Band-segment Protection in Multi-granular Optical Networks

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Abstract—Protections are traditionally realized at fiber level (e.g., link protection) or wavelength level (e.g., path protection) in wavelength routing networks. With the advancing of waveband switching (WBS) techniques, these schemes may fail to efficiently accommodate the major goal of minimizing the node size (i.e., port count) in WBS networks. To achieve both the survivability and port reduction, we introduce the band-segment (BS) concept in WBS networks by which we can operate the protection at waveband level thus saving ports. Accordingly, we propose shared and dedicated protection schemes using band-segments, namely shared band-segment protection (SBSP) and dedicated band-segment protection (DBSP) for WBS networks. Our simulation shows DBSP outperforms dedicated path protection dramatically in terms of port count, while SBSP can achieve both resource sharing and port reduction.

I. INTRODUCTION

Emerging applications such as IPTV, VoIP, and P2P promote a considerable increase of the Internet traffic. The foremost solution to satisfy the exploding traffic is the Wavelength Division Multiplexing (WDM) technology, whereby each fiber can carry many wavelengths and each wavelength can support traffic up to 100 Gbits/s or higher [1]. To efficiently accommodate the worldwide fiber deployment and the advancing of dense WDM technologies, waveband switching (WBS) is introduced to cope with the challenges such as the increasing of the node size, cost and control complexity. The primary advantage of WBS is the capability to switch multiple wavelengths as a single entity by employing multi-granular cross-connects (MG-OXCs) instead of the traditional optical cross-connects (OXCs) [2]. In this work, we adopt the three-layer MG-OXC [2] that consists of fiber cross-connect layer, band cross-connect layer, and wavelength cross-connect layer to organize and switch traffic at fiber, band and wavelength level, respectively.

Due to the high bit rate of one wavelength and the large number of wavelengths per fiber, network survivability is drawing much attention in optical networking design and modeling. Protection schemes are extensively studied in wavelength routed networks (WRNs), which can be roughly classified into path-protection, link-protection, and segment-protection. In path or link protection, one backup path is established for each working path or link, respectively, while in segment-protection each working path is divided into several segments and backup path is assigned per working segment. These protection schemes can be shared or dedicated protection depending on whether resources are allocated exclusively for each backup path or shared among several backup paths. In general, link or segment protection could have longer backup paths thus consuming more network resources than path protection, but they may provide faster restoration [3].

Protection issues in WBS networks are different from those in WRNs since one important goal of WBS schemes is to reduce port count [3]–[5]. Allowing only same-source-same-destination waveband grouping in dynamic traffic scenario, the authors of [4] discussed link utilization and blocking performance instead of port reduction for the two proposed dedicated path-protection schemes in WBS networks. In [3], the authors proposed a tree-based shared-path protection algorithm in WBS networks and an integer linear programming formulation, in which both waveband-level and wavelength-level protection are employed. In [5], the authors studied a graph-based shared-path scheme at wavelength level, and showed that the wavelength sharing undesirably impedes wavebanding and degrades the performance of port reduction. Hence the paper concluded that the resource sharing and port reduction are conflicting goals in their study. Clearly, efficient waveband protection and sharing while taking port reduction into consideration has not been studied, which motivates the work in this paper.

II. BAND-SEGMENT AND PROTECTION IN WBS NETWORKS

In this section, we introduce the band-segment concept and its application in WBS networks with dedicated and shared protection.

A. Concept of Band-segment

The band-segment (BS) of a given band \( b \) is defined as the portion of the fiber route between two MG-OXCs such that \( b \) is formed at the first MG-OXC, say node \( i \), and then demultiplexed at the second MG-OXC, say node \( j \). Considering the multi-fiber deployment, we denote this BS as \( AS_{i,j,f,b} \) where \( f \) is the index of the fiber that contains \( b \) at the first hop of this BS. Within one band-segment, all the wavelengths are kept at the band layer (i.e., without going through wavelength-to-band/band-to-wavelength multiplexers/demultiplexers). The introduction of band-segment brings the benefits of organizing the backup traffic at band layer and achieving the sharing without sacrificing the port reduction, which will be further discussed in Section B and C.
To facilitate the construction of band-segment in WBS networks, we separate the traffic demand into two categories: band-tier and wavelength-tier traffic. For example, assume that the band size, $B$, is 5, and the traffic, $T[s][d]$, between node pair $(s, d)$ has size of 12, then the number of wavelength-tier traffic denoted by $WT[s][d]$ ($WT[s][d] = T[s][d] / B$) is 2, and band-tier traffic denoted by $BT[s][d]$ ($BT[s][d] = (T[s][d] - WT[s][d]) / B$) is 2. Note that the band-tier traffic can be automatically constructed as band-segments by accommodating them at band layer. With an efficient WBS algorithm such as the one proposed in Section III, we can construct the wavelength-tier traffic as band-segments to achieve both resource sharing and port reduction.

