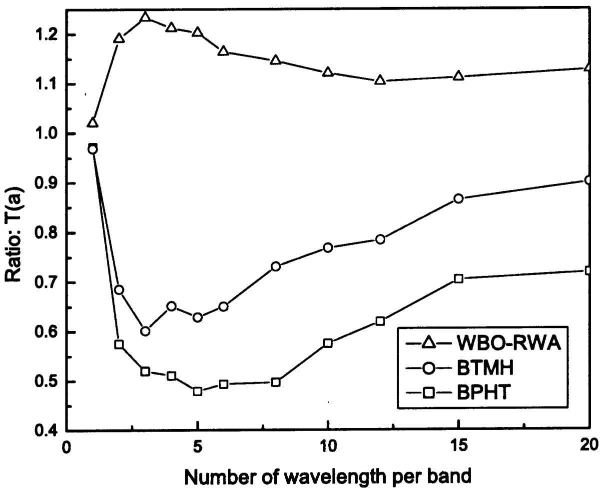


Fig. 7. $T(a)$ for random traffic.

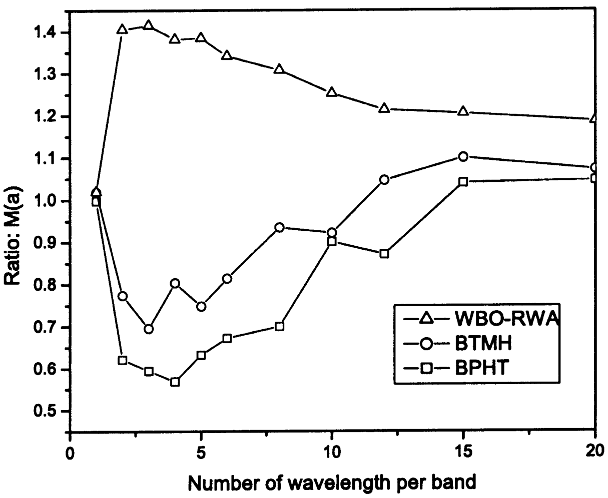


Fig. 8. $M(a)$ for random traffic.

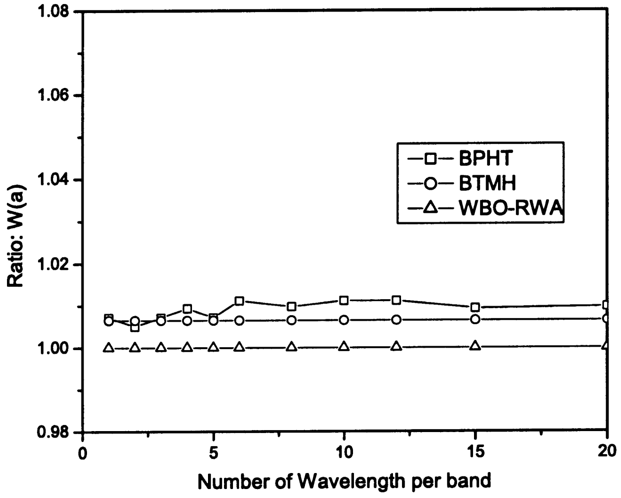


Fig. 9. $W(a)$ for random traffic.

D_3, and $S_0 \rightarrow D_4$. Using algorithm BTMH, we will assign wavelengths to $S_0 \rightarrow D_1$ followed by $S_0 \rightarrow D_2, S_0 \rightarrow D_3$, and $S_0 \rightarrow D_4$, and hence cannot group any of the lightpaths into bands. However, algorithm BPHT can save ports at nodes S_1, S_2, and S_3, by grouping the lightpaths $S_0 \rightarrow D_1$ with $S_0 \rightarrow D_3$ and $S_0 \rightarrow D_2$ with $S_0 \rightarrow D_4$ into bands.

