Elastic Versus WDM Networks With Dedicated Multicast Protection

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Abstract — We consider the routing and spectrum allocation (RSA) problem of protecting all-optical multicast sessions against a single link failure in elastic optical networks (EONs). A tree is derived to support a multicast session and can be considered as a set of paths originating from a common source. We use a scheme to protect each of the paths by an arc-disjoint backup path in a case of any link failure. For this problem, we provide a node-arc integer linear programming (ILP) formulation and propose a heuristic algorithm for this protection scheme. We evaluate the improvement achieved by flexible grid adopted in EONs over the fixed-grid wavelength-division multiplexing (WDM) networks. The evaluation is done by considering static modelling based on ILP and heuristics as well as dynamic simulations. We consider two approaches for heuristic algorithms: one is a two-step approach that computes the routing trees and then allocates spectrum. The other uses spectrum window plane (SWP), and constructs auxiliary graphs for the relevant range of spectrum to jointly solve the RSA problem. We evaluate the performances of the proposed algorithms under static and dynamic traffic models. Based on the studied scenarios, we observe consistent improvement in efficiency of flexible grid EONs over fixed-grid WDM networks. Moreover, we demonstrate that the network size (likely, because the availability of more alternative routes) can significantly affect the benefit in efficiency achieved by the SWP-based approaches over the two-step approaches.

Index Terms—All-optical multicasting; dedicated protection; elastic optical networks; routing and spectrum allocation.

I. INTRODUCTION

Traditional wavelength division multiplexing (WDM) networks use fixed 50-GHz grid and assign an entire wavelength channel to a connection even if its required capacity is much smaller than the channel capacity. This rigid coarse granularity leads to unoptimized usage of the spectrum and therefore low spectrum utilization for traffic with diverse transmission rates [1]. In order to improve the spectrum efficiency and allocation flexibility, elastic optical networks (EONs) with finer granularity (e.g. 12.5 GHz) have been introduced as promising alternatives [2]. Bandwidth-variable transponders (BVTs) [3] can flexibly set up connections with various ranges of frequency slots (FSs). As multiple FSs are allocated to a connection in EONs rather than only one wavelength in fixed-grid WDM networks, there is a need for sophisticated routing and spectrum allocation (RSA) algorithms in EONs. By assigning an appropriate number of FSs, algorithms designated for EONs significantly improve the spectrum efficiency over traditional WDM networks [4].

A. Background

Multicasting is widely used to support applications such as video streaming and content distribution. Compared to conventional IP multicasting, all-optical multicasting eliminates the expensive optical-electrical-optical (OEO) conversion and provides a transparent and power-efficient solution [5]. To realize multicast services on optical layer, an individual lightpath can be set up for each destination [6]. Furthermore, a more spectrum-efficient way is to construct a light-tree from the source node to all destination nodes by deploying multicast-capable nodes [7]. Multicast-capable nodes split the in-coming optical signal into multiple out-going copies using optical splitters [5]. Broadcast-and-select mechanism can efficiently accomplish all-optical multicasting with bandwidth-variable wavelength-selective switch (BV-WSS). As shown in Fig. 1, signals on different frequency are first sent to all out-going ports, and then BV-WSS is used to drop unwanted signals. All-optical multicasting has received extensive interests in both fixed-grid WDM networks and flexible grid (flex-grid) EONs [8]–[18]. The authors of [8] and [9] investigated the routing and wavelength assignment problem for all-optical multicasting in WDM networks with sparse splitting constraint. Cost bounds of constructing light-trees were studied for both full and sparse splitting cases in [10]. Lin et al. [11] investigated the wavelength assignment problem for all-optical multicasting in WDM networks with traffic grooming. Wang and Chen [12] evaluated the performance improvement of flex-grid EON over fixed-grid WDM
networks for all-optical multicasting. The light-tree scheme was studied and compared with the lightpath scheme for network planning in [13]. Gong et al. [14] formulated an integer linear programming (ILP) model and proposed a genetic algorithm for all-optical multicasting RSA problem. Moreover, studies on using the subtree scheme were also conducted for EONs [15]–[18]. For this scheme, a multicast session is supported by multiple light-trees, and each of the light-trees connects the source to a part of the destinations.

### B. Related Work

As the capacity carried by a single fiber increases, more information will be lost when failures such as fiber cuts occur. For multicast connections, a single link failure can affect the transmission to several destination nodes. Therefore, it is important to protect multicast connections.

The problem of network survivability for multicast sessions has been widely studied in the context of traditional WDM networks [19]–[23]. Singhal and Mukherjee [19] showed that a directed link-disjoint, or arc-disjoint, tree could protect a multicast session and efficiently utilize spectrum resources than a straightforward link-disjoint tree does. Several heuristic algorithms have been proposed and evaluated for network provisioning in [20]. Zhang and Zhong [21] proposed to protect a multicast tree using p-cycle protection schemes. Network coding technique was also introduced to protect multicast trees by using XOR functions at each node in the network [22]. Panayiotou et al. [23] proposed a level-based shared protection algorithm for multicast sessions. Most studies are based on WDM opaque networks where wavelength conversion capabilities are considered, which do not require wavelength continuity.

However, only few publications have considered the survivable all-optical multicasting problem for EONs [24]–[27]. Kniecek et al. [24] compared dual homing approach and double multicast tree approach using precomputed path pairs for the overlay network. Cai et al. [25] discussed the survivable all-optical multicasting problem with distance-adaptive resource allocation and provided some numerical results on various protection schemes. Cai et al. [26] considered shared protection of multicast sessions in flex-grid EONs with distance-adaptive resource allocation, without comparing with fixed-grid WDM networks. Compared to the dedicated protection that we consider in this paper, the shared protection is more spectrally efficient. However, this improved efficiency is achieved at the cost of a longer recovery time which adversely affects quality of service [22]. Aibin and Walkowiak [27] considered dedicated protection in EONs by deriving two disjoint trees for each request. However, if the procedure of deriving the two trees is unsuccessful, there may be a request blocking even if there are sufficient spectrum resources to accommodate the request. The protection we consider is based on self-sharing that was proposed and demonstrated in [20] to be able to avoid this problem. In addition to considering dedicated protection for flex-grid EONs, we also compare the bandwidth requirement between fixed- and flex-grid networks both with dedicated protection. Wang and Chen [12] did compare the performance of multicasting provision between fixed- and flex-grid networks, but they did not consider protection at all. Also, Vizzaino et al. [28] considered different protection schemes and compared fixed- and flex-grid networks. However, they did not consider multicasting and focused on the provision of lightpath connections and the evaluation of cost efficiency in terms of energy consumption and equipment expenses. Moreover, Fan et al. [17], [18] did not consider protection, nor did they compare fixed- and flex-grid networks.