B. Band-segment in Dedicated Protection

To achieve the goal of reducing nodal size, the combination of active traffic and backup traffic in the same band should be carefully considered to avoid the ill-effect on the port reduction. For example, as shown in Fig.1, the active path $AP_1$ is used to accommodate the traffic between node pair $(1, 4)$ using $\lambda_1$. Similarly, $\lambda_1$ and $\lambda_2$ are used along the active path $AP_2$ to accommodate the traffic between node pair $(1, 5)$. Now to protect $AP_1$, a backup path $BP_1$ (disjoint with $AP_1$) is deployed by using $\lambda_3$. Since both the wavelengths for active path $AP_2$ and backup path $BP_1$ are within band $b_0$ (assuming the band size is 3), the $b_0$ has to be demultiplexed at node 3 to switch the traffic within $b_0$ to nodes 4 and 5 separately, although originally the traffic in $b_0$ can be switched at the band layer using only one port. In fact, although the waveband grouping is extensively studied on active traffic accommodation [6]–[8], how to organize the backup traffic at band layer is not well considered in literatures.

With the BS concept, we notice that after accommodating the active traffic, one can transform them into active band-segments (ABS) and protect the ABS at band level using backup band-segments (BBS), by which the backup traffic does not affect the active traffic (i.e., the band-segment for active traffic can not be used by the backup traffic) and wavelength assignments for BBS can operate at band layer thus saving ports.

C. Band-segment in Shared Protection

The resource utilization can be improved by using shared protection schemes. However, if not considered properly, the resource sharing between backup paths (or segments) could lead to dramatic increase of the port number, which is undesirable in WBS networks. As shown in Fig.2, for active paths $AP_1$ and $AP_2$, the backup paths are $BP_1$ and $BP_2$, respectively. When the backup path resource-sharing is achieved at the wavelength level, for example, $BP_1$ and $BP_2$ share the wavelength $\lambda_3$, the shared $\lambda_3$ is switched to node 4 or 5 in case of failure from $AP_1$ or $AP_2$. As a result, even if all the remaining wavelengths in $b_0$ (i.e., $\lambda_1$ and $\lambda_2$) continue traveling to node 4, band $b_0$ has to be configured with demultiplexing capability at node 3 to cope with the failure of $AP_2$. Such demultiplexing can degrade the WBS performance in terms of port reduction. Actually, in the work by Varma and Jue [5], the wavelength-level sharing can increase the likelihood of a band being demultiplexed at a node, thus port saving can drop up to 15% in comparison with dedicated protections.

Instead, we observe that properly organizing active path into band-segments and realizing the sharing at band level is suitable in WBS networks [9]. As shown in Fig.3, three disjoint active band-segments are defined as $AB_1$, $AB_2$, and $AB_3$. To protect $AB_1$, one can employ $b_0$ along 1-2-3-4, which can be shared along 1-2-3 to protect $AB_2$. Further, the backup band $BB_3$ (i.e., 1-2-3-5) for $AB_3$ may share the band $b_0$ along 1-2-3 without additional ports at node 3 (since the input fiber is supposed to be demultiplexed into BXC layer at this node anyway).
III. BAND-SEGMENT PROTECTION SCHEME

In this section, we introduce efficient band-segment protection schemes to transform the active traffic into active band-segments with protection from backup band-segments. More specifically, we propose one shared band-segment protection scheme (SBSP) and one dedicated band-segment protection scheme (DBSP) for the WBS networks without wavelength conversion capability. The notations below are used in the following discussion.