Note that WBO-RWA may require more ports at MG-OXC than using ordinary-OXCs (as $\mathrm{T(WBO-RWA)} > 1$ in Fig. 7) indicating that WBO-RWA is ill-suited for networks with MG-OXCs. This is because such an oblivious algorithm uses ILP formulation to minimize the number of used WHs, it then groups wavelengths into bands and bands into fibers *only* as an afterthought (i.e., wavelengths are assigned without any consideration as to how they are going to be grouped). The reason for $\mathrm{T(WBO-RWA)} > 1$ here (and in Table I), is the large number of multiplexer/demultiplexer ports. On the other hand, as in the six-node network case, the ratio W(BPHT) does not change much with the change of waveband granularity and is bigger than 1 by *only* a small amount. Interestingly, the curves for BPHT in Figs. 7 and 8 indicate that with an appropriate wavelength granularity ($\mathcal{W} \simeq 5$), BPHT performs the best in terms of both $T(a)$ and $M(a)$, and can achieve more than 50% savings on the number of ports when using MG-OXCs instead of ordinary-OXCs.

Given that BPHT is better than its variation BTMH and due to space limitation, we will only present the results of the BPHT and WBO-RWA hereafter to show the advantage of using an intelligent WBS algorithm such as BPHT over using a trivial WBS algorithm like WBO-RWA or not using WBS at all.

Table II, shows in detail the number of ports used by each of the algorithms for a random traffic pattern, and for varying number of $\mathcal{B}$ and $\mathcal{W}$. Note that $\mathcal{K}$ (i.e., 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 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 $\mathcal{B}$ and $\mathcal{W}$. Columns FXC, BXC, and WXC represent the total number of ports at different layers. With increasing $\mathcal{B}$, the ports of BXC layer increase; the ports of WXC layer decrease; and the number of ports at FXC layer remains the same. Since we use a single-fiber system, hence the port number of FXC layer at a node is determined by the degree of that node (assuming there is some traffic on each fiber link). This fact is also evident in Tables III–IV.

Table III shows the number of the ports at an arbitrary node (node 2) in the NSF network using algorithms WBO-RWA and BPHT. Table IV gives the detailed port number information at randomly selected nodes in the NSF network. One can see that BPHT requires much less ports than WBO-RWA.

D. NSF Network—Nonuniform Traffic: Multifiber Case

In our experiments with multifiber networks, we once again find that BPHT performs better than its variations (including BTMH), and hence only show the comparison of algorithms BPHT and WBO-RWA, for the sake of conciseness.

1) Fixed Load: Figs. 11 and 12 illustrate how the ratios $T(a)$ and $M(a)$ vary with changing waveband granularity (i.e., number of wavelengths in a band) and number of fibers but a fixed number of wavelengths per link (i.e., $\mathcal{F} \times \mathcal{B} \times \mathcal{W} = 240$) and a fixed traffic load (i.e., the total traffic does not change

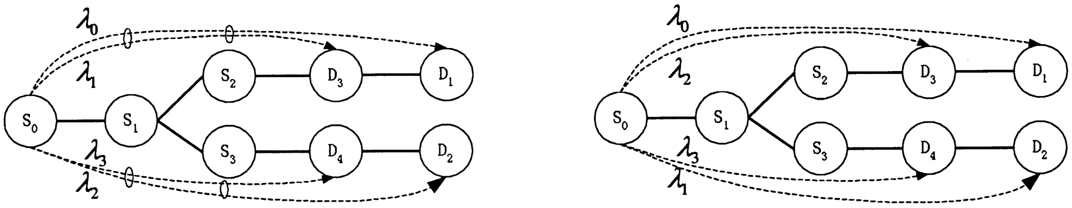


Fig. 10. Comparison of BPHT and BTMH.

TABLE II
TOTAL NUMBER OF PORTS IN NSF NETWORK ($\mathcal{F} = 1$)

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

TABLE III
NUMBER OF PORTS USED AT NODE 2 IN NSF NETWORK ($\mathcal{F} = 1$)

Scenarios	OXC	WBO-RWA				BPHT			
		FXC	BXC	WXC	Total	FXC	BXC	WXC	Total
$\mathcal{B}$=6,$\mathcal{W}$=20	262	6	36	248	290	6	24	103	133
$\mathcal{B}$=15,$\mathcal{W}$=8	262	6	83	212	301	6	45	24	75
$\mathcal{B}$=20,$\mathcal{W}$=6	262	6	106	182	294	6	52	18	76