New services such as cloud computing have attracted tremendous interest in both academia and industry. Such services require reliable multicasting. Although there exist studies on the evaluation of EONs over WDM networks for multicasting, to the best of our knowledge, they did not take into consideration protection which is considered an important attribute of optical networks. Moreover, the increasing volume and diversity of traffic that requires multicasting with protection, because it imposes unique and strong constraints on the network, may present results on the comparisons between EONs and WDM networks that are different than those obtained in cases where the traffic is considered to be only unicast. In this paper, we focus on the performance evaluation of flex-grid EONs over fixed-grid WDM networks for multicast with dedicated protection.

### C. Key Contributions

In this paper, we investigate the all-optical multicasting routing and spectrum allocation (AOM-RSA) problem with dedicated protection in EONs. We focus on the single link failure case, which is a common failure caused by fiber cuts. In order to reduce the network cost and alleviate the switching time from a primary path to its backup path, we consider that primary path and backup path for destinations in a multicast session use the same range of spectrum resources. We evaluate the improvement in spectrum utilization with flex-grid in EONs over fixed 50-GHz grid in traditional WDM networks. We formulate the problem by a node-arc ILP model that minimizes the required spectrum bandwidth. We also proposed two heuristic algorithms that are applicable to large-scale network planning and provisioning. One algorithm is a two-step (TS) approach that first computes the routing trees and then allocates spectrum resources. The other is a one-step approach based on the spectrum window plane (SWP) scheme [29]. The idea is to firstly obtain a graph where the available spectrum resources in its links are appropriate (e.g., obeying the continuity constraint) and sufficient. This is done by determining the required spectrum resources and removing from the original graph the links where the spectrum resources are unavailable. Then, routing algorithms are run...
on the obtained graph. In this way, the RSA problem is solved jointly. In this paper, we adapt a heuristic routing algorithm proposed in [30] to TS and SWP-based approaches and then use the resulted new algorithms as performance benchmarks to our heuristics. We evaluate the performances of the proposed algorithms under static and dynamic traffic. We consider that the optical channel is free of physical impairments. Linear impairments, such as noise and fiber's chromatic dispersion, would further limit the reach in a link. Although considering impairments may give rise to improved network performance, such impairment-aware design is beyond the scope of this work and could be considered in future work.

D. Organization

The rest of this paper is organized as follows. Section II describes the network model of AOM-RSA with dedicated protection. In Section III, we provide an ILP formulation in the network model. In Section IV, we first provide a scalable heuristic algorithm, and then apply it to the TS and SWP alternatives. Section V evaluates the simulation results and compares the performances of different schemes for both static and dynamic scenarios. Section VI summarizes and concludes this paper.

II. AOM-RSA WITH DEDICATED PROTECTION

In this section, we first present the network model used in this paper. Then, we describe the dedicated protection for the multicast sessions. After that, we state our problem.

A. Network Model

The network is represented by a directed graph \( G = (V, E) \), where \( V \) is a set of nodes and \( E \) is a set of directed links. All pairs of adjacent nodes are connected by two directed links in opposite directions. For instance, nodes \( (i, j) \) and \( (j, i) \) are connected by links \((i, j)\) and \((j, i)\), where link \((x, y)\) denotes a link that transmits traffic from node \( x \) to node \( y \). Let \( g_{\text{WDM}} \) be the bandwidth of a wavelength in fixed-grid WDM networks and let \( g_{\text{EON}} \) be the bandwidth of an FS in flex-grid EONs. We unify the two notations to be \( g_n, n \in \{\text{WDM}, \text{EON}\} \).

B. Dedicated Protection

In this paper, we focus on serving multicast requests with dedicated protection. We accommodate a multicast request by a primary tree, and protect each destination in the primary tree by having a backup path that is arc-disjoint to the path in the primary tree. Within the provision of a single request, the allocated spectrum resources in a link traversed by a path to its destination in the primary tree can be used to protect other destinations whose primary paths do not traverse through this link. Such a scheme is called self-sharing protection scheme [20]. However, the spectrum resources allocated to one request cannot be used to serve other requests.

C. Problem Statement

We denote a multicast request by \( r = (s_r, D_r, C_r) \), where \( s_r \) is the source node, \( D_r \) is the set of destination nodes, and \( C_r \) is the required bandwidth in unit of GHZ. The required number of wavelength channels or FSs, \( f_r \), is computed by \( f_r = \lceil C_r / g_n \rceil \), where \( \lceil x \rceil \) denotes the smallest integer that is equal to or greater than \( x \). We consider serving multicast requests with dedicated protection for the case of single link failure. We do not consider wavelength/spectrum conversion. For the self-sharing scheme discussed above, we consider that the allocated wavelength/spectrum in the primary tree is the same as those in the backup paths. A benefit of having the same spectrum is that we do not need to reconfigure the transponder in a case of link failure. We consider static and dynamic traffic scenarios in this paper.

1) Static Traffic

For the case of static traffic, all the multicast requests are given in advance. Under the condition that all multicast requests are accommodated, the objective is to minimize the maximum spectrum bandwidth among the spectrum required in all links. The objective is chosen because using less spectrum bandwidth implies cost savings for network planning. We compare the results in flex-grid EONs to those in fixed-grid WDM networks. For this problem, we provide an ILP model that can be applicable to both fixed- and flex-grid cases. We also propose efficient heuristic algorithms.

