Wavelength Assignment in Waveband Switching Networks with Wavelength Conversion

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Abstract—Waveband Switching (WBS) wherein wavelengths are grouped into bands and switched as a single entity can reduce cost and complexity of switching nodes by minimizing the port count. In this paper, we study the effect of wavelength conversion on the performance of WBS networks with reconfigurable Multi-Granular Optical Cross-connects (MG-OXCs) to satisfy online traffic. Since wavelength conversion is still expensive and can potentially increase the number of used ports in WBS networks, efficient usage of wavelength converters is of practical interest. We propose a novel heuristic algorithm, called Waveband Assignment with Path-Graph (WAPG), which takes efficient wavebanding and efficient usage of wavelength converters into consideration when satisfying new lightpath requests. We apply WAPG algorithm in WBS networks with full, intra-band, or limited number of wavelength converters, and compare with the FirstFit and RandomFit algorithms. Our results indicate that the proposed algorithm performs significantly better in terms of the blocking probability as well as the number of used wavelength converters.

I. INTRODUCTION

Optical network employing wavelength division multiplexing (WDM) is a promising solution to meet the high bandwidth requirements of emerging communication applications such as video-on-demand and transmission of media-rich content. Recently, Waveband switching (WBS) in conjunction with new Multi-Granular Optical Cross-connects (MG-OXCs) has attracted significant attention for its practical importance in reducing the port count, associated control complexity, and cost of photonic cross-connects [1]–[4]. The main idea of WBS is to group several wavelengths together as a band, and switch the band using a single port whenever possible (e.g., as long as it carries only bypass or express traffic), and demultiplex the band to switch individual wavelength only when some traffic needs to be added/dropped. Since most of the traffic in the network backbone is bypass traffic, only a limited number of fibers and bands need to be demultiplexed into wavelengths. Thus, not only the size of wavelength cross-connects, but also the overall port counts of the MG-OXCs can be reduced by using WBS.

An MG-OXC that can switch traffic at fiber, waveband and wavelength granularities was presented in [1], and the application of such Three-Layer MG-OXC architectures to metro-area networks was briefly demonstrated in [5]. Hybrid hierarchical switches (with all-optical waveband switching and OEO traffic grooming) have been studied in [4], [6]. The work in [6] also studied the benefit of using non-uniform waveband hierarchy while the authors of [7] presented MILP-based approaches for the design of a two-layer MG-OXC network using a simple lightpath grouping strategy, which does not take full advantage of the benefits of wavebanding. In our previous research [3], we presented an Integer Linear Programming (ILP) model and corresponding heuristics to minimize the total number of ports counts required to support a given static traffic pattern.

In wavelength convertible networks where an optical signal may be converted from one wavelength to another, a lightpath need not occupy the same wavelength on all the traversed links (i.e., there is no wavelength continuity constraint). There has been a significant amount of research on the benefit of wavelength conversion in reducing the blocking probability of Wavelength Routed Networks (WRNs) (see for example, [8]). On the other hand, wavelength conversion is expensive and can result in degradation of signal quality [9]. Hence, much attention in the literature has been paid to research topics on sparse placement of a limited number of wavelength converters or limited-range wavelength converters [10]–[13]. However, none of the existing works has addressed the effect on the blocking performance and efficient usage of wavelength converters in WBS networks with wavelength conversion.

There are three unique issues related to wavelength conversion in WBS networks. Firstly, request blocking may come from not only the limited number of wavelengths (and wavelength conversion capability), but also the limited number of ports at the MG-OXCs [14]. Secondly, one may use intraband wavelength conversion which is different from limited-range wavelength conversion studied for WRNs. Thirdly, even though a wavelength converter may be available for use to satisfy a request, performing wavelength conversion requires all the wavelengths in a band to be demultiplexed and hence consuming more ports, which in turn, may result in blocking.
of future requests.

