Abstract—To handle the challenge of increasing node size in wavelength routing networks (WRNs), waveband switching (WBS) is introduced to group multiple wavelengths together as a band or fiber and switch them using a single port whenever possible. Literature studies with the off-line traffic confirm that WBS can effectively reduce the port count and cost as well as control complexity. In the cases with online traffic, both the port reduction and call blocking probability should be considered due to the unknown traffic pattern and limited resources. In this work, we first analyze a reconfigurable switching architecture and the blocking probability in WBS networks. Based on the analysis, we then propose a novel dynamic graph-based waveband assignment algorithm in conjunction with adaptive routing. The proposed algorithm employs the ant optimization techniques to reduce ports and blocking probability in the network with online traffic in a distributed manner. Our simulation results show that our graph-based waveband assignment algorithm combined with adaptive routing can achieve the best performance when compared to other schemes. Our study also shows that even with limited resources, WBS can achieve an allowable blocking probability and port saving.

I. Introduction

To satisfy the increasing Internet traffic from emerging applications such as IPTV, VoIP, and P2P, Wavelength Division Multiplexing (WDM) technologies, whereby each fiber can carry many wavelengths and each wavelength can support traffic up to 100 Gbits/s or higher [1], is considered as the foremost solution. In wavelength routing networks (WRNs) using WDM technologies, the traditional optical cross-connects (T-OXCs) are employed to switch each wavelength from incoming fiber to outgoing fiber. With the worldwide fiber deployment and the advancing of dense WDM technologies, WRNs face challenges such as the increasing of the node size, cost and control complexity. Recently, waveband switching (WBS) is introduced to cope with such challenges. The basic principle of WBS is to switch multiple or a group of wavelengths as a single entity by employing multi-granular cross-connects (MG-OXCs) instead of T-OXCs [2], [3].

In WBS networks, the routing path and wavelength/waveband have to be properly selected to carry the traffic, which is defined as the routing and wavelength assignment (RWA) problem. Based on whether the traffic demands are known a priori or not, RWA problems are categorized as offline or online RWA problems. The offline RWA is generally formulated to satisfy a given set of traffic demands, while incurring the minimum cost or resources in the network, which is proven to be NP-Complete [2], [4], [5]. To resolve the RWA problem in the cases with offline traffic, the approach of integer-linear programming is widely adopted to optimally set up lightpaths in a small size network [2], [6] while heuristic algorithms are developed for large scale networks [2], [7]–[11]. The literature studies indicate that waveband switching has features such as smaller nodal size, lower cost and complexity.

In the case with online traffic, the network topology and the nodal architecture are given, the basic problem is how to minimize the blocking probability or maximize the throughput for dynamic traffic demands. In other words, given the limited amount of available networking resources (e.g., wavelengths, switching ports), how to efficiently accommodate the traffic demands which arrive and depart dynamically in an unknown manner. To the best of our knowledge, there is no detailed investigation in the literature focusing on how to distributively accommodate online traffic in WBS networks. In this work, for the first time, we propose a new routing scheme based on ant optimization techniques together with a graph-based waveband assignment algorithm to distributively satisfy online traffic while reducing the call blocking and used ports in the network.

The rest of this paper is organized as follows. Section II introduces the concept of dynamic waveband switching and related work. In Section III, we analyze the MG-OXC architecture and blocking probability in WBS networks under online traffic. An adaptive routing scheme based on ant optimization techniques is proposed in Section IV and a graph-based waveband assignment algorithm is developed in Section V. We present the simulation results of our proposed schemes in Section VI and conclude this work in Section VII.

II. Dynamic Waveband Switching

In circuit-switched networks (e.g., WRNs or WBS networks), it is not cost-efficient or infeasible to deploy maximum (or unlimited) number of equipments to guarantee successful call connection under all possible circumstances. To provide an acceptable performance, limited equipments and resources are normally allocated in practice. This also leads to the inevitable
blocking of some dynamic traffic demands as the future traffic demands are not known a priori and global optimization for all on-line lightpath demands is often difficult (if not impossible) to achieve [1]. Specially, the blocking in WBS networks can be caused by two factors: limited available wavelengths and the limited number of ports at the MG-OXCs [12], [13]. On one hand, the blocking can be due to the lack of free wavelengths (or channels) along the routing path [14], [15]. For example, without wavelength conversion, a lightpath request can be blocked as a result of the wavelength continuity constraint which requires the same wavelength being free continuously along the route.