2) Dynamic Traffic

For the case of dynamic traffic, the multicast requests arrive randomly and sequentially, then hold for a certain period, and finally depart. Due to the limitation of spectrum resources, a multicast request can be blocked. For this scenario, given the spectrum resources in all links, the objective is to minimize the request blocking probability in the network. We compare the blocking probabilities in flex-grid EONs to those in fixed-grid WDM networks.

III. ILP FORMULATION

In this section, we present a node-arc ILP model, which is applicable to both fixed-grid WDM networks and flex-grid EONs, to accommodate the multicast requests with dedicated protection. We assume that the following are given: the network topology as a graph \( G \), the type \( n \) of the network, \( n \in \{\text{WDM, EON}\} \), and a set of requests \( R \). Each fiber link carries \( N \) indexed wavelength in fixed-grid WDM networks or FSs in flex-grid EONs. \( M \) is a big number. The details of ILP model is as follows:

Variables:

- \( P_{i,j}^{r,d} \) binary, equals 1 if primary tree of request \( r \) from source \( s_r \) to destination \( d \) uses link \((i, j)\); 0, otherwise
- \( B_{i,j}^{r,d} \) binary, equals 1 if backup tree of request \( r \) from source \( s_r \) to destination \( d \) uses link \((i, j)\); 0, otherwise
- \( X_{i,j}^{r} \) binary, equals 1 if link \((i, j)\) is used by request \( r \); 0, otherwise
- \( c_{t_{1,2}} \) binary, equals 1 if request \( r \) shares common links with request \( r_2 \); 0, otherwise
- \( w_t \) integer, start index (FS or wavelength) of request \( r \)
- \( z_r \) integer, end index (FS or wavelength) of request \( r \)
- \( o_{t_{1,2}} \) binary, equals 1 if the end index of request \( r \) is smaller than the start index of request \( r_2 \); 0, otherwise
- \( z \) integer, number of FSs or wavelengths required to accommodate all the requests
Objective: \[
\min \ z \times g_a
\] (1)

Subject to:
\[
\sum_{i} P_{i,j} - \sum_{k} P_{j,k} = -1, \ \forall r \in R, \ d \in D_r, \ j = s_r
\] (2)
\[
\sum_{i} P_{i,j} - \sum_{k} P_{j,k} = 1, \ \forall r \in R, \ d \in D_r, \ j = d
\] (3)
\[
\sum_{i} P_{i,j} - \sum_{k} P_{j,k} = 0, \ \forall r \in R, \ d \in D_r, \ j \neq s_r, \ j \neq d
\] (4)
\[
\sum_{i} B_{i,j} - \sum_{k} B_{j,k} = -1, \ \forall r \in R, \ d \in D_r, \ j = s_r
\] (5)
\[
\sum_{i} B_{i,j} - \sum_{k} B_{j,k} = 1, \ \forall r \in R, \ d \in D_r, \ j = d
\] (6)
\[
\sum_{i} B_{i,j} - \sum_{k} B_{j,k} = 0, \ \forall r \in R, \ d \in D_r, \ j \neq s_r, \ j \neq d
\] (7)
\[
P_{r,s} + P_{r,d} \leq 1, \ \forall r \in R, \ d_1, d_2 \in D_r, \ (i, j), (k, j) \in E, \ i \neq k
\] (8)
\[
P_{r,s} + B_{r,d} \leq 1, \ \forall r \in R, \ d \in D_r, \ (i, j) \in E
\] (9)
\[
\sum_{d} P_{r,d} + \sum_{d} B_{r,d} \leq M \times X_{r,i}, \ \forall r \in R, \ (i, j) \in E
\] (10)
\[
X_{r,i} + X_{r,i} - c_{r,s} \leq 1, \ \forall r, r_2 \in R, \ r_1 \neq r_2, \ (i, j) \in E
\] (11)
\[
o_{r,s} + o_{r,s} = 1, \ \forall r, r_2 \in R, \ r_1 \neq r_2
\] (12)
\[
z_r - w_r + 1 \leq M \times (2 - o_{r,s} - c_{r,s}), \ \forall r, r_2 \in R, \ r_1 \neq r_2
\] (13)
\[
f_r \leq z_r - w_r + 1, \ \forall r \in R
\] (14)
\[
z_r \leq z_r, \ \forall r \in R
\] (15)

The objective function (1) is to minimize the required spectrum bandwidth in the network for all multicast requests.

Constraints (2)-(7) ensure that a primary path and a backup path are found for each destination in a multicast request. Constraint (8) ensures that all primary paths in a multicast request form a primary tree. For each destination in a multicast request, arc-disjointness between the primary path and the backup path is ensured by constraint (9). Constraint (10) guarantees that a link used by a multicast connection as primary or/and backup is used to serve its request. Constraint (11) models the situation when two multicast requests share common link. Constraints (12) and (13) ensure that the bandwidth in a link allocated to one connection cannot be used by any other connection. Constraint (14) ensures that the allocated bandwidth is not less than the required bandwidth for each multicast request. It also guarantees the spectrum contiguity constraint by allocating to requests the entire spectrum resources from the start index (included) to the end index (included). Meanwhile, the continuity constraint is ensured by utilizing two variables, i.e., the start and end indices, at the connection or request level, where the connection of a request is assigned the same spectrum in each of the traversed links. Constraint (15) gives maximum index among the end indices of all multicast requests.

The dominant number of variables is between the number of \( P_{r,s} \) and the number of \( c_{r,s} \), which is \( O(|R| \times |D| \times |E|) \), where \( |D| \) is the average size of destination set. The dominant number of constraints is between the numbers of constraints (8) and (11), which is \( O(|R| \times |D|^2 \times |E|^2 + |R|^2 \times |E|) \).