TABLE IV
NUMBER OF PORTS AT DIFFERENT NODES IN NSF NETWORK ($\mathcal{F} = 1, \mathcal{B} = 20, \mathcal{W} = 6$)

Node	OXC	WBO-RWA				BPHT			
		FXC	BXC	WXC	Total	FXC	BXC	WXC	Total
Node 5	320	6	118	280	404	6	76	96	178
Node 9	338	8	152	280	440	8	85	115	208
Node 14	276	6	107	228	341	6	62	67	135

with $\mathcal{F}$ or $\mathcal{B}$ or $\mathcal{W}$) but a random pattern. 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 BPHT is much less than those from WBO-RWA, and that heuristic WBO-RWA requires more ports at MG-OXC than using ordinary-OXCs. Here again, the curves for BPHT in Figs. 11 and 12 indicate that with an appropriate waveband granularity ($\mathcal{W} \simeq 6$), BPHT performs the best in terms of both $T(a)$ and $M(a)$, achieving a saving of nearly 70% in number of ports when using MG-OXCs instead of ordinary-OXCs.

More specifically, we notice that multifiber MG-OXC networks perform better than single-fiber MG-OXC networks, as they can achieve a larger reduction in port count when using BPHT. This is because with multiple fibers (e.g., $\mathcal{F} = 4$) there is a higher probability to switch lightpaths as a group (whole fiber or band). In single-fiber networks, the advantage of having a FXC layer and fiber switching is not evident [10]. On the other hand, the situation is reversed for WBO-RWA, since WBO-RWA does not consider band or fiber switching, the wavelength assignment is done in a manner unsuitable for reducing port count. Hence the benefit of multifiber in reducing port count does not show up in the WBO-RWA algorithm.

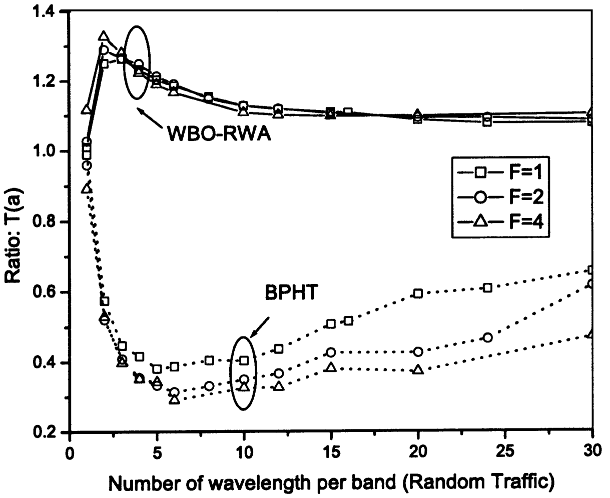


Fig. 11. Ratio $T(a)$, fixed load.

In addition, Fig. 13 shows how the ratios $T(a), W(a)$, and $M(a)$ vary with changing number of fibers per link (i.e., $\mathcal{F}$), but a fixed number of wavelengths per link (i.e., $\mathcal{F} \times \mathcal{B} \times \mathcal{W} = 240$), a fixed waveband granularity (i.e., $\mathcal{W} = 4$) and fixed traffic load. From Fig. 13, we can see that with appropriate number of fibers, having multiple fibers per link reduces necessary ports

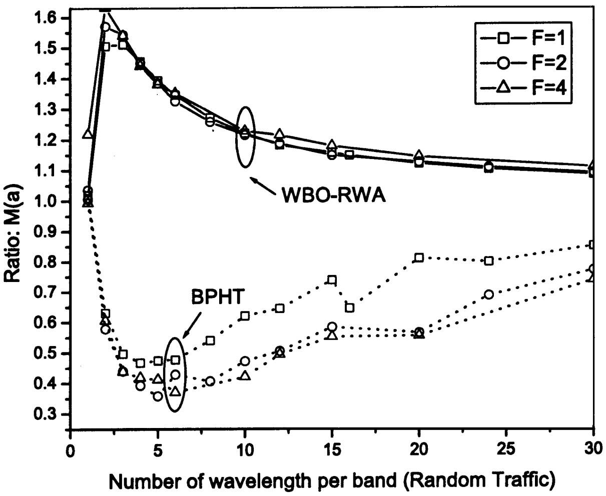


Fig. 12. Ratio $M(a)$, fixed load.