In this paper, we develop a novel algorithm called Waveband Assignment with Path-Graph (WAPG) algorithm that efficiently allocates wavelength converters and at the same time maximizes the benefit of wavebanding when satisfying a new lightpath request. We also apply the WAPG algorithm to WBS networks using MG-OXCs with varying port count and wavelength conversion capabilities. In addition, we compare intra-band wavelength conversion with unlimited and limited number of full wavelength conversion. We compare the performance of our proposed algorithm with other heuristics such as RandomFit and FirstFit through extensive simulations. Our results show that our proposed algorithm is especially useful in minimizing the number of used wavelength converters and ports, thus reducing network operating costs, while achieving a low request blocking probability.

This paper is organized as follows. Section II describes an MG-OXC architecture capable of wavelength conversion. In Section III, we present our heuristic algorithm and its application to different network scenarios. Simulation results that compare different heuristics are reported in Section IV, while Section V concludes the paper with a summary of its major contributions.

II. WAVELENGTH CONVERSION IN WBS NETWORKS

In this section, we describe the architecture of an MG-OXC and discuss different wavelength conversion technologies in WBS networks.

A. Reconfigurable MG-OXC Architecture

Figure 1 shows the MG-OXC architecture we consider in this work. Similar to a static (non-reconfigurable) MG-OXC [3], it includes the fiber cross-connect (FXC), band cross-connect (BXC) and wavelength cross-connect (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. The wavelength conversion bank is used to convert wavelengths of optical signals while some other technologies (such as intra-band wavelength conversion) can be implemented within the WTB/WTB multiplexer (s) / demultiplexers or the WXC switch. At the BXC layer, the wavelength cross-connect (BXC) switch is used to switch 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 switch fibers at the FXC layer.

Note that in the off-line case [3], where the MG-OXC can have as many ports as needed to guarantee that all the demands are satisfied, the MG-OXC in Figure 1 has only a predetermined limited port count. More specifically, let Z denote the number of incoming fibers, Y the number of BXC ports from FTB demultiplexers, α ≤ 1 the ratio of fibers (to the total number of fibers) that can be demultiplexed into bands using FTB ports, and similarly, β ≤ 1 the ratio of bands that can be demultiplexed to wavelengths using BTW ports. This MG-OXC architecture is reconfigurable (and hence flexible) in that any [αZ] fibers can be demultiplexed into bands and any [βY] of these bands can be demultiplexed into wavelengths simultaneously by appropriately configuring the MG-OXC.

In [3], [14], we have shown that it is unnecessary to demultiplex all the fibers into bands and bands into wavelengths, and even with limited reconfiguration (i.e., α < 1 or β < 1), intelligent algorithms can considerably reduce the port count required to satisfy dynamic incremental traffic with an acceptable request blocking probability. Hence, we set α = 1 to allow any fiber to be demultiplexed to bands in this work. However, we can/should limit the value of β to be less than 1 by allowing only a limited number of bands (i.e., [βY]) to be demultiplexed into wavelengths simultaneously. Hereafter, we concentrate on one of the proposed WBS schemes in [3], wherein each fiber has a fixed number (X) wavelengths partitioned into (B) bands and each band has a fixed number (W) as well as a fixed set of wavelengths.

B. Wavelength Conversion

Wavelength conversion capabilities can be incorporated at either all or some of the nodes (the latter is referred to as sparse wavelength conversion). Further, wavelength conversion can be full or limited-range (i.e., partial). In the case with limited-ranged wavelength conversion, a wavelength can be converted only to a subset of the wavelengths (e.g, wavelength numbered λ can only be converted to the wavelengths within the range [λ − δ, λ + δ] for some integer δ) [12]. In the case with limited number of wavelength converters, the nodal architecture can be share-per-node or share-per-link [10]. In this paper, we will focus on the share-per-link architecture, where a dedicated

\begin{figure}[h]
  \centering
  \includegraphics[width=0.5\textwidth]{fig1.png}
  \caption{Architecture of a Reconfigurable MG-OXC}
\end{figure}
number (say \( d \leq X \)) of wavelength converters are associated with each outgoing link.

