A New Dynamic Wavelength Assignment Scheme in Wavelength-Convertible WBS Networks

Ching-Fang Hsu, Fang-Sheng Lin and Ke-Kuan Hsu

Abstract—In the paper, we study the wavelength assignment problem in waveband switching (WBS) networks, which is composed of multi-granular optical cross-connect (MG-OXCs) interconnected by fiber links. WBS networks with MG-OXCs can route traffic at multiple granularities at the same time; therefore, the complexity of switching fabrics can be efficiently reduced. Moreover, in order to relax the wavelength continuity constraint on lightpath establishments, each MG-OXC node is equipped with certain number of wavelength converters. Focusing on minimizing the extra port consumption and utilizing wavelength converters in an efficient manner, we propose a heuristic algorithm, named Least-Configuration with Bounded Conversion (LCBC), under the dynamic traffic environment. Simulation results show that our algorithm can achieve a considerable port saving and significant performance gain by a well-design cost function.

Index Terms—Wavelength Assignment, Waveband Switching (WBS), Multi-Granular Optical Cross-Connect (MG-OXC)

I. INTRODUCTION

With the explosive growth of data traffic, all-optical networks using wavelength division multiplexing (WDM) [11]-[12] have become a practical and promising choice for Internet backbone. In the past few years of development, the rapid advances in dense WDM (DWDM) technology with hundreds of wavelengths (each operating at 2.5Gbps or higher) per fiber have significantly increased the available bandwidth. However, it also caused a tremendous raise in the cost and size of optical cross-connects (OXCs). Therefore traditional OXCs which switch traffic only at wavelength granularity will need a great deal of wavelength ports, resulting in unacceptable complexity and difficulty associated with controlling and management of such large OXCs. The key idea of Waveband Switching (WBS) is to aggregate a set of wavelengths into a band and switch the band using a single port whenever possible [6][10][13]-[14]. Consequently, a waveband route can reduce the number of required ports as compared with the corresponding wavelength route. A WBS network means a WDM network with full WBS capabilities, including waveband switching, waveband assignment, waveband aggregation, and waveband de-aggregation. The major objective of WBS problem is to minimize total port usage with given traffic loads.

As to lightpath establishment, one possible way to relax the wavelength continuity constraint is to exploit wavelength converters at switching nodes. Since wavelength converters are still very expensive under the current technology [12], it is more practical and cost-effective to share a set of limited range wavelength converters at each node. Furthermore, it has been shown in [16] that switching nodes with shared conversion resources can achieve performance very close to that of networks using switches equipped with one dedicated converter for each wavelength.

In the past few years, several OXC architectures were proposed to solve WBS problem in literatures [3]-[5][8]-[9]. Among these architectures, MG-OXC and hybrid hierarchical OXC are the most widely investigated ones. Certainly, the effectiveness of a WBS algorithm does not depend on OXC architectures only. There are much different factors to take into account in WBS algorithm design. In addition to OXC architecture, WBS differs from conventional wavelength routing in several ways, for example, different objectives. More specifically, those algorithms designed to address RWA problem for wavelength-routed networks cannot be directly applied to WBS networks.

The focus of our research is the wavelength assignment problem [1][15] in wavelength-convertible WBS networks for dynamic traffic. In order to yield more savings in port usage and converter consumption while maintaining the network performance at a reasonable level, we proposed a new heuristic algorithm based on the layered graph approach to solve this dynamic wavelength assignment problem efficiently. Briefly speaking, the key issue of the heuristic is how to determine the weight function for edges of the auxiliary graph.

The rest of this paper is organized as follows. In section II, we introduce the reconfigurable multi-granular OXC (MG-OXC) architecture. In section III we formally state the problem we investigated and the proposed algorithm for the wavelength assignment problem. Numerical results from our heuristic algorithm are presented in section IV. Finally, conclusions are given in section V with a summary of the major contributions of our research.