IV. HEURISTIC ALGORITHMS

Since the running time of solving ILP for realistically sized networks may be prohibitive, there is a need for scalable heuristic algorithms that provide near optimal solutions. In this section, we propose a dedicated path protection tree (DPPT) heuristic algorithm that computes arc-disjoint backup paths for each destination. The details of the DPPT algorithm are shown in Algorithm 1. We assume the self-sharing scheme that the backup paths can share links with the primary tree. This self-sharing scheme provides 1:1 dedicated protection that can be implemented by automatic protection switching architectures. Given a graph, DPPT iteratively constructs a primary tree by adding one minimum-cost path each time and then setting the cost of corresponding links to zero. If such a path cannot be found, this request will be blocked. Then the backup paths are also iteratively computed. Before calculating a backup path for an uncovered destination, the links in the corresponding primary path are temporarily removed from the graph. After the backup path is obtained, the removed links are added back to the graph. The minimum-cost path for any node pair can be achieved within \( O(|E| \log |V| + |V|) \) [31]. For primary paths and backup paths, only the minimum-cost path among all calculated paths is selected in each round. The complexity of selecting minimum cost paths for all destinations is \( O(|D|^2) \). Therefore, the complexity of the DPPT algorithm is \( O(|D|^2 \times |E| \log |V| + |V|) \).

We apply the DPPT algorithm to two RSA approaches, one is a TS approach applied to DPPT designated as DPPT-TS and the other is an application of SWP-based approach to DPPT as DPPT-SWP. Accordingly, DPPT-TS performs the RSA in two steps: routing followed by spectrum allocation, while DPPT-SWP jointly solves the RSA problem.

A. Two-Step Approach

The TS approach is straightforward and DPPT-TS computes routing trees from the physical network topology. Then it tries to find a range of spectrum resources that are all available in the links of the formerly computed routing trees. The details of DPPT-TS are shown in Algorithm 2. As the physical network topology is assumed unchanged, DPPT-TS performs a fixed routing scheme for any given multicast request. After executing Algorithm 1 for the routing purpose, DPPT-TS searches the spectrum to find a range of available bandwidth. This requires a computational complexity of \( O(|N| \times |E|) \). Therefore, the complexity of DPPT-TS is \( O(|D|^2 \times |E| \log |V| + |V|) \).

B. Spectrum Window Plane Based Approach

In DPPT-SWP, a virtual plane is constructed according to the availability of certain spectrum windows (SWs) in each link [29]. The availability of a link in a virtual plane (SWP) is subject to the availability of all spectrum resources of the SW that the link contains. If any spectrum of SW in a link is occupied, this link is marked to be unavailable in the
Algorithm 1 DPPT Algorithm
Input: multicast request \( r(s, D, C) \) and graph \( G(V, E) \)
Output: primary tree and backup paths, or block request
1: set all the destinations in \( D \) uncovered, \( D' \leftarrow D \\
2: for \( n = 1 \) to \( |D| \) do
3: for \( d \in D' \) where \( D' \) is the set of uncovered destinations do
4: calculate the minimum-cost path \( p_d \) of cost \( \mathcal{C}(d) \) from \( s \) to \( d \)
5: if \( p_d \) cannot be found then block \( r \) and return
6: end for
7: \( d^* \leftarrow \arg \min \{ \mathcal{C}(d) : d \in D' \} \) and add the path, \( p_{d^*} \), to the primary tree, \( D' \leftarrow D' \cup \{ d^* \} \)
8: for each link in \( p_{d^*} \) do
9: update the cost to zero and set the state of \( d^* \) covered
10: end for
11: end for
12: reset all the destinations in \( D \) uncovered, \( D' \leftarrow D \\
13: for \( n = 1 \) to \( |D| \) do
14: for \( d \in D' \) where \( D' \) is the set of uncovered destinations do
15: remove the links in \( p_d \) from \( G \)
16: calculate the minimum-cost path \( q_d \) of cost \( \mathcal{C}(d) \) from \( s \) to \( d \)
17: if \( q_d \) cannot be found then block \( r \) and return
18: add the links in \( p_d \) back to \( G \)
19: end for
20: \( d^* \leftarrow \arg \min \{ \mathcal{C}(d) : d \in D' \} \), and select the path, \( q_{d^*} \), as the backup path, \( D' \leftarrow D' \cup \{ d^* \} \)
21: for each link in \( q_{d^*} \) do
22: update the cost to zero and the state of \( d^* \) covered
23: end for
24: end for

Algorithm 2 DPPT–TS Algorithm
Input: multicast request \( r(s, D, C) \) requiring \( f \) wavelengths/FSs and graph \( G(V, E) \) with \( N \) wavelengths/FSs in each link
Output: Allocation of \( r \), or block request
1: run Algorithm 1 to compute primary tree \( P \) and backup paths \( B \)
2: if \( P \) or \( B \) is not found then block \( r \) and return
3: for \( i = 1 \) to \( N - f + 1 \) do
4: if spectrum resource from \( i \) to \( (i + f - 1) \) are available for all links in \( P \) and \( B \) then allocate these resources and return
5: end for
6: block request \( r \)

Algorithm 3 DPPT–SWP Algorithm
Input: multicast request \( r(s, D, C) \) requiring \( f \) wavelengths/FSs and graph \( G(V, E) \) with \( N \) wavelengths/FSs in each link
Output: Allocation of \( r \), or block request
1: for \( i = 1 \) to \( N - f + 1 \) do
2: construct SWP for spectrum resources from \( i \) to \( (i + f - 1) \)
3: run DPPT on SWP to obtain primary tree \( P \) and backup paths \( B \)
4: if both \( P \) and \( B \) are found then allocate resources and return
5: end for
6: block request \( r \)

corresponding SWP. Then the routing scheme is performed on an SWP. An example is shown in Fig. 2 to illustrate the concept of SWP in EONs. Fig. 2(a) shows the physical network topology and current spectrum usage in the network. A multicast request needs a connection from node A to node C and node D, and requires two FSs. Assume that there are four FSs in each link. Then, there are three SWs, namely, SW₁, SW₂, and SW₃. Each of the three SWs contains two contiguous FSs. Specifically, SW₁ contains FS1 and FS2; SW₂ contains FS3 and FS4. Figures 2(b)–2(d) show the corresponding SWPs to the three SWs under the given spectrum usage in the network.