For WBS networks, a practical wavelength conversion technology is called intra-band wavelength conversion, where a wavelength can only be converted to any other wavelengths within the same band. For example, assuming that the band size is 3, wavelengths \( w_1, w_2, w_3 \) are in the same band \( b_1 \), and wavelengths \( w_4, w_5, w_6 \) are in the same band \( b_2 \), then wavelength \( w_3 \) can only be converted to any wavelength in band \( b_1 \) (i.e., \( w_1 \) or \( w_2 \)) while wavelength \( w_4 \) can only be converted to any wavelength in band \( b_2 \) (i.e., \( w_5 \) or \( w_6 \)), which is different from the case with limited-range wavelength conversion. However, we note that our constrained shortest path first) is used in WBS networks with heuristic based on the layered-graph approach. For illustration existing connections are not re-arrangeable and develop our research on the benefit of wavelength conversion in WRNs has been done, but the blocking performance and efficient usage of wavelength converters, especially intra-band wavelength converters, in WBS networks has not been addressed at all.

III. WAVEBAND ASSIGNMENT WITH PATH-GRAPH (WAPG)

In this section, we propose a novel heuristic that reduces the blocking probability by efficiently grouping wavelengths into bands and reducing the number of wavelength converters when satisfying a new lightpath request. We assume that the existing connections are not re-arrangeable and develop our heuristic based on the layered-graph approach. For illustration purpose, we assume that fixed routing (shortest path first or constrained shortest path first) is used in WBS networks with intra-band wavelength conversion. However, we note that our algorithm can be applied to different wavelength conversion and routing schemes.

We use following notations, for a lightpath request using path \( l, s = s_0 \rightarrow s_1 \rightarrow ... \rightarrow s_i \rightarrow s_{i+1} \rightarrow ... d = s_n, H \) is the number of hops along the path and each link has \( X \) wavelengths, partitioned into \( B \) bands, each consisting of \( W \) wavelengths. Let \( \Lambda = \{w_1, w_2, ..., w_\lambda, ..., w_X\} \) be the set of wavelengths, and \( b \) the index of waveband set \( \xi = \{1,2, ..., \lceil X/B \rceil \} \) on each link. Then, wavelength \( 1 \leq \lambda \leq X \) belongs to band \( b = \lceil \lambda/B \rceil \).

We model a given path \( l \) using \( X \) layers of path-graph (one for each wavelength) as in Figure 2. The nodes in each layer of the path-graph correspond to the nodes in the network topology. For a given path-graph \( \lambda \), the links between the nodes in the same layer correspond to the existence of that wavelength between the physical nodes while the links between different layers imply the existence of wavelength converters at the physical nodes. For example, Figure 2 shows the case with intra-band wavelength converters. More specifically, let \( s_i^\lambda \) denote the corresponding node of the node \( s_i \) at layer \( \lambda \) of the path-graph.

The first five lines in the following algorithm WAPG create the path-graphs. Once the path-graph is created, the next step is to assign appropriate weights to each link in the graph so that we can use Dijkstra algorithm on the path-graph to assign appropriate wavelengths for the request.

Algorithm: WAPG

1: if \( H > 1 \) then
2: for each node \( s_i \) on the path \( l \), each wavelength \( w_\lambda \) do
3: Create logical node \( s_i^\lambda \) in the path-graph.
4: if there are intra-band wavelength converters from \( \lambda \) to \( \lambda' \) at the node then
5: Create logical link between node \( s_i^\lambda \) and \( s_i^{\lambda'} \) in the path-graph.
6: Set the weight of the logical link \( s_i^\lambda \rightarrow s_i^{\lambda'} \) as
\[ w(s_i^\lambda, s_i^{\lambda'}) = X \times H. \]
7: end if
8: end for
9: for each link \( s_i \rightarrow s_{i+1} \) on the path \( l \), each wavelength \( w_\lambda \) do
10: if wavelength \( w_\lambda \) is available on link \( s_i \rightarrow s_{i+1} \) then
11: Create logical link between node \( s_i^\lambda \) and \( s_{i+1}^{\lambda} \) in the path-graph.
12: Set the weight of the logical link \( s_i^\lambda \rightarrow s_{i+1}^{\lambda} \) as
\[ w(s_i^\lambda, s_{i+1}^{\lambda}) = \lambda. \]
13: end if
14: end for
15: Create logical node \( s, d \) and links \( s \rightarrow s_0^\lambda, s_n^\lambda \rightarrow d \).
16: Set the weight of the logical links \( s \rightarrow s_0^\lambda \) and \( s_n^\lambda \rightarrow d \) as 0.
17: Use Dijkstra algorithm search proper wavelengths to accommodate the new request
18: else
19: Use FirstFit algorithm to accommodate the new request.
20: end if