On the other hand, to accommodate online traffic in WBS networks, a reconfigurable MG-OXC architecture (see Fig. 1) is generally adopted [16], which may block lightpath requests due to the limited fibers/bands that can be demultiplexed into bands/wavelengths through the FTB/BTW demultiplexes. In other words, the exhaustion of multiplexers/demultiplexers at a certain node along the routing path may trigger the rejection of a new lightpath request [12]. To optimize the allocation of the resources (e.g., wavelengths) in the network, efficient routing algorithms are necessary [14], [17], [18]. Generally, the routing schemes are broadly classified into three categories: fixed routing, alternative routing, and adaptive routing. In the case with fixed routing, the routes between node pairs are preconfigured and fixed while the alternative routing scheme selects route from a set of candidate routes that are precomputed (e.g., k-shortest paths [19]). In the case with adaptive routing, the routes can be adapted according to the system status (e.g., resource allocation, congestion) to optimize the routing decision. As an appealing strategy to satisfy online traffic demands with limited resources, adaptive routing schemes based on tabu-search, agent-based or swarm intelligence are proposed to adaptively change the routing table in the network according the network status. For example, ant system is adopted in telecommunication networks to balance the traffic load and adaptively learn the routing tables [18], [20]. The techniques based on ant system have also been incorporated to enhance the performance of routing and protection in WRNs [14], [15], [21]. In this work, we introduce the ant optimization techniques into WBS networks. By defining artificial ants and pheromone, we develop an adaptive routing scheme which is combined with the proposed graph-based waveband algorithm to balance and optimize the allocation of resources such as wavelengths and multiplexers/demultiplexers in WBS networks.

III. Waveband Switching with a Reconfigurable MG-OXC

In this section, we introduce a reconfigurable MG-OXC node and analyze the blocking performance of the nodal architecture. The following notations will be used in our discussion.

![Fig. 1. A Reconfigurable three-layer MG-OXC](image)

- $X$: Number of fibers connected to a node;
- $F$: Number of wavelengths per fiber;
- $B$: Number of wavelengths per band;
- $P$: Number of bands per fiber;
- $\alpha$: The ratio of fibers (to the total number of fibers) that can be demultiplexed into bands using FTB ports;
- $\beta$: The ratio of bands that can be demultiplexed to wavelengths using BTW ports;
- $D_n$: Number of BTW demultiplexers at Node $n$;
- $M_n$: Number of WTB multiplexers at Node $n$;
- $V$: Visited nodes in a network;
- $FW$: Number of continuous free wavelength(s) along one path;
- $DM$: The minimum number of free demultiplexers among all nodes along one path;
- $PB_{Li}$: The probability of selecting link $Li$ as the outgoing link;
- $P_{Li}$: The pheromone value of link $Li$;
- $\lambda_{s,d}$: Arrival rate of the lightpath request from $s$ to $d$, which follows the Poisson process;
- $\lambda_n$: Arrival rate of the lightpath request at Node $n$, which follows the Poisson process;
- $\Lambda_k$: The birth rate of an M/M/C/C Markov chain when $k$ servers are in use;
- $\mu_k$: The death rate of an M/M/C/C Markov chain when $k$ servers are in use;
- $P_{s,d}$: Routing path for node pair $(s,d)$;
- $H_{s,d}$: Hop number of $P_{s,d}$;