II. RECONFIGURABLE MG-OXC AND RELATED WORK

The MG-OXC is composed of three cross-connect layers as shown in Fig. 1: fiber cross-connect (FXC) layer, band cross-connect (BXC) layer and wavelength cross-connect (WXC) layer. The cross-connect at each layer is used to switch data traffic at corresponding granularity. In addition to cross-connects, both the BXC and WXC layers consist of multiplexers and de-multiplexers. At the BXC layer, those de-multiplexers called fiber-to-band (FTB) de-multiplexers are used to de-multiplex fibers into bands, and multiplexers called band-to-fiber (BTF) multiplexers are used to multiplex bands into fibers. Similarly, The WXC layer also includes band-to-wavelength (BTW) de-multiplexers and...
wavelength-to-band (WTB) multiplexers. Lightpaths are added/dropped at the WXC layer using \( W_{\text{add}}/W_{\text{drop}} \) ports of the WXC.

The MG-OXC switches a fiber using just two ports (input/output) of the FXC if all wavelengths within this fiber are switched to the same output port and none of them is used to add/drop a lightpath. Otherwise, it uses an inactive FTB de-multiplexer to de-multiplex the fiber into bands. In the worst case, some wavelengths need to be added or dropped, and then this incoming fiber has to be pulled to the WXC layer from the FXC layer, consuming a great number of ports. The challenges of designing RWA algorithms for WBS networks with wavelength conversion require all MG-OXC architectures are how to achieve a low blocking probability and large savings in port count.

In [4], the authors proposed a new MG-OXC architecture, which is reconfigurable and more flexible. They suggested that WBS networks only need some of fibers to de-multiplex into bands, and only a limited number of these bands to de-multiplex into wavelengths. In order to reduce the size and cost of the switching nodes, they use two parameters \( \alpha \) and \( \beta \) to restrict the number of ports at BXC and WXC layers, respectively. \( \alpha \) is the ratio of fibers that can be de-multiplexed into bands, while \( \beta \) is the ratio of wavebands that can be de-multiplexed into wavelengths. More specifically, if \( X \) denotes the number of incoming fibers and \( Y \) denotes the number of ports at the BXC layer from FTB de-multiplexers, only fibers can be de-multiplexed into bands, and similarly, only bands can be de-multiplexed into wavelengths simultaneously. According to the investigation of the authors in [4], it is necessary to set \( \alpha = 1 \) in the single-fiber systems (only one fiber for each link) to allow all incoming fibers at the FXC layer to de-multiplexed into bands, otherwise, the blocking probability is too high.

Because of much flexibility of the reconfigurable MG-OXC, our research is based on this architecture to develop a heuristic algorithm to solve the wavelength assignment problem of WBS networks with wavelength converters. In order to support the conversion capability in WBS networks, the reconfigurable MG-OXC architecture is equipped with a wavelength conversion bank at the WXC layer. There is a unique issue related to using wavelength converters in WBS networks, every performance of wavelength conversion requires all wavelengths in a band to be de-multiplexed and consumes many ports. Hence, inefficient banding and employment of converters may cause more blocking to future requests due to the limitation of OXC ports.

Based on the share-per-link architecture, the authors in [2] proposed a heuristic algorithm called waveband assignment with path-graph (WAPG) to address the effect on the blocking performance and efficient usage of wavelength converters in WBS networks with wavelength conversion. Note that WAPG can be easily applied on the share-per-node architecture as well. The objective of WAPG is to minimize the usage of wavelength converters when accommodating a new connection request, and therefore, reducing port consumption caused by exploitation of wavelength conversion. In most situations, nevertheless, using wavelength converters inappropriately causes more extra port usage than employing wavelength converters regularly. Disregard of those extra port usage consumed by conversion leads more requests to be blocked, resulting from the limited number of ports at the MG-OXCs. Based on the observation that minimizing the total port usage for satisfying each connection demand can efficiently overcome the performance lose caused by limited number of BTW and WTB ports at MG-OXCs, we proposed a novel heuristic algorithm.