As the unavailable links will be removed from the corresponding SWP, the connectivity of SWP can be different from that of physical network topology. Therefore, the SWP-based algorithm selects the routing path according to the availability of spectrum resources. The resulted routing scheme can be more load balanced than that of the TS approach. The details of DPPT-SWP are shown in Algorithm 3. For any given SW size, the complexity of constructing SWPs is \( O(|N||F||E|^2/D^2\log_r(|E|/|V|)/|V|) \).

V. NUMERICAL RESULTS
We evaluate the performance of algorithms in three different network topologies shown in Fig. 3. We assume that all nodes in the network are multicast-capable and equipped with a sufficient number of BVTs. Wavelength/spectrum conversion is not considered in this paper. A bidirectional link is deployed between two adjacent nodes. Each link is considered to have a unit cost and carry 4-THz bandwidth. For fixed-grid WDM networks, we assume that each link carries 80 wavelengths in each direction and each wavelength has a bandwidth of 50 GHz. For flex-grid EONs, we assume that each link carries 320 FSs in each direction, where each FS has a bandwidth of 12.5 GHz [32]. For fair comparison, as in [4], [12], both traditional WDM networks and EONs are assumed to have the same spectral efficiency and we consider the scenario that no guard band is needed in the EONs though the case considering guard bands can be applied. In particular, each 50-GHz wavelength channel in fixed-grid WDM networks has a capacity of 100 Gbps and each 12.5-GHz FS in flex-grid EONs provides 25-Gbps capacity. Therefore, the total capacity of a fiber link in each
direction is 3200 Gbps for both fixed- and flex-grid cases.

We compare the results of our heuristic algorithms to the algorithms that are based on the routing algorithm, i.e., Step 2 of directed-graph multicast protection (DMP) heuristic where DMP is proposed in particular for WDM optical networks with wavelength conversion capability in [30]. We also consider the TS and SWP-based approaches, which resulted in the two algorithms called DMP-TS and DMP-SWP, respectively.

Due to the assumption that EONs and WDM optical networks have the same spectrum efficiency may not hold, we provide another experiment to investigate the impact of spectrum efficiency difference on the benefit of the flex-grid EON over the fixed-grid WDM network.

A. Static Scenario

We evaluate the performance of ILP versus all the above-mentioned heuristic algorithms using the six-node nine-link (N6S9) network shown in Fig. 3(a). Algorithms are applied a set of 10 requests that are assumed to be known in advance. To generate a request of a given multicast session size $|D| = 1, 2, \ldots, 5$, we randomly shuffle the list of nodes and select the first $|D|$ nodes as a multicast where the first node is the source and the remaining are the destinations. The required capacity for each request is uniformly distributed between 25 Gb/s and 100 Gb/s. As heuristic algorithms serve the requests one by one, the served sequence of requests can significantly affect the result. For each set of 10 multicast requests, we shuffle the sequence of the requests up to 10000 times to generate 10000 sequences. For each of the sequences, we obtain a value of the required bandwidth. Then we choose the minimum among the values for all request sequences as the result for each set of requests. In this way we obtain near optimal allocation for each heuristic algorithm and a given set of 10 requests. (Please note that to reduce time consumption, the run of each heuristic algorithm for a demand sequence is terminated if the value exceeds the current minimum based on the previous runs, where we continue runs for the remaining demand sequences.) For better evaluation of the heuristic algorithms we repeat the above for 10 different sets of requests. Each data value presented in this paper is the average of the results for the 10 sets of requests.

The algorithms are implemented using Java environment on Eclipse 4.6.3, while we use a commercial optimization software, i.e., Gurobi 7.0 [33], to solve the ILP problem. Our test platform is a Lenovo M900 running Microsoft Windows 10 Enterprise (64-bit), which has 64-GB RAM and an Intel® Core™ i7-6700 CPU running at 3.4 GHz.

Table I shows the performances of the heuristic and ILP algorithms in terms of both bandwidth requirement and running time for the N6S9 network. We observe that the required bandwidth for the flex-grid cases is on average 22%–25% less than that for fixed-grid case regardless of algorithms. For each of the fixed- and flex-grid network cases, the values in bold are those with firstly the minimum bandwidth requirement and secondly the minimum running time. We consider two cases, one with 10 demands, and the other with 100. We see that the ILP algorithm performs the best for the small problem instances, i.e., the case with 10 demands and multicast session size of under four. For the other cases except one, the algorithms using DPPT and DMP present close performance of required spectrum while DPPT requires shorter running times. Also, DMP has a computational complexity of $O(|D|^2/|L|/\log_{|L|/|V|} |V|)$ [30], which is higher than that of DPPT given by $O(|D|^2/|L|/\log_{|L|/|V|} |V|)$.

We also observe that the SWP-based algorithms can obtain results that are very close to those of the optimal ILP solution. On the other hand, the TS-based algorithms provide solutions that are up to 10% more expensive than that provided by the ILP in terms of bandwidth requirements. Notice that for the extreme cases of unicast ($|D| = 1$) and broadcast ($|D| = 5$), TS approaches give results that are close to the results of SWP-based approaches. This effect can be explained as follows. For the unicast case, each request consumes less network resources than the cases where the destination sets are larger. Therefore, in these scenarios, the traffic is light and the benefit of the knowledge of the availability of certain spectrum resources achieved by the SWP-based approach is not very significant. On the other hand, for the broadcast case, each multicast request occupies a large number of links, causing network congestion, and SWP as well as ILP cannot exploit available spectrum on partially used links to accommodate additional broadcast requests to achieve improvement over the straightforward TS algorithm. Finally, we also observed from Table I that, under static scenarios on the N6S9, the proposed DPPT algorithms achieve slightly better performance than the DMP algorithms.