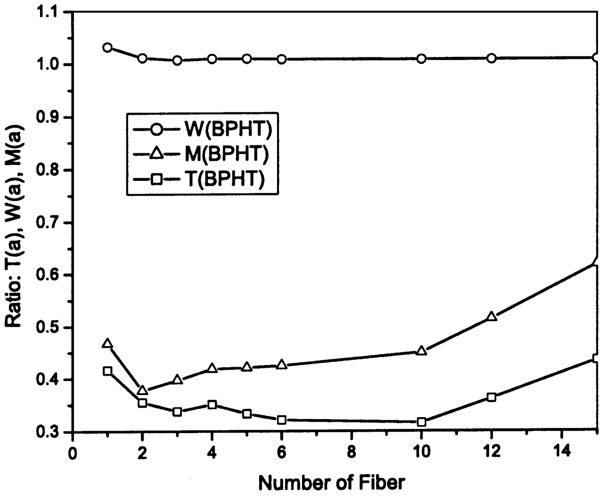


Fig. 13. Effect of multiple fibers per link (fixed load).

when compared with having only a single fiber. On the other hand, having too many fibers causes an increase in port count. The ratio W(BPHT), does not vary much with a change in the number of fibers and remains larger than one by a small amount indicating the tradeoff between the number of WHs and ports.

2) Proportional Load: Figs. 14–16 depict the variation in total port number, wavelength-hops and maximum port number with changing waveband granularity and fiber number but with a fixed number of wavelengths per fiber (i.e., $\mathcal{W} \times \mathcal{B} = 60$). The traffic demand is directly proportional to the number of fibers (i.e., if $\mathcal{F}$ is doubled, the traffic demand $T[p]$ is also doubled). We see that the WHs increase almost proportionally to the number of fibers (and traffic load) for BPHT. On the other hand, we notice that the total number of ports and maximum port number increase *sublinearly* with an increase in the number of fibers (and traffic load) for BPHT. This is because there is a higher probability for wavelength grouping (into fibers and bands) in multifiber networks using the BPHT algorithm. However, we find that the total port number and maximum port number for WBO-RWA increase rapidly with an increase in the number of fibers, further indicating the effectiveness of our proposed BPHT algorithm.

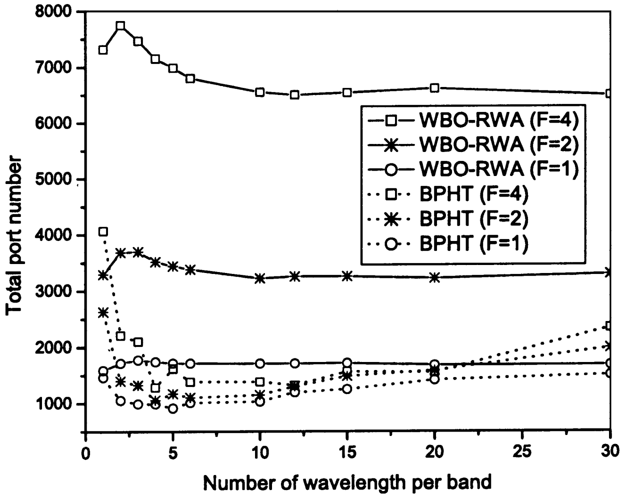


Fig. 14. Total port count (Proportional Load).