III. THE PROPOSED SCHEME

A. Problem Definition

Let us model the network topology as an undirected graph, which consists of \( N \) vertices and \( L \) edges. Each vertex \( n \) corresponds to a MG-OXC node equipped with intra-band or full degree wavelength converters, while each edge \( e \) stands for a bidirectional fiber link in the given network. For simplicity, assume that each fiber link has \( W \) wavelengths, which are uniformly partitioned into \( B \) wavebands, and we use \( \Lambda = \{ \lambda_0, \lambda_1, ..., \lambda_{B-1} \} \) to denote the set of wavelengths. According to the index continuity, a fixed number, say \( K \) wavelengths in the set are chosen to be grouped into a band. More specifically, the waveband \( b_i (i = 0, ..., B-1) \) contains the wavelengths with contiguous indices from \( iK \) to \( (i+1)K-1 \). As a single-fiber system is considered, we set \( \alpha = 1 \) to avoid substantially degrading the blocking performance, whereas the value of \( \beta \) is adjusted to limit reconfiguration. Under the assumption that each port in an MG-OXC would cause identical cost increasing, we would like to address two major objectives of wavelength assignment problem while keeping the network performance as good as possible in convertible WBS networks with dynamic traffic. The first one is to minimize the total number of ports used, whereas the second one is to utilize wavelength conversion in a most efficient manner.

B. The Proposed Wavelength Assignment Algorithm

In this subsection, we proposed a new heuristic algorithm, called Least-Configuration with Bounded Conversion (LCBC), to accommodate each request with minimum induced port consumption and constricted conversion. For brevity, necessary notations are defined as TABLE I. Let us use an example to illustrate how LCBC algorithm works and exploits layered graph model. For a new demand \( req(s, d) \), the first step is adopting the fixed routing algorithm to pick out the pre-computed path \( p_{s,d} \) whose hop length, say \( h_{s,d} \), is minimum.
In Fig. 2(a), $h_{s,d}$ is 2 and $p_{s,d}$ is represented as a directed path with the only intermediate node $v_1$. Then, we can construct the corresponding auxiliary graph $G_{s,d}$ as shown in Fig. 2(b). Since

<table>
<thead>
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<th>TABLE I. NOTATIONS</th>
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<tr>
<td>$G = (V, E)$</td>
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<tr>
<td>$req(s, d)$</td>
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<tr>
<td>$p_{s,d}$</td>
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<tr>
<td>$\lambda$</td>
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<tr>
<td>$G_{s,d} = (V_{s,d}, E_{s,d})$</td>
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Here, $\delta_{\lambda}^{s,d}$ is the extra configuration cost required at node $v_i$ if the input channel and output channel are on wavelength $\lambda$ and $\lambda'$ respectively. While $\lambda \neq \lambda'$, it means that a conversion takes place at node $v_i$. $\phi$ is a flag denoting whether conversion would take place or not. $\epsilon$ is the weight factor used to decrease the probability of utilizing wavelength conversion. $D$ is the wavelength conversion degree.

$G_{s,d} = \bigcup_{\lambda=0}^{W-1} G_{s,d}^{\lambda}$ if wavelength converters are absent at all intermediate nodes, as long as each $G_{s,d}^{\lambda} \lambda$ is constructed, we can obtain $G_{s,d}$ successfully. On the other hand, those edges which connect virtual nodes in different layers should be created while there are still available wavelength converters at some intermediate nodes. Exploiting the concept of layered graph model, each $G_{s,d}^{\lambda}$ corresponds to a layer. Within an auxiliary graph $G_{s,d}$, there are several components whose definitions are given as follows.

1. **Transmitting nodes and receiving nodes**
   - For each transmitting node of wavelength $\lambda$ on $p_{s,d}$, create $v_{i_1}^{s,d}$ as its corresponding transmitting node on wavelength $\lambda$ on $p_{s,d}$. Similarly, for each receiving node of wavelength $\lambda$ on $p_{s,d}$, create $v_{i_2}^{s,d}$ as the corresponding receiving node on wavelength $\lambda$ on $p_{s,d}$.

2. **Transmission edges**
   - For each wavelength $\lambda$ and each link $(v_i, v_{j+1})$ on $p_{s,d}$, create transmission edge $e_{i,i+1}^{s,d}$ from $v_{i_1}^{s,d}$ to $v_{i_1+1}^{s,d}$ if wavelength $\lambda$ is available on link $(v_i, v_{j+1})$, $0 \leq i \leq h_{s,d}$.1.