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- **b**: Waveband index;
- **w**: Wavelength index;
- **m**: Available waveband found in current iteration;
- **n**: Available wavelength found in current iteration, and **t** is the corresponding band that wavelength **n** belongs to;
- **F**: Fiber size;
- **B**: Band size;
- **W**: Minimum overlapping hops among routing paths;
- **AS**: The set containing all the active band-segments;
- **BS**: The set containing all the backup band-segments;
- **MarkC**: Array which saves the overlapping ends for band-segment created in current iteration;
- **BT**: Band-tier traffic demand of node pair (**s, d**);
- **WT**: Wavelength-tier traffic demand of node pair (**s, d**);
- **Path**/**Sub**: Routing path for node pair (**s, d**) and sub-path of **Path**/**Sub** with two end nodes **i, j**;
- **HopsPath**, **AS**, **BBS**: Hop number of **Path**, band-segment using band **b** within fiber **f** at the first hop, and with two end nodes **i, j**;
- **WPath**: Wavelength-tier traffic accommodation. The band-segment formation in this stage is to construct the band_segments based on the path overlapping as shown in Algorithm 2.

Our wavebanding policy is to group traffic between the node pairs which have the same source or destination node and have at least **W** (**W ≥ 2**) overlapping hops in the routing paths. There are four steps in the proposed schemes. Stage 1 produces the routes for active traffic, and Stage 2-3 is for the band-tier traffic and wavelength-tier traffic accommodation (along with band-segment formation). In Stage 4, we consider the protection of active band-segments formed in previous two stages.

**Stage 1**: Active path generation. Firstly, use the k-shortest path algorithm [10] to generate the k path(s), namely **P**/**Path**/**Sub**/**AS**, **BBS** where **h = 1, 2, ..., k**, for each node pair (**s, d**). Secondly, starting with the node pair (**s, d**), which has the longest shortest-path, select one routing path for (**s, d**), namely **Path**/**Sub**/**AS**, **BBS** from the candidates that minimizes the overlapping with existing active paths. Assume the nodes along **Path**/**Sub**/**AS**, **BBS** are **s, s1, s2, ..., d**. Thirdly, for all the same-source sub-paths **Sub**/**AS**, **BBS** and same-destination sub-paths **Sub**/**AS**, **BBS** of **Path**/**Sub**/**AS**, **BBS**, if this sub-path satisfies the wavebanding policy (i.e., at least **W** overlapping hops with **Path**/**Sub**/**AS**, **BBS**), we choose it as the active path for respective node pairs. Continue this process until all routing paths are selected.

**Algorithm 1** Band-tier Traffic Accommodation for Node Pair (**s, d**)

1: while **BT**[**s, d**] >= **B** do
2: Find free band **m** starting with **b** along the path;
3: if the band **m** exists then
4: **b** ← (**m** + 1)%**B**
5: else
6: **WT**[**s, d**] ← **WT**[**s, d**] * **B** + **WT**[**s, d**]
7: exit
8: end if
9: Assign band **m** to this traffic;
10: **BT**[**s, d**] ← **BT**[**s, d**] − 1
11: Add the **AS**/**Sub**, **BBS** (fiber **f** contains **m** at the first hop) to the **AS**/**BS**;
12: end while

**Stage 2**: Band-tier traffic accommodation. The major aim of this stage is to efficiently accommodate traffic at the band layer using Algorithm 1, where **b** (initialized to 0) is the index of the waveband from which to search an available waveband using First-Fit scheme. We start with the node pair (**s, d**), along the same-source sub-paths **Sub**/**AS**, **BBS** sequentially, until all the band-tier traffic is considered. At the end of this stage, all the band-tier traffic is accommodated, and relative routing paths are formed as active band-segments in **AS**/**BS**.

**Stage 3**: Wavelength-tier traffic accommodation. The band-segment formation in this stage is to construct the band-segments based on the path overlapping as shown in Algorithm 2. Note that the overlapping of band-segments indicates that two band-segments share the same link(s) and use the same band within the same fiber at these link(s). In lines 1 to 10 of Algorithm 2, we use First-fit scheme to assign a vacant wavelength to accommodate the current traffic. Once the wavelength is assigned, lines 11 to 25 update the active band-segments.