A. System Model

Figure 1 shows a reconfigurable three-layer MG-OXC that consists of fiber cross-connect layer (FXC), band cross-connect layer (BXC), and wavelength cross-connect layer (WXC) to organize and switch traffic at fiber, band and wavelength level, respectively [22]. MG-OXCs switch a fiber using...
one port at the FXC layer if none of the wavelengths is used to add or drop traffic. Otherwise, the fiber will be demultiplexed into bands using the FTB demultiplexer. Similarly, an entire band can be switched using one port at the BCX layer if none of the wavelengths needs to be added or dropped. The FTB/BTF demultiplexers, BTF/WTB multiplexers are used to connect different layers. As shown in Fig. 1, \( X \) denotes the number of input fibers, \( Y \) denotes the number of BCX ports from FTB demultiplexers, \( \alpha \leq 1 \) is the ratio of fibers (to the total number of fibers) that can be demultiplexed into bands using FTB ports, and similarly, \( \beta \leq 1 \) is the ratio of bands that can be demultiplexed to wavelengths using BTW ports. Therefore such MG-OXC architecture only allows \( \lceil \alpha X \rceil \) fibers to be demultiplexed into bands and \( \lceil \beta Y \rceil \) of these bands to be demultiplexed into wavelengths simultaneously. Symmetrically, the limited deployment for BTF and WTB multiplexers only allows a limited number of bands and wavelength to be multiplexed to fiber and band layer, respectively. We assume that \( \alpha = 1 \), which means each MG-OXC node is equipped with the maximum number of FTB/BTF demultiplexers/multiplexers and all fibers can be demultiplexed to the BCX layer simultaneously. However the number of bands that can be demultiplexed to the WXC layer at Node \( n \) is limited by \( D_n = X * P * \beta \). Similarly, the number of bands multiplexed from the WXC layer is limited by \( M_n = X * P * \beta \). Hence, we hereafter only focus on the BTW/WTB demultiplexers/multiplexers and ports. We refer a band without traffic as empty band. When all the lightpaths within one band go through only the FXC layer at a node, we call this band as bypass band. Otherwise, the band is called as non-bypass band, which has to be demultiplexed or multiplexed through the BCX layer. Furthermore, we assume that no wavelength conversion is presented in the system.

### B. Allocation of the Multiplexer and Demultiplexer

In WBS networks, the allocation of extra demultiplexers/multiplexers is directly related to traffic grouping. Inefficient traffic grouping may lead to the exhaustion of the demultiplexers/multiplexers at an MG-OXC node, which may block future traffic requests going through this node. For a specific lightpath request, we define the input band as the band contains the wavelength for the lightpath in the input fiber, and the output band as the band contains the wavelength for the lightpath in the output fiber. Due to the wavelength continuity constraint, input band and output band must have the same band index. Figure 2 shows an example of traffic grouping and the necessary allocation of the demultiplexer/multiplexer (DEMUX/MUX). As shown in the figure, an existing lightpath resides in a bypass band from input band \( A \) to output band \( O \). To satisfy a new lightpath request from input band \( I \) to output band \( O \), the node has to allocate demultiplexers/multiplexers for the traffic grouping. This is because the bands from \( A \) and \( I \) have to be demultiplexed first at this node. Then the two lightpaths are multiplexed together to form the band leaving \( O \) of this node. Such traffic grouping requires two additional demultiplexers and one multiplexer. If the node has less than two unused demultiplexers and one unused multiplexer, the new traffic has to be blocked by this node.

In fact, to accommodate a new lightpath request from input band \( I \) to output band \( O \), there are 10 possible cases based on the existing configuration or traffic of this node as shown in Fig. 3. The input band \( I \) and output output band \( O \) can be bypass, non-bypass, or empty band, which generate 9 combinations, namely, case (A), (B), (C), (E), (F), (G), (H), (I), and (J) as shown in Fig. 3. When both \( I \) and \( O \) are occupied by a bypass band, case (E) only indicates the bypass band through \( I \) and \( O \) are different. Hence, we need an additional case (D) to represent the possible bypass band from \( I \) directly to \( O \).

The example in Fig. 2 corresponds to the case (A). In case (B), the band through \( I \) is empty and existing traffic from \( A \) to \( O \) is non-bypass band (going through DEMUX/MUX). Grouping the new lightpath request to \( O \) only requires one more demultiplexer. In cases (C), no extra DEMUXs/MUXs are required since both \( I \) and \( O \) are empty. When the existing lightpath has the same input and output band as the new request, the wavebanding can be achieved without costing extra DEMUXs/MUXs as shown in case (D). Case (E) costs the most extra DEMUXs/MUXs among all the cases because we have to demultiplexe/multiplex two bands for the grouping at this node. The amount of additional DEMUXs/MUXs required for this node to satisfy a new request in other cases can be similarly derived, which is shown in Table I. Note that among all the 10 cases, four cases require 0 additional DEMUXs, two cases require 2 additional DEMUXs, and four cases require 4 additional DEMUXs. Similarly, four cases require 0 additional MUXs, two cases require 2 additional MUXs, and four cases require 4 additional MUXs.