(3) **Internal edges**
   - For each common intermediate node $v_i$, create an internal edge $e_i^{s,d}$ from $v_i^{s,d}$ to $v_i^{s,d}$ if at least one wavelength converter is available at $v_i$ on $p_{s,d}$, where $0 \leq \lambda \leq W-1$, $0 \leq i \leq W-1$, and $|\lambda - \lambda'| < D$.

(4) **Dummy source node, dummy destination node, generation edges and termination edges**
   - Create $s'$ and $d'$ asdummy source and dummy destination node. Add directed edges, named generation edges, from $s'$ to all transmitting nodes $v_0^{s,d}$ individually, $0 \leq i \leq W-1$.
   - Similarly, add directed edges called termination edges from all receiving nodes $v_H^{s,d}$ to $d'$ respectively.

Once the auxiliary graph is constructed, appropriate weights should be individually assigned to edges in the layered graph. As we aim at minimizing usage of converters and extra ports, the cost of transmission edges are not considered here and set to zeros. In order to effectively minimize the extra port consuming and use wavelength converters more efficiently, we designed a novel cost function for weight determination in the auxiliary graph. In our proposed cost function, the extra configuration cost is taken into consideration. Moreover, the conversion capability of wavelength converters and a proper constraint are applied to effectively reduce hardware cost as wavelength conversion is inevitable.

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**Fig. 2.** Illustration of layered graph construction (a) A sample shortest path $p_{s,d}$ (b) The auxiliary graph corresponding to (a) based on the layered graph model if there is no existing lightpath and $v_1$ equips with full-degree converters.

![Diagram](image-url)
1 if \( \lambda \neq \lambda' \) and equal to 0 if \( \lambda = \lambda' \). Meanwhile, to minimize the number of wavelength converters required, we should stress the cost of utilizing converters. Intuitively, the cost of a wavelength converter should be in proportion to its conversion capability. Here, we use the ratio \( \frac{D}{W} \) to represent this capability, where \( D \) indicates the wavelength conversion degree and \( W \) stands for the link capacity. Furthermore, the number of converters required can be bounded to a particular value. To achieve the suppression of converter usage, we add the weight factor \( e \) to control the significance of conversion on the total cost of lightpath establishment. The function \( \theta \) is defined as follows.

\[
\theta(\delta_{s,d}^{i,k}, \phi, D, W, e) = \delta_{s,d}^{i,k} \left( 1 + \phi \frac{D}{W} e \right),
\]

\[ \phi = \begin{cases} 0, & \text{no wavelength conversion performed} \\ 1, & \text{wavelength conversion occurred} \end{cases} \] (1)

For generation edges and termination edges, we only concern about the extra induced port consumption \( \delta_{s,d}^{i,k} \), where \( \lambda' = \lambda \). On the other hand, since wavelength converters are still very expensive devices, we take conversion capability into account while determining the weighting of an internal edge \( \phi_{s,d}^{i,k} \), where \( \lambda \neq \lambda' \). If there exists a wavelength which is free on all the links of \( p_{s,d} \), a wavelength-continuous lightpath on \( p_{s,d} \) can be established. As a result of adequately multiplying conversion capability by a weight factor \( e \), it can be guaranteed that wavelength converters would be used only when we cannot find a wavelength-continuous path.

Finally, the well-known Dijkstra algorithm is exploited to determine a path from \( s' \) to \( d' \) with minimum cost. The associated wavelength(s) with this path are chosen to accomplish the new connection demand. If no path can be found, the request is blocked. Moreover, to avoid the occurrence of wavelength conversion whenever possible, we can further optionally restrict the operation of conversion at a node by reasonable constraints even though the node still has available wavelength converters. For example, we can predetermine a threshold of \( \delta_{s,d}^{i,k} \) and conversion is allowed at node \( v \) only when \( \delta_{s,d}^{i,k} \) does not exceed the threshold.