Based on the observation that FirstFit wavelength assignment facilitates grouping wavelengths into bands and hence helps reducing the blocking probability [14], [15], we set the weight of the links in each wavelength layer to be the index number of the wavelength (i.e., see line 13 of the Algorithm), and therefore, the Dijkstra algorithm will prefer using the lower indexed wavelength as much as possible. In addition,
to minimize the usage of the wavelength converters, we set the weight of link between different path-graph layers (i.e., the cost of using a wavelength converter) to be $X \times H$ (as in line 6 of the Algorithm).

According to the way we set the weight of each link, Dijkstra algorithm will

- first try to find a wavelength-continuous lightpath (i.e., using the same wavelength on all links along the path) without wavelength converter using the lowest indexed wavelength similar to the FirstFit algorithm.
- then try to find a non wavelength continuous path using minimum number of wavelength converters.

The request will be blocked if neither wavelength continuous lightpath (using the same wavelength all along path $l$) nor non wavelength-continuous lightpath (with help of wavelength converters) can be found. We call the above algorithm Waveband Assignment with Path-Graph, or WAPG.

WAPG can be effectively applied to the case with sparse wavelength conversion, full wavelength conversion or limited-range wavelength conversion as well. In the case with full wavelength conversion at every node, there will be links from one layer to all other layers representing the full wavelength conversion. On the other hand, in the case with sparse wavelength conversion only at the selected node, there are some links between different layers, while in the case with limited-range wavelength conversion, only limited links between different layers exist at every node. It is obvious that in the case without wavelength conversion, no links exist between different layers, in which our algorithm works exactly as the FirstFit algorithm.

We compare WAPG with FirstFit and RandomFit algorithms. The FirstFit algorithm tries to use the first available wavelength-continuous path. On the other hand, if such a wavelength-continuous path is not found, it then assigns the first available wavelength to the first link of the path, for example $\lambda_i$. On the next link, only if $\lambda_i$ is not available, the first available wavelength, for example $\lambda_j (i \neq j)$ is chosen and a wavelength converter is employed to convert wavelength $\lambda_i$ to $\lambda_j$, this process is continued until a wavelength has been assigned to all the links along the path. Similarly, RandomFit algorithm randomly allocates wavelengths to satisfy the new connection request.

### IV. PERFORMANCE EVALUATION

In this section, we conduct extensive simulations to compare the performance of WAPG with FirstFit and RandomFit under different network scenarios. We assume that the traffic is uniformly distributed to all node pairs in the USA Net topology with 46 nodes and 76 links. The lightpath requests arrive according to a Poisson process and the holding time is exponentially distributed. We also assume that every link has one bi-directional fiber, each fiber has 20 bands and each band has 4 wavelengths. Thus the total number of wavelengths on a link is set to $X = 80$.

Due to the dynamic nature of the traffic (i.e., connections are established and released dynamically), it does not make sense to compare different algorithms in terms of port count reduction or to assess the benefits of wavelength conversion in reducing the port count. Instead, we will use blocking probability and the maximum number of used wavelength converters at any given time as the performance metrics.

#### A. Performance in WBS networks when $\beta = 1$

In WBS networks using MG-OXC architecture as shown in Figure 1, when $\beta = 1$, there is no limitation on the number of bands that can be demultiplexed into wavelength using BTW ports, which means blocking only comes from the limitation on the number of wavelengths [14].

In this section, we compare the performance of WAPG algorithm with FirstFit and RandomFit wavelength assignment algorithms in above USA Net with or without wavelength converters. We use “NWC”, “IWC”, “FWC” and “LWC” to denote the case without any wavelength converters, with maximum number of intra-band wavelength converters, with maximum number of full wavelength converters, and with limited number of full wavelength converters, respectively.