More specifically, for all the node pairs with **HopsPath**[**s, d**] ≥ **W**, following steps are adopted to accommodate the wavelength-tier traffic demand and form the active band-segments.

1) Starting with node pair (**s, d**), which has the least hops with the longest routing path, use Algorithm 2 to accommodate its traffic demand.
2) Use Algorithm 2 to accommodate the traffic demand for all the same-source sub-paths **Sub**/**AS**, **BBS** which satisfy our wavebanding policy.
3) Update **w** to the first wavelength of next band.
4) Use Algorithm 2 to accommodate the traffic demand for all the same-destination sub-paths **Sub**/**AS**, **BBS** which satisfy the wavebanding policy. Then goto Step 1, until all
traffic demands for node pairs with \( H_{\text{Path}} s,d \geq W \) are satisfied.

At the end of this stage, the traffic for node pairs having less than \( W \) hops along the routing path is accommodated at band-layer whenever possible before being considered at the wavelength layer using Algorithm 2 to preserve the port reduction from the existing band-segments.

Algorithm 2 Wavelength-tier Traffic Accommodation for Node Pair \((s, d)\)

\[
\begin{align*}
1: & \text{ while } W T[s][d] > 0 \text{ do} \\
2: & \quad \text{Find a free wavelength } n \text{ starting with } w \text{ along the path;} \\
3: & \quad \text{if the wavelength } n \text{ exists then} \\
4: & \quad \quad t \leftarrow \lceil n/B \rceil \\
5: & \quad \quad w \leftarrow (n + 1)\%F \\
6: & \quad \text{else} \\
7: & \quad \quad \text{Break} \\
8: & \quad \text{end if} \\
9: & \quad \text{Assign wavelength } n \text{ to this traffic;} \\
10: & \quad \text{WT}[s][d] \leftarrow WT[s][d] - 1 \\
11: & \quad \text{if AS}_{s,d,f,t} \text{ already exists in ASet then} \\
12: & \quad \quad \text{Update } AS_{s,d,f,t}; \\
13: & \quad \quad \text{Continue} \\
14: & \quad \text{else} \\
15: & \quad \quad \text{Create band-segment } AS_{s,d,f,t}; \\
16: & \quad \quad \text{end if} \\
17: & \quad \text{for all } AS_{i,j,x,t} \text{ that overlaps with } AS_{s,d,f,t} \text{ do} \\
18: & \quad \quad \text{Add the overlapping ends to array } MarkC; \\
19: & \quad \quad \text{Split and update } AS_{i,j,x,t} \text{ using the overlapping ends;} \\
20: & \quad \text{end for} \\
21: & \quad \text{Add } s, d \text{ to the } MarkC \text{ when necessary, sort } MarkC \text{ according to the node sequence of } Path_{s,d}; \\
22: & \quad \text{for } i = 1 \text{ to size of } MarkC - 1 \text{ do} \\
23: & \quad \quad \text{Add } AS_{MarkC[i],MarkC[i+1],g,t} \text{ to ASet;} \\
24: & \quad \text{end for} \\
25: & \text{end while}
\]

Stage 4: Band-segment protection. In this stage, we use backup band-segments to protect all active band-segments. Note that the traffic accommodation of backup band-segments is achieved at band-layer.

For dedicated band-segment protection, firstly generate \( l \) disjoint backup paths for each active band-segments. Then starting with \( \text{AS}_{i,j,f,k} \) in ASet that has the longest routing path, select \( \text{BBS}_{\text{AS}_{i,j,f,k}} \) from the \( l \) candidate backup paths which has minimal number of hops as well as vacant band along the backup path and add the backup band-segment to the BSet. Continue this process until all the active band-segments are protected.

For shared band-segment protection, note that the band-level sharing is only allowed for the backup band-segments whose active band-segments are disjoint. First, for each active band-segment, find \( l \) disjoint backup paths. Secondly, starting with \( \text{AS}_{i,j,f,k} \) that has the longest routing path, select one path from the \( l \) candidate backup paths which has maximum overlapping with existing backup band-segments to form \( \text{BBS}_{\text{AS}_{i,j,f,k}} \).