Similar to WAPG, the computation complexity of LCBC strongly depends on the size of layered auxiliary graph. Given a request \( req(s, d) \), assume that a shortest path from \( s \) to \( d \) with length \( h_{s,d} \) is picked out. Then, an auxiliary graph which consists of \( W \times h_{s,d} \) vertices is constructed. The time complexity of calculating \( \delta_{s,d}^{i,k} \) is constant and the number of times of weight calculation is equal to the number of edges in the auxiliary graph excluding the transmission edges, the total time complexity for calculation of port consumption is \( O(h_{s,d} WD) \). When \( D \) approaches the order of \( W \), the complexity is equivalent to \( O(h_{s,d} W^2) \). On the other hand, the time complexity for applying Dijkstra algorithm to the auxiliary graph is \( O(h_{s,d} W \log(h_{s,d} W) + h_{s,d} WD) \) by implementing a Fibonacci heap. Consequently, suppose that \( H \) denotes the average length of the shortest path from source node to destination node, the asymptotic time complexity of LCBC is \( O(HW \log(HW) + HWD) \), which is identical to that of WAPG.

### IV. PERFORMANCE EVALUATION

To demonstrate the superiority of LCBC, we evaluate its performance under various scenarios in this section. WAPG, which was proposed in [2], is assessed as well so that the whole evaluation could be fair and meaningful. With our simulation results, we investigate the effects on blocking performance brought by varied waveband granularities and link capacity. Moreover, the usage of switching ports and wavelength converters is another effectiveness measure we would like to observe as well.

#### A. Simulation Environment

The network topology considered in our simulation scenarios is USAnet backbone [2], which consists of 46 nodes and 76 links. Assume that each link is a bidirectional fiber and has identical capability, there are 80 wavelengths in a fiber (\( W = 80 \)) and the wavelength partitioning follows a uniform fashion. The waveband granularity, denoted as \( K \), refers to the number of wavelengths in each waveband. Furthermore, each node in the WBS networks is assumed to be a MG-OXC. Because it will incur a significant reduction of blocking performance when \( a < \)
1 in single-fiber systems, a large value for $\alpha$ (say, $\alpha = 1$) is preferred. On the other hand, we set $\beta=0.75$ to limit the number of BTW/WTB ports of MG-OXCs.

Considering the dynamic characteristics of data traffic, traffic load is offered in form of connection requests following a Poisson process with mean $\gamma$. For each request, two nodes are randomly chosen as the source and the destination. The connection duration time is assumed to be exponentially distributed with mean of 1 time unit. For simplicity, supposed that no existing lightpaths can be rearranged accommodate the incoming request. According to distinct wavelength assignment constraint, a wavelength which has been occupied can not be used again until its corresponding connection is released. Briefly speaking, our simulation results can be categorized into three cases in terms of the conversion capability. In the "NWC" case, no wavelength conversion is allowed in the network. In contrast, for the "IWC" and "FWC" cases, converters are equipped with intra-band and full-degree of conversion capability respectively.

B. Numerical Results

(1) The Effect of Waveband Granularity

![Fig. 3. Blocking probability vs. waveband granularity with $P = 80$](image)

First, we evaluate network blocking performance with waveband granularities $K = 4$, 8, 10 and 16 under different traffic loads. The number of wavebands on a link depends on what level of granularity $K$ is chosen. Further, the number of limited ports (BTW/WTB ports) is determined by the total number of wavebands in the node as the ratio $\beta$ is fixed. Consequently, it becomes more and more critical to save reconfiguration cost efficiently while a high waveband granularity is considered. The relation between waveband granularity and blocking probability is shown in Fig. 3. Trivially, it is expectable that heavier traffic load results in higher blocking probability. In general, the blocking performance of WAPG is much more sensitive to waveband granularity than that of LCBC. In the case of WAPG, the performance gap between various waveband granularities is much more apparent. The rationale behind this phenomenon is whether the waveband grouping is considered properly.