Fig. 3. Network topologies: (a) 6-node 9-link N6S9, (b) 14-node 21-link NSFNET, and (c) 24-node 49-link USNET.
Considering that the WDM optical network and its elastic counterpart may have different spectrum efficiency, we study a range of spectrum efficiency values, namely, 0.8, 1.2, 1.6, 2, and 2.4, for EONs by varying the capacity per 12.5-GHz FS, namely, 10, 15, 20, 25, 30 Gb/s, respectively, and compare to the WDM optical network where we keep its spectrum efficiency to be 2, i.e., 100 Gb/s per 50-GHz wavelength. We choose DPPT-SWP as the algorithm while the other assumptions remains unchanged. As the observations for the cases of different multicast session sizes are similar, we provide in Fig. 4 the data point by averaging the required bandwidth values for the five cases of different destinations. We can see in the figure that the cross point is at 1.5, which means that EONs with spectral efficiency of 1.5 bit/s/Hz present the comparable performance as the 2-bit/s/Hz WDM counterpart. Compared to this WDM network, EONs with spectrum efficiency values below and above 1.5 bit/s/Hz acquire degraded and enhanced performance, respectively. In particular, the EONs with spectrum efficiency values of 0.8 and 2.4 bit/s/Hz require 74% more and 33% less spectrum compared to the 2-bit/s/Hz WDM counterpart, respectively.

The performance of our heuristic algorithms vary when different numbers of randomly shuffled demand sequences are considered. To investigate the impact of such number on the algorithm performance, we present in Fig. 5 the bandwidth savings achieved the different algorithms for fixed- and flex-grid, by increasing the number of sequences tenfold. We consider increases from 1 to 10, from 10 to 100, from 100 to 1000, and from 1000 to 10000. In the figure, we see diminishing marginal benefit where we obtain additional improvement for more considered demand sequences. We define the number of demand sequences sufficient when less than 1% performance gain is obtained for a tenfold increase in the number of sequences. We can see in Fig. 5(a) that 10 demand sequences give sufficiently accurate results for the 10-demand case, while 100 sequences are sufficient for the 100-demand case, as shown in Fig. 5(b).

We also use tabu search algorithm proposed by Glover [34] to explore the potential of the demand ordering. A bandwidth requirement value can be obtained by applying a solution obtain by tabu search to an algorithm, e.g., DPPT-SWP. The tabu search algorithm is performed as follows. We firstly provide a demand sequence to a given algorithm (e.g., DPPT-SWP) and mark it as the current and the best solution. Then, we repeat the following until a termination condition is met, e.g., reaching the maximum number of iterations. We generate a candidate set of moves (the word

| Table 1 | PERFORMANCE COMPARISON IN TERMS OF BANDWIDTH REQUIREMENT (BR) IN UNITS OF GHz AND RUNNING TIME IN UNITS OF SECONDS AMONG THE HEURISTIC ALGORITHMS WITH 10000 RANDOM SEQUENCES VERSUS THE ILP OPTIMAL ALGORITHM |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| BR | Time | BR | Time | BR | Time | BR | Time | BR | Time | BR | Time | BR | Time | BR | Time |
| 1 | 255 | 3.43 | 255 | 2.23 | 250 | 3.27 | 250 | 2.52 | 250 | 1.09 | 195 | 3.70 | 196.26 | 2.26 | 193.75 | 4.77 | 193.75 |
| 3 | 430 | 17.48 | 425 | 5.36 | 395 | 12.82 | 395 | 6.82 | 390 | 10.92 | 326.25 | 17.60 | 326.25 | 5.7 | 298.75 | 16.71 | 298.75 |
| 4 | 500 | 31.51 | 500 | 8.06 | 475 | 23.39 | 475 | 9.8 | 475 | 13.45 | 372.5 | 33.18 | 372.5 | 8.4 | 372.5 | 13.45 | 372.5 |
| 5 | 500 | 51.41 | 500 | 11.24 | 400 | 42.75 | 500 | 12.36 | 500 | 11.34 | 372.5 | 54.34 | 372.5 | 8.4 | 372.5 | 14.89 |
| 6 | 715 | 26.75 | 715 | 12.33 | 710 | 56.94 | 710 | 19.18 | 710 | 25.17 | 313.25 | 22.64 | 313.25 | 10.24 | 313.25 | 25.17 | 313.25 |
| 7 | 2575 | 78.48 | 2580 | 26.03 | 2545 | 134.35 | 2545 | 101.31 | - | - | 2021.25 | 91.22 | 2028.75 | 44.84 | 1982.5 | 229.50 | 1982.5 |
| 8 | 3610 | 173.83 | 3470 | 46.32 | 3340 | 254.76 | 3340 | 180.24 | - | - | 2763.75 | 187.76 | 2767.5 | 72.01 | 2585 | 393.59 | 2582.5 |
| 9 | 4985 | 326.32 | 4725 | 75.16 | 4390 | 468.61 | 4385 | 307.14 | - | - | 3790 | 355.72 | 3603.75 | 115.31 | 390 | 689.17 | 395 |
| 10 | 5000 | 531.89 | 5000 | 104.01 | 5000 | 638.83 | 5000 | 348.12 | - | - | 3902.5 | 552.34 | 3802.5 | 142.56 | 3802.5 | 671.10 | 3802.5 |

Fig. 4 Impact of spectrum efficiency on the benefit of EONs over WDM

Fig. 5. Diminishing marginal benefit over tenfold increase in the number of demand sequences: (a) 10-demand case; (b) 100-demand case.
move is used in [34] to refer to a change in the potential solution. Here, a demand sequence solution is obtained by applying a move to the current solution. We obtain the admissible candidate solutions by applying non-tabu moves, i.e., moves that are not in the tabu list, to the current solution (a tabu list is a set of moves that are forbidden to be used by the algorithm). Among these solutions, the best one is marked as the current solution. If the best candidate is better than the best solution, it is marked as the best solution, thereby an improvement is attained. The associated move is then added into the tabu list.