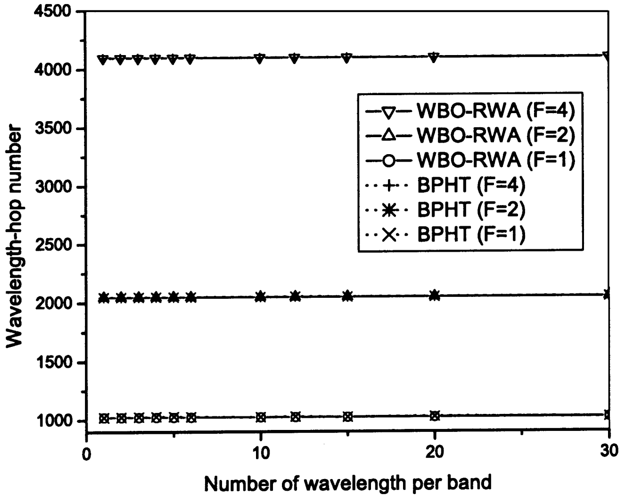


Fig. 15. Total wavelength-hops (proportional load).

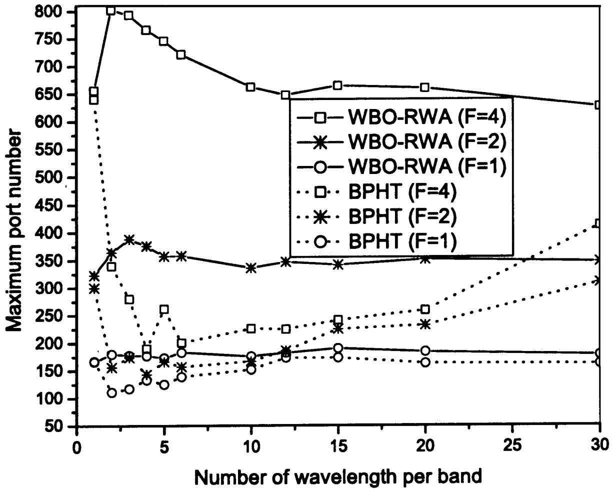


Fig. 16. Maximum number of ports (proportional load).

VII. CONCLUSION

One of the major factors contributing to the cost (and complexity) of OXC is its port count. In this work, we have studied the problem of WBS in multigranular optical networks. We have adopted the most powerful waveband assignment strategy and developed a corresponding ILP formulation, and an efficient heuristic algorithm, BPHT for the WBS problem. The ILP model and the heuristic algorithm (which use a new multifiber waveband assignment algorithm) can handle the case with both single and multiple fibers per link, and hence are generalized solutions.

We have verified that the proposed BPHT heuristic can achieve near-optimal results by comparing its performance with that of the ILP formulation (which is feasible for small networks only). In addition, the performance of BPHT has been analyzed and the results from analysis are verified with simulation. We have also compared the performance of BPHT with that of a heuristic that uses ILP to perform optimal RWA (WBO-RWA) and BTMH (which is a variation of BPHT) via extensive simulations for varying network topologies and traffic patterns, and shown that BPHT is significantly better.

Our performance evaluation has shown that WBS is even more beneficial in multifiber networks, and that the waveband granularity has a large effect on the performance of WBS networks. In particular, with appropriate waveband granularity, using MG-OXCs can save up to 50% ports in single-fiber networks and up to 70% ports in multifiber networks, when compared with using ordinary-OXCs. While our ILP formulations and heuristic are especially useful for the efficient design of MG-OXC nodes (i.e., the dimensioning of the switching matrices) for a given set of traffic demands, they can also be used to minimize the number of used active ports in an existing network and, thus, lower network operating costs and reduce blocking probability of future requests.

REFERENCES

[1] K. Harada, K. Shimizu, T. Kudou, and T. Ozeki, “Hierarchical optical path cross-connect systems for large scale WDM networks,” in *Proc. Optical Fiber Communication Conf. (OFC)*, Feb. 1999, pp. 356–358.

[2] L. Noirie, M. Vigoureux, and E. Dotaro, “Impact of intermediate grouping on the dimensioning of multi-granularity optical networks,” in *Proc. Optical Fiber Communication Conf. (OFC)*, 2001, p. TuG3-3.

[3] E. Dotaro *et al.*, “Optical multi-granularity architectural framework”, Aug. 2002. draft-dotaro-ipo-multi-granularity-02.txt.

[4] A. A. M. Saleh and J. M. Simmons, “Architectural principles of optical regional and metropolitan access networks,” *J. Lightwave Technol.*, vol. 17, pp. 2431–2448, Dec. 1999.