### C. Upper Bound of \( \beta \)

Under the assumption that \( \alpha = 1 \), the total number of ports, namely \( TP \), requires an MG-OXC node can be calculated as in Eq. (1), where \( X \) is the number of fibers, \( F \) is the number
of wavelengths per fiber, and $P$ is the number of bands per fiber. To be cost-efficient, the port number $TP$ for the MG-OXC should be no more than the corresponding T-OXC (i.e., $TP <= 2 * X * F$). Thus based on Eq.(1), the upper bound of $\beta$ can be obtained as in Eq.(2). For example, when $X = 1$, $F = 100$, $P = 10$, we have $\beta <= 0.8$, and $\beta = 0.8$ is the upper bound.

\[ TP = 4 * X + 2 * (1 + \beta) * X * P + 2 * X * F * \beta \]  
\[ \beta <= 1 - 2 \frac{P + 1}{P + F} \]  

We model the consumption of DEMUXs at Node $n$ using an $M/M/C/C$ ($C = D_n$) Markov chain (Repairman Model), as shown in Fig. 4. The birth rate for this Markov chain is $\Lambda_k = \lambda_n$, for $k = 0, ..., D_n - 1$, and the death rate is $\mu_k = k$, for $k = 1, ..., D_n$, and $\mu_0 = \Lambda_{D_n} = 0$. According to the Erlang’s formula, we let $\pi_n(c)$ denote the probability that $c$ DEMUXs are in use at Node $n$. Then the blocking probability at Node $n$ are given in Eq.(4).

\[ \lambda_n = E * \sum_{n \in P_{s,d}} \lambda_{s,d} \]  
\[ \pi_n(D_n) = \frac{(\lambda_n)^{D_n} / D_n!}{\sum_{j \in [0,D_n]} (\lambda_{D_n})^j / j!} \]  

If the allowable blocking probability for node pair $(s, d)$ is know, say $Q$, then the blocking probability along the route should be no more than $Q$, which constrains the lower bound of $\beta$ as shown in Eq.(5)

\[ 1 - \prod_{n \in P_{s,d}} (1 - \pi_n(D_n)) <= Q \]
IV. Ant-based Adaptive Routing

With ant optimization, individuals (i.e., ant) cooperate through self-organization to find a good solution for a certain problem (e.g., food hunting) [23]. Instead of using a central control mechanism, the individuals use stigmergy for the indirect communication, which is a chemical substance called pheromone. The pheromone is deposited by ants and allows other ants to sense. By following the strong-pheromone route, the ants can quickly converge to the shorter path (or the best path) to the food. Based on this principle, we define artificial ants and pheromone to track the available demultiplexers/multiplexers and free wavelengths in the network distributively. There are three types of ants, forward ants, backward ants, and decision ants. Forward ants are walking in the network to explore good routes. When forward ants reach the destination, they are changed to backward ants. The backward ants trace back along the opposite direction of the original path of corresponding forward ants and update the pheromone table at each node they traversed. After launching a number of ants, the final route is selected along the path which accumulates the highest pheromone value. And a decision ant is launched to decide the waveform to accommodate the new lightpath request.

Each ant carries a stack consisting of the available continuous wavelength(s), demultiplexers/multiplexers, and the visited nodes. As shown in Fig. 5(a), the visited nodes are kept for avoiding a route loop. The free wavelengths are recorded by a free wavelength mask. Whenever a new node is visited, the free wavelength(s) mask is updated to record the continuous free wavelength(s). Similarly, information for demultiplexers/multiplexers is recorded using DM and updated hop by hop until the destination node is reached. We will further elaborate the updating in the following subsection. Each node in the network has a pheromone table containing pheromone value that is calculated based on the free wavelengths and demultiplexers/multiplexers. In this table, each incident link of the node has a pheromone value. For example, as shown in Fig. 5(b), Node 3 has a pheromone table, which consists pheromone values for its outgoing links. A higher pheromone value indicates that more available wavelengths and demultiplexers/multiplexers can be accessed by going through this link. The pheromone value is used for ants to make decision on the way to the destination, and also is used for creating the final route for the new lightpath request.

A. Updating of ant stack and pheromone table

The available continuous wavelengths are recorded using a mask, which contains multiple bits. Each bit represents a unique wavelength. When a wavelength is available all the way down to the current node from the source node, the corresponding bit is set to be 1. A logical AND operation can be conducted to update the mask of the ant stack whenever the forward ant traverses through a link. At the destination node, the number of continuous free wavelength(s) along one path, denoted by FW, can be counted from the mask. Similarly, the demultiplexers/multiplexers information along a path should be updated. We use DM to represent the minimum number of available demultiplexers along one path.