We take the DPPT-SWP algorithm as an example. As in [35], to explore the demand ordering, we also define a move as a swap between two demands. We consider the same test conditions for the 100-demand case, and a total of 1000 moves which correspond to the number of random demand sequences considered before. As the number of the candidate moves and the size of the tabu list affect the performance of the tabu search algorithm, we consider a range of cases. The number of random moves for each iteration varies, namely, 10, 20, and 40, which corresponds to the termination condition of 1000, 500, and 250 iterations, respectively. Also, we consider varied maximal sizes of the tabu list, namely, 40%, 60%, and 80% of the number of considered moves. (When the list reaches its maximal size and a new move enters, another move leaves the list based on the FIFO principle.) As these cases provide close performance, to avoid presentations of repetitive results, we show only those with the best performance and compare them to the algorithm using the random shuffle method. For the fixed-grid case, the tabu search algorithm, for all the cases, provides the same performance as the random shuffle method. Therefore, we do not present the comparison results for conciseness.

For the flex-grid cases, the comparison results are shown in Table II, where we present the nine cases of the tabu search algorithm and compare them to the case of random shuffle method. We observe that for the same number of considered demand sequences, the tabu search algorithm for all cases slightly outperforms the random shuffle. In particular, the one considering 20 random moves per iteration with a tabu list size of 12, i.e., 60% of the number of the considered moves, performs the best on average, and achieves less than 0.5% spectrum savings over the random shuffle method.

B. Dynamic Scenario

We also implement the algorithms for dynamic traffic in the three network topologies with average nodal degrees of 3, 3, and 3.58, respectively, in Fig. 3. For dynamic traffic, we assume that multicast requests arrive one by one in accordance with a Poisson process with parameter $\lambda$ and the corresponding holding times follow a negative exponential distribution with parameter $\mu$. Hence, the traffic load is calculated as $\lambda/\mu$ erlang.

For each multicast request with a session size of $|D|$, the generation of multicast requests are the same as in the static case. For each traffic load, we run 10 separate simulations of dynamic traffic. In each run, there are $10^5$ multicast requests. We evaluate the performance by request blocking probability, which is defined as the ratio of the number of blocked requests over the number of total requests. Then, similar to the static scenario, the average of the 10 blocking probability results are provided in Figs. 6–11.

Figs. 6 and 7 provide the values obtained for the blocking probability versus traffic load in N6S9 for the cases of $|D| = 2$ and $|D| = 3$, respectively. As expected, all blocking probability values are increasing with the traffic load. In particular, in Fig. 6, we provide the error bar of the 95% confidence intervals based on Student-t distribution for all cases, where we find that for each case, the algorithms with DPPT and DMP achieve comparable performance as the error bars overlap significantly. Please note that for better exposition, we do not show the error bars in the remaining figures as they overlap. DPPT achieves slightly lower

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>PERFORMANCE COMPARISON FOR FLEX-GRID NETWORKS BETWEEN THE TABU SEARCH ALGORITHM AND THE RANDOM SHUFFLE METHOD ON THE EXPLORATION OF DEMAND SEQUENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tabu Search</td>
<td>Random Shuffle</td>
</tr>
<tr>
<td>10 Candidate Moves</td>
<td>20 Candidate Moves</td>
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<tr>
<td>40%</td>
<td>60%</td>
</tr>
<tr>
<td>1303.75</td>
<td>1303.75</td>
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<tr>
<td>3 2546.25</td>
<td>2546.25</td>
</tr>
<tr>
<td>4 3361.25</td>
<td>3361.25</td>
</tr>
<tr>
<td>5 3802.5</td>
<td>3802.5</td>
</tr>
<tr>
<td>Average</td>
<td>2594</td>
</tr>
</tbody>
</table>

Fig. 6. Blocking probability versus traffic load for N6S9 with $|D| = 2$.

Fig. 7. Blocking probability versus traffic load for N6S9 with $|D| = 3$. 

As these cases provide close performance, to avoid presentations of repetitive results, we show only those with the best performance and compare them to the algorithm using the random shuffle method. For the fixed-grid case, the tabu search algorithm, for all the cases, provides the same performance as the random shuffle method. Therefore, we do not present the comparison results for conciseness.

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blocking probability than DMP for the case of $|D| = 3$ (see Fig. 7).

Due to the finer granularity in flex-grid case, the algorithms for flex-grid case achieve much lower blocking probability than those for fixed-grid case. In Fig. 6, when traffic load is 180 erlangs, DPPT-TS and DPPT-SWP achieve reduction of 57.7% and 61.4%, in blocking probability under flex-grid relative to fixed-grid. Using SWP did not improve efficiency significantly over TS-based algorithms. This is because the alternative routes in N6S9 is limited, the benefit of SWP could not be significantly realized.

In Fig. 6, we also observe that when we set the grade of service (GoS) requirement to blocking probability of $10^{-3}$, DPPT-SWP can support 110 erlangs and 130 erlangs of traffic load for the fixed- and flex-grid cases, respectively. This implies a bandwidth saving of 18% by flex-grid relative to fixed-grid. Then when we increase the destination set size to 3, as observed in Fig. 7, the benefit of bandwidth savings of flex-grid relative to fixed-grid is increased to 25%. These results observed in Figs. 6 and 7 imply that more requests can be served under the same network condition for the flex-grid case than under fixed-grid. The improvement in efficiency of flex-grid versus fixed-grid which is within 18–25% is similar to the previous results of 22–25% savings in capacity requirements observed for N6S9 under the static modelling.

Figure 8 shows the blocking probability versus traffic load in NSFNET for the case of $|D| = 3$. Here we observe a significant improvement of DPPT-TS over DMP-TS in both fixed- and flex-grid cases. At 100 erlangs (in Fig. 8), DPPT-TS achieves reduction of 17.1% and 38.5% in blocking probability for fixed- and flex-grid case, respectively. On the other hand, for the SWP-based approaches, DPPT-SWP achieves comparable performance with DMP-SWP. For NSFNET, as shown in Fig. 8, again reduction of blocking probability achieved by flex-grid over fixed-grid is observed. For example, when the traffic load is 170 erlangs, DPPT-TS and DPPT-SWP reduce the blocking probability by 39.9% and 63.4%, respectively, by adopting flex-grid.

