Survivable Multicast Routing and Spectrum Assignment in Light-Tree-Based Elastic Optical Networks

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Abstract: We formulate MILP models and develop efficient heuristic algorithms for survivable multicast routing and spectrum assignment in light-tree based elastic optical networks considering physical layer impairments. Numerical results demonstrate the performance of our heuristics.

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1. Introduction

Recently, bandwidth-intensive multicast applications such as inter-datacenter content replication, video conferencing, and high-definition television have gained popularity and contributed to Internet traffic growth. To support multicast services, a concept namely light-tree [1] was proposed as an extension of the lightpath concept to tree topologies where data in the form of light propagates through a tree in the optical domain and has been shown to reduce cost and energy consumption if the multicasting portion of the traffic is significant [2]. To protect a light-tree connection from link failures, various multicast protection schemes have been developed such as tree-based [3], path-based [4], segment-based [5], ring-based [6], and p-cycle [7] multicast protection for wavelength-division multiplexing optical networks. As a promising candidate of the next-generation optical transport network, the flexi-grid (elastic) optical network architecture was proposed and has shown to be more spectrum-efficient for its flexible bandwidth allocation [8]. While significant effort has been made on protection of point-to-point lightpath connections [9], only little attention has been given to multicast connection protection [10].

In this paper, we aim to protect multicast connections from potential single-link failure in elastic optical networks. A multicast request can be denoted as \( \{ s; d_1, d_2, \ldots, d_n; T \} \), where \( s \) is the source node, \( d_i \) (\( i = 1, 2, \ldots, n \)) is a destination node, and \( T \) is the offered traffic [Gb/s]. Note that a unicast connection is considered here as a special case of multicast connection where there is only one destination. Accordingly, this paper also considers unicast connections. To protect a light-tree, for each source-destination (SD) pair, e.g., \( s; d_1, d_2 \), two disjoint (primary and backup) paths are required so that when the primary path fails, the backup one is invoked to recover the connection. For a higher spectral efficiency in elastic optical networks, we adopt the self-sharing and cross-sharing protection schemes proposed for WDM optical networks in [11]. Also, we include physical layer impairments in the design and consider spectrum continuity constraint, that is, a multicast connection occupies the same contiguous spectrum resources on its links. Our objective is to find survivable multicast routing and spectrum assignment (RSA) that minimizes the required spectrum resources so as to accommodate all given multicast requests. We formulate mixed integer linear programming (MILP) models for small networks, and develop several heuristic algorithms for large networks. Numerical results show that for elastic optical networks, the cross-sharing scheme requires fewer spectrum resources than the self-sharing one, and our heuristics perform close to that of the MILP models.

2. Problem statement and related concepts

Our problem is as follows. Given a network and a set of multicast requests, and assume that each node in the network is multicast-capable, and each edge corresponds to a pair of fiber links in opposite directions, minimize the required spectrum resources to accommodate and protect all the requested connections considering also physical layer impairments. For this problem, we consider self-sharing and cross-sharing protection schemes.

**Self-sharing and cross-sharing schemes:** For path-based multicast protection, two protection schemes, i.e., self-sharing and cross-sharing are considered, as proposed in [11]. For self-sharing, the primary and backup paths of each SD pair within a multicast request do not share common spectrum resource on any link, while paths of different SD pairs for a given multicast connection may share spectrum resources on common link(s). However, resource sharing among different multicast connections is not allowed. Thus it could be implemented as 1+1 dedicated protection. In contrast, cross-sharing allows sharing of backup-only resources among different multicast connections in addition to sharing allowed by self-sharing, namely, paths of different SD pairs for a given multicast connection may share spectrum resources on common link(s).
Distance adaptive modulation assignment: Since elastic optical networks support flexible modulation formats, different modulation formats can be assigned adaptively for each multicast connection. If a connection is assigned with a higher modulation format, fewer spectrum resources are required on its links. However, to meet the quality of service requirement, different modulation formats have different maximum transmission distances (transparent reach). And the higher modulation format the connection utilizes, the shorter distance it can transmit. For example, the maximal transmission distance of BPSK and QPSK can be 4000 km and 2000 km, respectively [12]. Thus, for each multicast request, a trade-off should be made between the modulation format and the transmission distance of the paths. For simplicity, we do not consider the use of regenerators, but use a transmission distance constraint that does not allow a path length to exceed the relevant transmission distance. In our examples, every SD pair will have at least one pair of disjoint paths subject to the transmission distance constraint.

3. Methodology
We have developed MILP formulations of the two problems (i.e., self-sharing and cross-sharing) for small networks. As our MILP problems for large networks are computationally prohibitive, we also develop several efficient heuristic algorithms. Due to the page limit, the MILP formulations are not provided here.

