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CAI, Anliang; XU, Kai; ZUKERMAN, Moshe

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Comparison of Different Multicast Approaches in Elastic Optical Networks

Anliang Cai, Kai Xu, and Moshe Zukerman, Fellow, IEEE
Department of Electronic Engineering, City University of Hong Kong, Hong Kong SAR, China
Tel: (852) 3442 4243, Fax: (852) 3442 0562, e-mail: m.zu@cityu.edu.hk

ABSTRACT
Internet traffic is experiencing an enormous growth and increased demand for new services. To enhance flexibility and improved spectral efficiency of traditional WDM optical networks that use ITU-T fixed frequency grid, Elastic Optical Networks (EONs) have been proposed. Moreover, multicast services, including live Internet video delivery and inter-datacenter database synchronization, gain popularity, and they usually generate large volume of traffic. To address the growth of multicast services, we focus here on routing and spectrum allocation for the multicast traffic in EONs considering distance-adaptive transmission. For the accommodation of multicast traffic, existing studies focus on using light-tree and lightpath technologies while the light-trail technology was not considered for EONs. In this paper, we compare the effectiveness, in term of spectrum and transmitter usage, among light-trail, lightpath and the light-tree in multicast accommodation. We also evaluate, in EONs, the benefit of having distance-adaptive transmission for these approaches. Numerical results illustrate their performances for a range of cases.

Keywords: Multicast, elastic optical networks, lightpath, light-tree, light-trail, distance-adaptive transmission.

1. INTRODUCTION
Internet traffic has experienced enormous growth in the past few decades. This growth is continuing unabated due to the increasing demand and popularity of new services. Traditional Wavelength-Division Multiplexing (WDM) optical networks follow fixed frequency-grid ITU-T standard, where a wavelength is allocated to every channel even when the requested data rate is only a small fraction of the channel capacity. This leads to inefficient resource utilization. To mitigate this inefficiency, Elastic Optical Network (EON) technology with finer and flexible frequency grids has been proposed where just-enough amounts of spectra are allocated to connections. Also, popular services, e.g., database synchronization among geographically distributed datacenters and ultra-high-definition video delivery [1], involve significant multicasting and typically require large bandwidth. For such multicast services, EONs have advantage over WDM optical networks [2].

To accommodate a multicast demand in optical networks, there are generally three technologies, namely, lightpath, light-trail, and light-tree. In this paper, we compare the performance of approaches derived based on the three technologies for EONs. The benefit of distance adaptive transmission of EONs is also evaluated. Numerical results demonstrate the effectiveness of these approaches.

2. RELATED WORK
Extensive studies on accommodating multicast services in optical networks have been reported in the literature. Kmiecik et al. [3] considered accommodating multicast demands by lightpaths in EONs. Le and Merabet [4] provided an Integer Linear Programming (ILP) formulation to accommodate a single multicast by light-trails in WDM networks. The light-trail was also studied in EONs but for unicast demands [5]. In this paper, we make use of the light-trail technology to accommodate multicast in the context of EONs.

Recent studies focus on establishing multicast connections in EONs by light-trees. Ruiz and Velasco [6] considered a similar problem to the one we presented in this paper. They evaluated the three approaches for multicast demands, namely, path, tree, and subtree. However, they omitted the distance-adaptive spectrum allocation, which is an important feature for improving spectrum efficiency in EONs and possibly makes the lightpath approach superior in terms of spectrum usage compared to that of using a single light-tree, as we will show later on. Also, they did not compare with means of using the light-trail technology for the multicast demands, which we do in this paper. Fan et al. [7] presented a performance comparison between using multiple light-trees and using a single light-tree for a multicast. However, they did not compare with the lightpath or light-trail technology, which we do in this paper. Walkowiak et al. [8] formulated a flow multicast model for a similar problem. Due to the high computation complexity, they also formulated a candidate tree model and proposed a heuristic algorithm, both based on pre-calculated candidate trees. Yu et al. [9] considered a network with modulation-enabled nodes, where signals going through such nodes can change their Modulation Schemes (MSs). Moharami et al. [10] investigated the impact of the number of Multicast-Capable (MC) nodes and the multicast degree on the network design problem of minimizing the spectrum requirement in links. Moreover, survivability was also included in the EON design. Cai et al. [2] considered dedicated protection for multicasting in EONs. Taking into account also the distance-adaptive transmission in EONs, shared protection was investigated in [11] and was further compared with cases of no protection and dedicated protection in [12].
3. MULTICAST ACCOMMODATION APPROACHES

A multicast connection involves transmission of data from the source to multiple destinations. We denote a multicast demand \( r \) by \( (s_r; F_r; t_r) \), requesting a data transmission from source \( s_r \) to the set of destinations \( F_r \) at the requested bit rate \( t_r \). To accommodate such multicast demands, five approaches, namely, lightpath, light-tree, multi-light-tree, light-trail, and multi-light-trail, can be constructed from the three technologies according to network node architectures.