Unlike the case of N6S9 where we did not see a very significant benefit of SWP over TS, under NSFNET, such benefit becomes more prominent. NSFNET provides more alternative routes that in turn provide more opportunities to the SWP-based approaches to take advantage of its computations of routing trees according to current spectrum usage in the network, which the TS approach does not do. In particular, for the case of 170 erlangs traffic load (see Fig. 8), DPPT-SWP achieves the blocking probabilities, which is 41.8% and 64.5% lower than DPPT-TS, for fixed- and flex-grid cases, respectively. In terms of bandwidth savings, we also observe benefit for SWP over TS-based approaches. Again setting the GoS requirement to blocking probability of $10^{-3}$, in Fig. 8, SWP-based algorithms can support around 110 and 130 erlangs for fixed-grid and flex-grid, respectively. On the other hand, the TS-based algorithms can support only 80 and 100 erlangs for for fixed-grid and flex-grid, respectively. This implies improvement in efficiency of 37.5% and 30% of traffic load as compared to their respective TS-based algorithms. In Fig 7, using SWP, we observe that flex-grid saves 18% of the bandwidth required under fixed-grid. While under TS the benefit is 25%. These results represent similar benefit achieved by flexible grid over fixed-grid under N6S9.

In Fig. 9, we present results obtained under NSFNET for the blocking probability versus the multicast session size $|D|$ when the traffic load is fixed at 80 erlangs. We observe that when the size increases to a certain value, the corresponding blocking probability saturates and becomes stable for larger session sizes. In particular, for TS-based algorithms, blocking probability values become saturated at $|D| = 6$, whereas $|D| = 7$ for SWP-based algorithms, for both fixed- and flex-grid cases. This is because, under the spectrum continuity constraint, the same range of spectrum bandwidth has to be allocated to all fiber links in the tree. Therefore, when the size of the destination set increases to a certain level, the computed routing tree can cover many links and the spectrum on the remaining links is insufficient for additional requests. For example, the broadcast case may face the same condition as the case $|D| = 10$ for NSFNET under the spectrum continuity constraint, because they both occupy many links so that the next request cannot share the same range of spectrum. When $|D| = 7$, flex-grid (for both TS and SWP-based algorithms) achieves about 19 times reduction in blocking probability over the fixed-grid cases. For blocking probability below $10^{-3}$, one additional destination can be served for each multicast request for
flex-grid cases regardless of algorithms. It is important to observe that the saturation blocking probability value for fixed-grid is significantly higher than that for flex-grid. This again illustrates performance benefit of flex-grid EONs over fixed-grid WDM networks.

For the USNET network topology, we set \( |D| = 5 \), and present the various performance results in Fig. 10. By considering the GoS requirement to blocking probability of 10^{-3}, SWP-based algorithms can support around 110 and 130 erlangs for fixed-grid and flex-grid, respectively. On the other hand, the TS-based algorithms can support only 70 and 90 erlangs for fixed-grid and flex-grid, respectively. This implies that flex-grid using SWP saves 18% of the bandwidth required under fixed-grid. While, under TS, the benefit is 29%. We also observe the improvement in efficiency of 57% and 44.4% in traffic load as compared to their respective TS-based algorithms. The improvement in using SWP for USNET is much larger than that for NSFNET, because USNET has much larger size and higher average nodal degree. This allows SWP-based approaches to exploit more alternative routes in USNET than in NSFNET.

In Fig. 11 we present additional results obtained for USNET, where we fix the traffic load at 80 erlangs and vary the multicast session size, the required multicast session size for blocking probability saturation is larger in USNET than that in NSFNET. We also observe that the benefit of SWP over TS is higher for the larger USNET network than that for NSFNET. Again, as in the case of NSFNET, we observe that the saturation blocking probability value for flex-grid is significantly lower than that for fixed-grid networks.

VI. SUMMARY

We have considered the AOM-RSA problem with dedicated protection for EONs. We have provided a node-arc ILP formulation for optimizing resource utilization. We have also proposed a DPPT heuristic algorithm that uses backup paths to protect each destination in the primary tree, under both static and dynamic scenarios. We have applied the DPPT algorithm to the TS and SWP-based algorithms, which resulted in the two new algorithms DPPT-TS and DPPT-SWP, respectively. In a case of a small six-node network, DPPT-SWP achieved comparable performance against the benchmarked ILP algorithm, and better performance than DPPT-TS. We have also shown some improvement of DPPT-SWP and DPPT-TS over the equivalent algorithms DMP-SWP and DMP-TS that resulted from our adaptation of DMP. In addition to the static modelling, we have also used dynamic simulations to study the network performance and efficiency in larger networks. Please note that this paper assumed optical channels free of physical layer impairments. The impairment-awareness could be considered in future work.

Based on our static models, for the six-node network N6S9 in scenarios we considered, we have demonstrated that flex-grid EONs have achieved saving of 22%–25% of the required bandwidth as compared to fixed-grid WDM networks. Then our dynamic scenarios were based on three network topologies: N6S9, NSFNET and USNET. For these scenarios, we have observed benefit of efficiency of flex-grid over fixed-grid within the range of 18–29%, where the improvement in efficiency was not significantly dependent on the network size. We have also observed a significant improvement in blocking probabilities for flex-grid case over fixed-grid case. This significant improvement was especially noted when we have observed the difference between the saturation level in Figs. 9 and 11 in favor of flex-grid over fixed-grid.

While the results of the comparison between flex-grid and fixed-grid cases have not been significantly dependent on the network topology and size, we have observed based on our dynamic modeling and scenarios that the benefit of SWP over TS is very much dependent on the network topology and size probably because SWP-based algorithms can benefit from availability of more alternative routes in larger networks. For N6S9, the improvement observed has been small, while for NSFNET, within 30–37.5% for flex-grid case, and for USNET, with 44.4–57%. These illustrate the importance of using the polynomial-time SWP-based algorithms for large networks for which ILP is not scalable.

ACKNOWLEDGMENT

This work was supported by a grant from the Research Grants Council of the Hong Kong Special Administrative
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