(2) Mean Extra Port Consumption

One main objective of LCBC is to minimize the extra port consumption for each connection request. Let $\hat{\delta}$ stand for the mean extra port consumption through the simulation period. To investigate $\hat{\delta}$ of WAPG and LCBC, we set $K = 10$ and $\varepsilon = 320$ and adopt various conversion capabilities. Based on the share-per-node architecture, each switch node is equipped with 25 converters. Fig. 4 shows the value of $\hat{\delta}$ under various arrival rates in USAnet. As shown in the figure, while conversion is performed at the wavelength level, more number of extra switching ports is consumed to utilize converters. The "IWC" case of WAPG, which is contributive to effective waveband grouping as compared with the "FWC" case, provides more opportunities to utilize converters and results in a better performance with the price of higher port usage. In LCBC, port consumption is a major consideration even if conversion is necessary. Therefore, the flexibility of "FWC" is adequately made use of, leading to a fewer switching cost. Undoubtedly, LCBC is more beneficial than WAPG observed in port utilization.

![Fig. 4. Mean extra port consumption vs. traffic load](image)

(3) Blocking Performance and Converter Utilization

Following previous assumptions, we set $K = 10$ and $\varepsilon = 320$ and allocate 25 converters to each switch node. For evaluating wavelength converter utilization, we measure the maximum number of required converters at a node (denoted as $WC_{max}$). Specifically, it is obtained by observing the maximum converter consumption of each node during the simulation period and then picking out the maximum. Thus this metric signifies an upper bound of converter requirement and needs to be distributed over the whole network so that there would be no blocking resulted from the lack of converters if the number of equipped converters is no less than this bound.

Fig. 5 shows the benefit of efficient grouping to improve the blocking performance. For example, LCBC outperforms WAPG by 93.2% with $\gamma = 320$, 42.1% with $\gamma = 440$ and 30.7% with $\gamma = 520$ in the "IWC" case. A notable phenomenon is that, WAPG yields less performance gains on blocking performance with "FWC" capability than with "IWC" capability. At a node which equips with "FWC" converters, a wavelength can be shifted to the other wavelength which is not guaranteed to be in the same wavelength. WAPG, which only concentrates on the same waveband, shifts to the other wavelength which is not guaranteed to be in the same waveband. WAPG, which only concentrates on the same waveband, shifts to the other wavelength which is not guaranteed to be in the same waveband.
are very close in LCBC. Consequently, using "IWC" converters ought to be a more cost-effective way.

![The blocking performance](image)

Fig. 5. Blocking probability vs. traffic load

The comparisons of wavelength converter usage are depicted in Fig. 6. LCBC has much higher converter usage than WAPG at light load and the rationales come from two aspects. First, LCBC leaves more vacant ports for necessary conversion and consequently offers more chances to establish lightpaths experiencing conversion. On the other hand, instead of focusing on using converters as few as possible, LCBC prefers the feasible choice with least configuration cost, even though sometimes little more converters are required in this way. However, we can observe that converters are exploited adequately in heavy traffic load, and LCBC still has a significant performance improvement over WAPG. Consequently, LCBC offers great advantages, including switching ports saving and network performance gain, in wavelength-convertible MG-OXC networks.

![Maximum number of required converters per node](image)

Fig. 6. WC_{max} vs. traffic load

V. CONCLUSIONS

In this paper, we proposed a heuristic algorithm, named LCBC, to solve the dynamic wavelength assignment problem in wavelength-convertible MG-OXC networks. Adopting fixed routing as the routing selection algorithm, we transform the wavelength selection sub-problem into an equivalent shortest-path problem in an auxiliary graph. Moreover, we proposed a cost function to assign an appropriate weight to each edge, such that limited resource, including BTW/WTB ports and wavelength converters, could be exploited more efficiently.

To investigate the superiority of the proposed approach, we developed the simulation to observe the performance of LCBC and that of WAPG with various waveband granularities, link capacities, and conversion degrees under USAnet backbone. The simulation results show that LCBC outperforms WAPG significantly in terms of blocking performance. Particularly, for a large waveband granularity and high link capacity, LCBC can achieve much significant blocking performance gain and just a little more converter usage under light loads.

REFERENCES