Each forward ant also has to make a decision for next hop if the current node is not the destination. Among all the incident links of the current node, the probability of using one link to next node is calculated as Eq.(6), where \( V \) is the set of visited nodes. With Eq.(6), the ant will be more likely to take the link with higher pheromone value, which promotes the convergence of the optimized route selection. However, if the ant has visited all the neighbors of the current node, the ant will be killed immediately.

\[
P_{B_{L_i}} = \frac{P_{L_i}}{\sum_{j \in V} P_{L_j}}
\]

Once the forward ant arrives at the destination node, the ant is changed to be a backward ant and updates the pheromone value for the traversed link at each corresponding incident node according to Eq.(7). With Eq.(7), the routes having more available continuous wavelength (i.e., larger \( FW \)), less bottleneck nodes (i.e., larger \( DM \)), and shorter length (i.e., smaller \( H_{s,d} \)) are set with more pheromone value (since these routes have less chances to block the traffic requests). The variable \( \theta \) is a scalar to tune the impacts of free wavelengths or demultiplexers/multiplexers. Note that for a route with \( FW = 0 \), we will not increase the pheromone value along the route.

\[
P_{L_i} = P_{L_i} + \theta \cdot \frac{FW}{H_{s,d}} + (1 - \theta) \cdot DM
\]

When enough backward ants arrive at the source, the source can decide the final routing path for the lightpath request. The routing path is decided hop by hop according to the link that has the highest pheromone value. Specifically, the source selects the next node by using the link with the highest pheromone. Then the same manner is followed by the next node until the destination is reached.

Fig. 5. Ant stack and pheromone table
B. Ant Walking Algorithm and System Process

Now we present the ant walking algorithm, which effectively identifies the routing path for the online traffic requests in a distributed (on-demand) manner. To accommodate a new arriving lightpath request, the following process is performed in the WBS networks with reconfigurable MG-OXCs. The algorithm used to decide the waveband will be elaborated in the next section.

1) For the new request from $s$ to $d$, the source launches multiple forward ants to the destination;
2) Each ant walks distributively until reaching the destination using Algorithm 1;
3) Once the forward ant reach the destination, the ant is changed to backward ant, which follows the reverse path of the original forward ant using Algorithm 1, and updates the pheromone table at the node along the way;
4) When enough backward ants arrive at source, the new path can be generated. The source sends one decision ant along the new path to the destination for choosing the waveband to use for the lightpath request.
5) The decision ant goes back to the source from the destination.
6) Along the new path and the decided waveband, establish the lightpath for the new request.

**Algorithm 1 Ant Walking**

```
if (a forward ant) then
    if (current node is not the destination) then
        Update DM and FW;
        Make decision for next hop;
    else
        Kill itself;
    end if
else
    Current node is the destination, change itself to backward ant;
    Move to the last visited node;
end if
else
    Current ant a backward ant, update the pheromone value at current node;
    if (current node is the source) then
        Kill itself;
    else
        Move to the next node towards the source;
    end if
end if
```

V. A Graph-based Waveband Assignment Algorithm

When accommodating a new lightpath request along the selected routing path, additional demultiplexers/multiplexers may be used as enumerated in Fig. 3 and Table I. Instead of randomly choosing or using a first-fit strategy to select the band, we propose a graph-based waveband assignment algorithm to use minimum number of additional demultiplexers/multiplexers in the process of satisfying dynamic traffic requests.