Then, accommodate \( \text{BBS}_{\text{AS}_{i,j,f,k}} \) by sharing the allocated resources in overlapping links and add it to the BSet. If no sharing can be achieved, use Last-fit scheme to assign a band for the backup band-segment. For each such sub-path of \( \text{BBS}_{\text{AS}_{a,z,x,q}} \) used by any unprotected active band-segment, say \( \text{AS}_{a,z,x,q} \), as candidate backup path, choose this sub-path as \( \text{BBS}_{\text{AS}_{a,z,x,q}} \) and add it to BSet, where \( a \) and \( z \) are the starting and the ending node of the sub-path, respectively. Continue this stage for next active band-segment from ASet until all active band-segments are considered.

IV. PERFORMANCE EVALUATION AND COMPARISON

In this section, we study the performance of DBSP and SBSP by comparing them with the dedicated path protection (DPP) and shared path protection (SPP). Specifically, the DPP uses First-fit scheme to accommodate the active traffic demand and protects the active traffic at wavelength-level using Last-fit scheme. The SPP differs from DPP by considering resource sharing at wavelength level when realizing the protection. The simulation is conducted on the 24-node topology with \( F = 100 \), and \( B = 5 \).

A. W and the Port Reduction

The parameter \( W \) is the minimum overlapping hop among routing paths that we take into consideration for band grouping, our simulation indicates that the \( W \) has a direct impact on the performance of port reduction as shown in Fig.4. The X-axis denotes the traffic size in terms of lightpath requests and Y-axis represents the total port count required in the network. In Fig.4, the port count is collected under difference \( W \) without considering the protection. The figure shows that larger the \( W \), the smaller the node size (given the same amount of traffic demand). This is because longer overlapping (with larger \( W \)) facilitates wavebanding in WBS networks and more wavelength-tier traffic is accommodated at band-layer at the end of Stage 3. However, our study also shows that over large \( W \) (e.g., \( W > 7 \)) reduces the probability to group multiple traffic from different node pairs into bands and hence negatively impacts the performance in terms of node size, and over small \( W \) (e.g., \( W < 4 \)) does not help in either port reduction or BS formulation. Therefore, we set the \( W \) to 4-6 in the 24-node topology. Note that when the traffic is a multiple of band size (i.e., 5, 10), the port count required in the network drops significantly since more wavelength assignment is operated at the band layer.

B. Dedicated Band-segment Protection

Fig.5 shows the comparison between BPHT [6] without protection, DPP, and DBSP with \( W = 5 \). Without providing any protection for all the traffic, the BPHT scheme requires the minimum number of ports among the three schemes. The DPP scheme requires more than twice the port count from BPHT. The reason is that the dedicated protection scheme is realized by using First-fit and Last-fit on active path and backup path, respectively, and the accommodation of active traffic and backup traffic within the same band can not be avoided. However, the proposed DBSP outperforms the DPP by more than 25% on average in terms of port reduction, which indicates that the band-level protection is more appealing than the one with wavelength-level protection.
C. Shared Band-segment Protection

We collect the port count from SPP, DBSP, SBSP and DPP in Fig.6, and W is set to 5. As shown in Fig.6, DPP outperforms SPP due to the fact that the wavelength-level sharing degrades the wavebanding performance as discussed in section II. However, from the simulation results, the proposed SBSP outperforms the DBSP in terms of port reduction, which indicates that the band-segments provide a better granularity for resource sharing. We further note that the port count from both band-segment schemes (DBSP and SBSP) is lower compared to that of path protection (i.e., DPP and SPP), though the difference becomes less when the traffic demand is a multiple of the band size. Hence, different with the findings in [5], this simulation result shows that band-segment sharing can improve resource utilization without degrading the performance of port reduction if intelligent wavebanding algorithm is employed.

V. CONCLUSION AND FUTURE WORK

In summary, we have introduced the concept of band-segment and proposed the dedicated and shared band-segment protection schemes for WBS networks to provide protection while reducing node size. Our simulation shows that, in terms of port reduction, band-level protection is better than wavelength-level protection in both the dedicated and shared protection, and resource sharing can be achieved by using band-segment sharing schemes without degrading the performance of port reduction.

REFERENCES