[5] O. Gerstel, R. Ramaswami, and W. Wang, “Making use of a two stage multiplexing scheme in a WDM network,” in *Proc. Optical Fiber Communication Conf. (OFC)*, Mar. 2000, pp. 44–46.

[6] 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 *Proc. Optical Fiber Communication Conf. (OFC)*, Mar. 2002, pp. 442–443.

[7] R. Lingampalli and P. Vengalam, “Effect of wavelength and waveband grooming on all-optical networks with single layer photonic switching,” in *Proc. Optical Fiber Communication Conf. (OFC)*, Mar. 2002, pp. 501–502.

[8] R. Izmailov, S. Ganguly, Y. Suemura, I. Nishioka, Y. Maeno, and S. Araki, “Waveband routing in optical networks,” presented at the IEEE Int. Conf. Communications (ICC’02), New York, NY, 2002.

[9] 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 J. Select. Areas Commun.*, vol. 20, pp. 166–171, Jan. 2002.

[10] X. Cao, Y. Xiong, V. Anand, and C. Qiao, “Wavelength band switching in multi-granular all-optical networks,” in *SPIE’s Proc. OptiComm’02*, vol. 4874, Boston, MA, 2002, pp. 198–210.

[11] D. Banerjee and B. Mukherjee, “A practical approach for routing and wavelength assignment in large wavelength-routed optical networks,” *IEEE J. Select. Areas Commun.*, vol. 14, pp. 903–908, June 1996.

[12] B. Mukherjee, D. Banerjee, S. Ramamurthy, and A. Mukherjee, “Some principles for designing a wide-area optical network,” *IEEE/ACM Trans. Networking*, vol. 4, pp. 684–696, Oct. 1996.

[13] I. Chlamtac, A. Ganz, and G. Karmia, “Lightpath communications: An approach to high bandwidth optical WAN’s,” *IEEE Trans. Commun.*, vol. 40, pp. 1171–1182, July 1992.

[14] L. Berger *et al.*, Ed., “Generalized multi-protocol label switching (gmpls) signaling functional description,” IETF, RFC 3471, IETF Proposed Standard, Jan. 2003.

[15] L. Berger *et al.*, Ed., “Generalized MPLS signaling—CR-LDP extensions,” IETF, RFC 3472, IETF Proposed Standard, Jan. 2003.

[16] L. Berger *et al.*, Ed., “Generalized MPLS Signaling—RSVP-TE Extensions,” IETF, RFC 3473, IETF Proposed Standard, Jan. 2003.

[17] “Link Management Protocol (LMP)”, J. Lang *et al.*, Eds., Internet Draft, Nov. 2002. draft-ietf-ccamp-lmp-07.txt.

[18] R. Douville *et al.*, “Extensions to generalized MPLS in support of waveband switching”, Feb. 2003. draft-douville-ccamp-gmpls-waveband-extensions-03.txt.

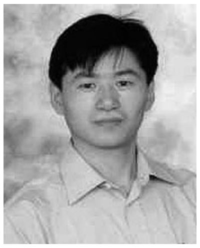
[19] A. Mokhtar and M. Azizoglu, “Adaptive wavelength routing in all-optical networks,” *IEEE/ACM Trans. Networking*, vol. 6, pp. 197–206, Apr. 1998.

[20] R. Ramaswami and G. H. Sasaki, “Multiwavelength optical networks with limited wavelength conversion,” in *Proc. INFOCOM’97*, 1997, pp. 490–499.

[21] G. Jeong and E. Ayanoglu, “Comparison of wavelength-interchanging and wavelength-selective cross-connects in multiwavelength all-optical networks,” in *Proc. INFOCOM’96*, 1996, pp. 156–163.

[22] R. Sabella, E. Iannone, M. Listani, M. Berdusco, and S. Binetti, “Impact of transmission performance on path routing in all-optical transport networks,” *J. Lightwave Technol.*, vol. 16, pp. 1965–1972, Nov. 1998.

[23] J. Yen, “Finding the k shortest loopless paths in a network,” *Manage. Sci.*, vol. 17, no. 11, pp. 712–716, 1971.



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