Figure 3 shows the blocking probability of the network versus the traffic load for different algorithms with different wavelength conversion schemes, while Figure 4 depicts the performance in terms of the number of used wavelength converters.

The simulation results in Figure 3 show that network with intra-band wavelength converters can achieve almost the same performance as that with full wavelength converters. Since we are employing fixed routing scheme, the blocking performance of WAPG and FirstFit in the case without wavelength converters is identical, which is slightly better than that of RandomFit. The blocking performance of all the three algorithms in the case with full wavelength converters is identical. Although not shown, we note that WAPG performs slightly better than the other two in the cases with intra-band or limited-range wavelength converters.

![Fig. 3. Blocking Performance in USA Net](image)

From Figure 4, we note that WAPG performs significantly better than the FirstFit algorithm and much better than RandomFit algorithm in terms of reducing the number of used wavelength converters. Due to the space limitation, simulation results for networks with limited number of wavelength converters, networks with sparse wavelength converters or
networks with limited-range wavelength converters are not reported here. We note that WAPG is significantly better than FirstFit and RandomFit.

B. Performance in WBS networks when $\beta = 0.75$

Due to the space limitation, we present results of WAPG in WBS networks with a limited number, $d = 10$, of full wavelength converters (per link) hereafter to show the advantage of using an intelligent WBS algorithm such as WAPG over using a trivial WBS algorithm like RandomFit and FirstFit. Unlike the previous case in Section IV-A where each MG-OXC has a maximum number of BTW/WTB ports (i.e., $\beta = 1$), in this section, we set the ratio of bands that can be demultiplexed to wavelengths using BTW ports to be $\beta = 0.75$. Such a limited number of BTW ports may also cause request blocking if wavebanding is not considered properly.

![Figure 5. Blocking performance in Fig. 6. Max number of used wave-length converters in WBS networks](image)

Figure 5 shows the blocking probabilities of the heuristics and Figure 6 shows the maximum number of used wavelength converters. When compared with Figure 3, we see that the difference between the blocking performance of three algorithms is much more significant when $\beta < 1$ than when $\beta = 1$. In particular, RandomFit is ill-suited for networks with MG-OXCs as it assigns wavelength randomly and consumes a large number of wavelength converters as shown in Figure 6, which results in inefficient usage of the limited number of ports in MG-OXCs and high blocking probability. More specifically, the inefficient usage of the limited ports comes from two aspects. One is that the random wavelength assignment does not take waveband grouping into consideration. The other is that wavelength conversion can only happen at the WXC layer, which means the fiber carrying the wavelength(s) has to be demultiplexed into bands, and then into wavelengths, thus consuming resources (e.g., ports and multiplexers/demultiplexers) in the MG-OXCs, and resulting in poor blocking performance.

On the other hand, FirstFit is very likely to assign wavelengths to lightpaths sequentially, which helps in wavebanding and thus reducing the number of used ports and blocking probability, but it does not minimize the number of wavelength converters in case they are needed. In fact, FirstFit still consumes a significant number of wavelength converters as shown in Figure 6, which in turn consumes ports and hurts its blocking performance. Since the WAPG algorithm tries to use a minimal number of wavelength converters while assigning wavelength sequentially, it performs better than FirstFit and much better than RandomFit, and is especially useful when both the number of ports and the number of wavelength converters are limited.

V. CONCLUSION

In this work, we have developed an efficient heuristic algorithm called Waveband Assignment with Path-Graph (WAPG) algorithm, which tries to use a minimal number of wavelength converters and group wavelengths to band efficiently, thus achieving good blocking performance in waveband switching networks. The WAPG algorithm has been applied to the case with full wavelength conversion, intra-band wavelength conversion and limited wavelength conversion to accommodate fully dynamic traffic. Through extensive simulations, we have shown that WAPG is significantly better in terms of minimizing the number of used wavelength converters and outperforms RandomFit and FirstFit in terms of blocking probability. Some of the issues such as comparison of the intra-band and limited-range wavelength conversion, the impact of sparse wavelength converters placement and other dynamic/adaptive routing algorithms in WBS networks need further investigation.

REFERENCES