When network nodes only support unicast capability, the lightpath method is used to accommodate the multicast demand, where a multicast demand is considered as a set of unicast demands, each requiring a transmission of the data from the source to each destination. When network nodes are MC, e.g., based on broadcast-and-select architecture, the multicast demand can be accommodated using the light-tree technology by a single light-tree or multiple light-trees. Here, a light-tree is an optical channel from a source to multiple destinations, which is an extension of the concept of lightpath [13]. For a light-tree, a signal is transmitted in the optical domain along a tree structure that connects the source to the destinations. In particular, a lightpath can be considered a special case of a light-tree that has only one destination. Thus, in MC networks, the light-tree approach uses a single light-tree to accommodate a multicast demand while multiple light-trees are utilized in the multi-light-tree. The third technology is the light-trail [14], where the nodes between the two end nodes of the trail can also receive the signal by tapping a small portion of the power, while switching the remainder to the output. The light-trail requires the network node to have Tap-and-Continue (TaC) functionality [15]. Similar to the light-tree, the light-trail can also support optical multicasting by allowing multiple nodes along the trail to receive the signal. Also, the lightpath is a special case of the light-trail where only the end node of the trail receives the signal. Therefore, for the TaC-based node architecture, a multicast may be accommodated by a single light-trail in the light-trail approach or multiple light-trails in the multi-light-trail.

Figure 1 illustrates the usage of these five approaches to accommodate multicast demand \( A; \{B, C, D\}; 30\text{Gb/s} \). The lightpath solution considers the multicast demand as three unicast demands accommodated by separate lightpaths. In Fig. 1a, we note that the three lightpaths aim for the same capacity but occupy different numbers of Frequency Slots (FSs). This is because lightpaths are established based on distance-adaptive transmission, where a shorter path implies that less spectrum is required. The lightpath solution consumes a total of eight FSs and three transmitters. In Fig. 1b, the light-tree uses a single light-tree to cover all the destinations. It uses one additional FS compared with the lightpath since the light-tree adopts a less efficient MS for also short transmissions, e.g., \( A \rightarrow D \). To reduce FS usage, multiple light-trees are utilized as shown in Fig. 1c. Compared with the light-tree method, the multi-light-tree saves two FSs at the cost of one additional transmitter. Figure 1d shows the light-trail approach where a light-trail is utilized to cover all the destinations resulting in 12-FS usage. Instead of a single light-trail, multiple light-trails are utilized in the multi-light-trail. It has the same FS and transmitter usage as the multi-light-tree shown in Fig. 1c in this example.
4. NUMERICAL RESULTS

We aim to compare the five approaches by the minimized spectrum consumption (the top priority) and transmitter usage for the accommodation of a single multicast demand subject to the spectrum contiguity, continuity and non-overlapping constraints [11]. We developed Mixed Integer Linear Programming (MILP) formulations for these problems and solved them by a commercial solver, i.e., Gurobi [16].

We consider three six-node networks, namely, six-link ring (N6S6) network, nine-link (N6S9) network, 15-link fully-mesh (N6S15) network. We consider a single multicast demand. Without loss of generality, the source and destinations of a demand are selected randomly and uniformly. We investigate the impact of different multicast session sizes, i.e., numbers of destinations on the performance comparison. For each size, 100 experiments are conducted for randomly generated demands. We obtain a value for each experiment and take the average of the values as the result. Assume that all the demands request a bit rate of 100 Gb/s. For the case of distance-adaptive resource allocation, we consider three MSs; each demand has spectrum requirements of eight, four, and three FSs with transparent reaches of 4,000 km, 2,000 km, 1,000 km when it is modulated by BPSK, QPSK, and 8QAM, respectively. For the other case with no distance-adaptive spectrum allocation, only BPSK is available for connections as long as its transmission distance is within 4,000 km.