The heuristic algorithms are based on using for each multicast request a survivable multicast routing algorithm that minimizes the number of links used. Two survivable multicast routing algorithms are developed, one is to find a Disjoint Path Pair (DPP) for each SD pair, and the other is to find a Path-Disjoint Tree Pair (PDTP) where paths of each SD pair from two trees are link-disjoint. Then after this is done for all multicast requests considering the distance constraint, spectrum resources are allocated. If some of the constraints cannot be met, additional resources are allocated. We provide the pseudo-code of the heuristic algorithm for self- and cross-sharing as follows.

Main algorithm — objective: find survivable multicast RSA that nearly minimizes the required spectrum [GHz]

| Input: | A network topology, a set of multicast requests $M$, and a set of modulation formats & the max. distances |
| Output: | Survivable multicast RSA, and the required spectrum resources [GHz] for each multicast request $m$ |

for each multicast request $m \in M$, do

Run Suurballe’s algorithm [13] to obtain disjoint shortest path pair for each SD pair and the longest distance of all paths, and find a set $F_m$ of suitable modulation formats for $m$;

Call a survivable multicast routing algorithm that minimizes the number of links used, to find primary and backup paths for each SD pair of $m$ subject to the distance requirement of the highest modulation format in $F_m$;

Compare the results of the above two algorithms, and record the one with fewer primary links (primary consideration) and then fewer total number of links (secondary consideration) for the cross-sharing case, or the one with fewer total number of links for the self-sharing case, as the temporary routing subgraph for $m$;
end for

Order the multicast requests in the decreasing order of their required spectrum according to their highest among their suitable modulation formats and obtain an ordered request list $R$;

for each multicast request $m \in R$, do

Order the modulation formats in $F_m$ in decreasing order;

for each modulation format in $F_m$ in decreasing order, do

Obtain the corresponding spectrum resources in terms of Frequency Slots (FSs) and maximum distance $d_m$;

Scan spectrum-window planes [14] until the survivable multicast routing sub-algorithm finds the primary and backup paths for each SD pair of $m$ on an SWP, subject to the constraint of maximum distance $d_m$;

if it is successful in finding disjoint primary and backup paths for each SD pair of $m$, then

Allocate the spectrum and assign the primary and backup paths for each SD pair of $m$; break;
end if
end for

if it is not successful in finding disjoint primary and backup paths for each SD pair of $m$, then

Add the number of required FSs of the highest available modulation format to each fiber link;

Assign the temporary routing subgraph to $m$;
end if
end for

Obtain the number of FSs on each link. Then, after all multicast requests are served via survivable multicast RSA, we can obtain the required spectrum [GHz] on each fiber link.

4. Numerical results
To evaluate the performance of self-sharing and cross-sharing schemes, we consider two networks, namely a four-node ring (n4s4) network (with 400 km each link), and we add to it two links of 600 km each to obtain a
four-node fully-mesh (n4s6) network. The granularity of each frequency slot is 12.5 GHz. Three modulation formats BPSK, QPSK, and 8QAM are considered, with their corresponding transparent reaches: 4000 km, 2000 km, and 1000 km, respectively. Ten multicast requests are generated randomly, where the traffic follows a uniform distribution of range (0, 400) Gb/s and the multicast sessions are obtained by randomly shuffling the set of network nodes. We evaluate the impact of the number of destination nodes to the required spectrum resources.

The self-sharing and cross-sharing schemes are denoted as “SS” and “XS,” respectively. The heuristic algorithms or MILP models are denoted as the name of sub-algorithms or “MILP” with the name of the protection scheme as a prefix. For example, a heuristic SS_PDTP is for the self-sharing protection scheme and adopts PDTP as the survivable multicast routing algorithm. In Figs. 1 and 2, with the increase of number of destination nodes, the required spectrum resources increase. In Fig. 1, for the n4s4 network, the heuristic algorithms achieve almost the same performance as the MILP for both self-sharing and cross-sharing protection. Specifically, by comparing the optimal results of MILP models, the self-sharing protection requires on average 22% more spectrum resources than that of cross-sharing protection. In Fig. 2, for the n4s6 network, the self-sharing heuristics achieve the same performance as the SS_MILP; and the cross-sharing heuristics require on average 24% more spectrum resources compared to the optimal results of the XS_MILP. Specifically, for the optimal results of the MILP models, the self-sharing protection requires on average 97% more spectrum resources compared to cross-sharing protection.

5. Conclusion

We have evaluated the self- and cross-sharing protection schemes for distance-adaptive multicast routing and spectrum assignment in elastic optical networks. Numerical results show that cross-sharing outperforms self-sharing in terms of the required spectrum resources, and our heuristic algorithms achieve performance close to the optimum.

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References