To effectively and cautiously allocate the demultiplexers/multiplexers, in the waveband assignment, we construct an auxiliary graph for each node along the routing path. The edges in the auxiliary graph are assigned weight based on the demultiplexers/multiplexers information. A band corresponds to minimum weight is selected to preserve more demultiplexers/multiplexers for future traffic thus saving ports and reducing blocking probabilities. Figure 6 shows an example in the basic steps of the proposed algorithm constructing the auxiliary graph for waveband assignment. To satisfy a lightpath request for the node pair $(S, D)$ along the path $S-W-U-D$ (Fig. 6(a)), we use $P$ Band Node, $W_0, W_1,...,W_{P-1}$ to represent Node $W$, where $P$ is the number of bands per fiber. Similarly, Node $U$ is represented by $U_0, U_1,...,U_{P-1}$ as shown in Fig. 6(b). If we assume that each link consists of $X$ fibers, a band $b$ may come from any of the $X$ input fibers and and leave the node through any of the $X$ output fibers. Accordingly, we create a bipartite complete graph for each Band Node, which is called as Band Graph. Since we assume $X = 2$ and $P = 2$ in this example, the bipartite complete graph for $W_0$ (or $W_1$) (see Fig. 6(c)) contains 2 nodes for each disjoint set of the bipartite graph, and has $2+2$ edges corresponding to the combination of 2 input fibers and 2 output fibers. Specifically, vertex $IFB_{0,0}$ $(IFB_{1,0})$ is created for input fiber 0 (1) while vertex $OFB_{0,0}$ $(OFB_{1,0})$ is created for output fiber 0 (1) in the Band Graph of $W_0$. After the auxiliary Band Graph is constructed, we can assign the weight for each edge to reflect the cost (in terms of additional demultiplexers/multiplexers) for a new lightpath request using the band from the corresponding input fiber to the output fiber. As shown in Fig. 3, any band $b$ can be bypass, non-bypass or empty band at Node $n$. Hence, we assign weight $BT_{n,o}^{b}$ to the edge between $IFB_{i,b}$ and $OFB_{i,b}$ using Eq. (8).

\[
\begin{align*}
BT_{n,o}^{b} &= \begin{cases} 
-1; \forall b \in \text{case}(D) 
\text{(i)} \\
0; \forall b \in \text{case}(C,J) 
\text{(ii)} \\
1/D_n; \forall b \in \text{case}(B) 
\text{(iii)} \\
1/M_n; \forall b \in \text{case}(I) 
\text{(iv)} \\
1/D_n + 1/M_n; \forall b \in \text{case}(H,F) 
\text{(v)} \\
2/D_n + 1/M_n; \forall b \in \text{case}(A) 
\text{(vi)} \\
1/D_n + 2/M_n; \forall b \in \text{case}(G) 
\text{(vii)} \\
2/D_n + 2/M_n; \forall b \in \text{case}(E) 
\text{(viii)} 
\end{cases} 
\end{align*}
\]

Eq.(8) assigns the weight to the edges in Band Graph based on the available demultiplexers/multiplexers and the additional demultiplexers/multiplexers to satisfy a request. For example, in case (E), the weight is set to $2/D_n + 2/M_n$ at node $n$ to reflect the two additional demultiplexers and two extra multiplexers. The weight value is set to $-1$ in case (D) since case (D) is desirable for waveband grouping and no extra demultiplexers/multiplexers are required. Based on the above
Algorithm 2 Graph-based Waveband Assignment

if (Current node \( n \) is not the destination node) then
    Create the Band-Graph for current node;
    Assign the weight in the Band-Graph using Eq.(8);
    Calculate the value of \( WT_{n,b} \) for each band \( b \);
    Update the weight field \( RT_b \) of the decision ant for each band \( b \);
    Move to the next node towards the destination;
else
    Current node is the destination node, send the decision ant back to the source node for band selection;
end if

To distributively select the waveband for the new lightpath request, Algorithm 2 is used for the decision ant to find the minimum weight band when travels along the routing path. The decision ant has a weight field consisting of minimum cost for using each band \( b \) along the routing path, denoted by \( RT_b \), as shown in Fig. 7. \( RT_b \) is updated node by node through adding the \( WT_{n,b} \) to the current \( RT_b \). Thus, the source node can choose the band with the minimum \( RT_b \) to accommodate the lightpath request. As one can see that the proposed waveband assignment algorithm cautiously selects a band that requires minimum number of additional demultiplexers/multiplexers. In this way, we can preserve more demultiplexers/multiplexers for future traffic demands and potentially reduce the blocking probability. In addition, the more the demultiplexers/multiplexers are used at the Node \( n \), the larger the weight will be as shown in Eq. (9), which can balance the demultiplexers/multiplexers usage in the network.

VI. Simulation and Performance Evaluation

We simulate the adaptive routing in conjunction with the graph-based waveband assignment algorithm using the 14-node NSF network as the network topology. There are two fibers for each link, with one per direction. We set \( F = 15 \), \( P = 5 \), and \( \theta = 50\% \). The lightpath requests arrive at the network according to a Poisson process. The traffic arrival rate is \( \lambda \), and randomly distributed over the network. The request holding time is exponentially distributed with one unit as the mean value. All simulations are conducted with more than 50 thousands dynamic lightpath requests, and results are collected as the mean of multiple running instances of the simulation.