Figure 2 shows the comparison of spectrum consumption of the five accommodation strategies. In Fig. 2a for the N6S6 network, on average, the light-trail and lightpath methods present the highest spectrum usage, while the multi-light-trail and multi-light-tree use the least spectrum; the light-tree lies in-between. Compared with the lightpath, the light-trail uses 6.2% more spectrum while the light-tree achieves about 16% spectrum savings. By employing additional transmitters, the multi-light-trail and multi-light-tree reduce the spectrum consumption by around 28% and 9.4% compared with the light-trail and light-tree, respectively. For the N6S9 network as shown in Fig. 2b, on average, the light-trail solution has the highest spectrum usage; the light-tree and lightpath follow, while the multi-light-trail and multi-light-tree use the least spectrum. For the N6S15 network as shown in Fig. 2c, the light-trail solution shows the most spectrum consumption, the lightpath, multi-light-trail and multi-light-tree the least, while the light-tree uses a moderate amount of spectrum. Compared with the lightpath method, on average, the light-trail and light-tree utilize 77% and 54% more spectrum, respectively, while the multi-light-trail and multi-light-tree have the same spectrum usage as the lightpath. This is because in complete networks, the lightpaths for a multicast reach the destinations by one hop and use separate MSs, while the light-tree/light-trail approach uses the same spectrum-inefficient MS subject to the longest transmissions to all destinations. Moreover, we observe a competition between the lightpath and light-tree. When the network is sparsely connected, the light-tree consumes less spectrum, while the lightpath shows lower spectrum usage for densely connected networks.

![Figure 2. Spectrum usage of the five approaches: (a) N6S6; (b) N6S9; (c) N6S15.](image)

As shown in Fig. 3, for transmitter usage, the light-trail and light-tree solutions use only one transmitter, while the lightpath uses the most transmitters, which equal the number of destinations of a multicast. The multi-light-tree and multi-light-trail have a moderate usage of transmitters, with the latter having a slightly higher usage than the former. Otherwise, the multi-light-trail would consume more spectrum (use lower-level MS) because the signal would need to travel a longer transmission distance to cover more destinations. The figures for the remaining two networks are similar to Fig. 3.

![Figure 3. Transmitter usage in the N6S6 network.](image)

| Spectrum savings of distance-adaptive spectrum allocation for a multicast demand. |
|---------------------------------|--------|--------|--------|
|                                | N6S6   | N6S9   | N6S15  |
| Lightpath                       | 36.1%  | 39.9%  | 45.0%  |
| Light-Tree                      | 14.6%  | 14.2%  | 15.2%  |
| Multi-Light-Tree                | 23.3%  | 30.7%  | 45.0%  |
| Light-Trail                     | 1.9%   | 2.3%   | 2.9%   |
| Multi-Light-Trail               | 23.3%  | 30.7%  | 45.0%  |

Table 1.
We also evaluate the benefit of distance-adaptive transmission as shown in Table 1 by comparing two network cases, i.e., one with it, the other without it. Comparing the three six-node networks, with the increase of network density, higher percentages of spectrum savings by the distance-adaptive transmission are observed for the lightpath, multi-light-tree, and multi-light-trail approaches than for the light-tree and light-trail where the saving percentages do not change significantly. This is due to the modulations used by the light-tree and light-trail are of low level so as to cover all the destinations of a multicast. Furthermore, some of the source-destination pairs with short distances still need to use the spectrum-inefficient modulation leading to excessive spectrum usage.

5. CONCLUSIONS

We compared the five approaches, namely, lightpath, light-tree, multi-light-tree, light-trail, and multi-light-trail, to accommodate a single demand in the context of EONs considering distance-adaptive transmission. The multi-light-tree and multi-light-trail methods have the lowest spectrum usage, the light-trail consumes the most spectrum, and the lightpath and light-tree lie in the middle. For the latter two, when the network is densely connected, the lightpath wins for a lower spectrum usage, while for sparse network cases, the light-tree wins. From the perspective of transmitter usage, the lightpath approach has the highest requirement; the light-tree and light-trail have the lowest usage. Both the multi-light-tree and multi-light-trail have moderate usage of transmitters with the latter slightly higher than the former. Moreover, spectrum savings brought by the distance-adaptive transmission have been seen for all network cases and are significant for the lightpath, multi-light-tree, and multi-light-trail.

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