A. Ant Number and the Blocking Probability

As stated in Section IV, for each new arriving lightpath request, a number of ants are launched to explore the optimal (or the near-optimal) route. The number of ants to launch can affect the performance of the blocking probability in the network. As shown in Fig. 8. For the network with heavy or light traffic load, the blocking probability can be reduced significantly by increasing the number of ants when the number of ants is no more than 100. This is because more ants can facilitate identify better paths. However, when the number of ants is large enough (e.g., > 100), the blocking performance almost does not change with the increasing of the number of ants. This is due to the convergence on the best found paths by the ants. In addition, we can also observe that the blocking probability can be improved more significantly by launching more ants in the case with heavy traffic load. This implies that reinforcing learning techniques could be helpful by adjusting the number of ants to be launched under different traffic load.

B. Comparison between Fixed Routing and Adaptive Routing

According to our discussion in Section III, the upper bound of \( \beta = 1 - 2 \frac{F+1}{P+P} = 1 - 2 \frac{10}{10+30} = 0.45 \), which means \( \beta \) should be no more than 0.45 to be cost-efficient. As shown in Fig. 9, our algorithm can actually approach the lowest blocking probability when \( \beta = 0.4 \). When \( \beta > 0.4 \), further increasing \( \beta \) (i.e., deploying more demultiplexers/multiplexers) does not help in reducing the blocking probability in the network since the major reason for the blocking is the shortage of wavelengths. A lower bound for \( \beta \) based on the simulation is 0.25 if the allowable blocking probability is 0.05. Hence, WBS network can save ports and achieve an allowable blocking probability when accommodating dynamic traffic requests.
Furthermore, it can be seen that the proposed adaptive routing scheme outperforms the fixed (shortest path) routing under various $\beta$ and traffic load as shown in Fig. 9 and Fig. 10. This is because the adaptive routing efficiently takes the limited resources into consideration and the route selection based on the availability of demultiplexers/multiplexers and free wavelengths. The advantage of the proposed scheme is even more obvious when very limited resources are deployed (e.g., $\beta < 0.3$, traffic load > 120).

C. Comparison between First-fit and the Graph-based Waveband Assignment Algorithm

To study the performance of the proposed graph-based waveband assignment algorithm (GWB), we compare the GWB and first-fit waveband assignment scheme (FF) together with adaptive or fixed (shortest path) routing schemes. Based on the simulation results for the scheme using adaptive routing and GWB (Adaptive+GWB) as well as the scheme using adaptive routing and FF (Adaptive+FF) shown in Fig. 11, we can see that the former scheme outperforms the later one. This is because the former scheme tries to balance and minimize the usage of demultiplexers/multiplexers, which can avoid the exhaustion of demultiplexers/multiplexers at a single node thus reducing the blocking probability. For the same reason, we can see that the scheme using fixed routing and GWB (Fixed+GWB) outperforms the scheme using fixed routing and first-fit scheme Fixed+FF. Note that the advantage of GWB under fixed routing is even more significant since demultiplexers/multiplexers are more likely be unevenly used in the network with fixed routing scheme.

VII. Conclusion

In this paper, we have analyzed the blocking probability in WBS networks with a reconfigurable three-layer MG-OXC architecture. For the first time, we have introduced an adaptive routing scheme for WBS networks. The routing scheme distributively selects optimum routing paths for dynamic traffic demands based on the ant optimization techniques. In addition, we have proposed a new graph-based waveband assignment algorithm. Our simulation have demonstrated that the proposed adaptive routing scheme and graph-based waveband assignment algorithm can reduce active ports and achieve lower blocking probability compared to the traditional fixed routing scheme and first-fit waveband assignment algorithm.
For the future work, we plan to further study adaptive routing and dynamic waveband assignment in WBS networks in the following aspects: i. Analyzing the signaling protocols in WBS networks based on the GMPLS plane; ii. Applying reinforcement learning techniques to further improve the intelligence of the ants for better routes discovery; iii. Study of the blocking and port usage performance in the WBS networks with proactive computation of the routes and periodical update of the paths.

References


