On the Spectrum-Efficient Overlay Multicast in Elastic Optical Networks Built with Multicast-Incapable Switches

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***Abstract*—We study overlay multicast (OL-M) in multicast-incapable elastic optical networks (EONs), and propose a spectrum-efficient OL-M scheme that relies on the spectrum-flexible member-only relay, i.e., OL-M-SFMOR. Our simulation results indicate that OL-M-SFMOR achieves significant improvements on the spectrum-efficiency of multicast in EONs, when compared with other multicast schemes, even including the all-optical multicast schemes in multicast-capable EONs.**

***Index Terms*—Overlay multicast, elastic optical networks (EONs), optical orthogonal frequency-division multiplexing (O-OFDM), energy-efficient networking.**

I. INTRODUCTION

NOWADAYS, the optical orthogonal frequency-division multiplexing (O-OFDM) technology has attracted intensive research interests since it makes the elastic optical networks (EONs) possible [1]. Unlike their single-carrier counterparts in the wavelength-division multiplexing (WDM) networks, O-OFDM transponders utilize a few subcarrier frequency channels (slots) that are contiguous in the spectrum domain for high-speed data transmission, and can adjust the bandwidth allocation flexibly, i.e., changing the number of assigned frequency slots. Meanwhile, the liquid crystal-on-silicon wavelength selective switches (LCOS-WSS') can be implemented in the nodes [2], and a switching granularity at 12.5 GHz or less is achievable in the optical domain.

Together with the aforementioned advantages, O-OFDM also brings challenges for the planning and provisioning of EONs, for example, the routing and spectrum assignment (RSA) problem. To address RSA, previous work has proposed several algorithms to serve unicast connections [3]–[5]. With the evolution of the Internet, multicast has become a key enabling technology for emerging bandwidth-intensive applications, such as teleconferencing, cloud computing, e-Science and etc. Some of these applications have time-varying bandwidth demands, and therefore, EONs can potentially support them more efficiently than the traditional WDM networks, with the agile bandwidth management capabilities in the optical layer.

Recently, based on the assumption that all optical switches are multicast-capable (MC), Wang *et al.* proposed two RSA algorithms for all-optical multicast (AO-M) over EONs, by leveraging the famous shortest-path tree (SPT) and minimum spanning tree (MST) based multicast-routing algorithms [6]. However, since the MC switches usually have complicated structures [7] and can be prohibitively expensive, it is not practical to build EONs with them. To this end, it would be interesting to investigate overlay multicast (OL-M) in EONs built with multicast-incapable (MI) switches. For OL-M, a logic light-tree is constructed for a multicast request and multiple unicast lightpaths are then set up to actually carry it [8]. Therefore, multicast is accomplished over the MI infrastructure, and cost-effective network planning and provisioning are feasible, especially when multicast traffic is not dominant. Nevertheless, OL-M uses more optical transmitters than AO-M and may occupy more spectra too, since redundant unicast connections may be set up on certain links.

This letter investigates OL-M schemes in EONs. We first study a simple scheme that a unicast connection is set up from the source to each destination in a multicast group, and then propose a spectrum-efficient OL-M scheme that relies on the spectrum-flexible member-only relay. The rest of the paper is organized as follows. We formulate the problem of OL-M in EONs built with MI switches in Section II. Section III describes the details of the OL-M schemes and the performance evaluations are discussed in Section IV. Finally, Section V summarizes the paper.

II. PROBLEM FORMULATION

Let V denote the set of nodes in an EON, E denote the set of fiber links, and we use the directed graph $G = (V, E)$ to represent the physical topology. We assume that all nodes in V are equipped with MI switches, and none of them can perform optical splitting. A multicast request is modeled as $R_i = \{s_i, D_i, B_i\}$, where i is its unique index, its bandwidth requirement is B_i in Gb/s, and $s_i \in V$ and $D_i \subset V \setminus \{s_i\}$ are the source and the set of destinations (i.e., the multicast group), respectively. Here, we have $D_i = \{d_{i,j}\}$, where $d_{i,j}$ is the j-th destination in the multicast group. We define the source and all destinations of a multicast request R_i as its member nodes, denoted as $M_i = \{s_i, D_i\}$. For overlay multicast (OL-M), we have a logic light-tree $\mathcal{T}_i$ for R_i, which is rooted at s_i and reaches all destinations (i.e., $\forall d_{i,j} \in D_i$). A set of unicast lightpaths P_i is set up to support $\mathcal{T}_i$. Note that in order to save transmitters, we only consider the case that all unicast lightpaths in P_i end at multicast destinations. Therefore, we have $P_i = \{p_{i,j}\}$, where $p_{i,j}$ is the lightpath ending at $d_{i,j}$.

In EONs, an O-OFDM transmitter can select its modulation-level based on the transmission impairments. We assume that the bandwidth of a subcarrier frequency slot (FS) is 12.5 GHz. Hence, if we assume that the transmitter can pick its modulation-level from BPSK, QPSK, 8QAM and 16QAM, then the corresponding capacity of an FS is $C_{FS} = 12.5$ Gb/s, 25 Gb/s, 37.5 Gb/s, and 50 Gb/s, respectively. In this

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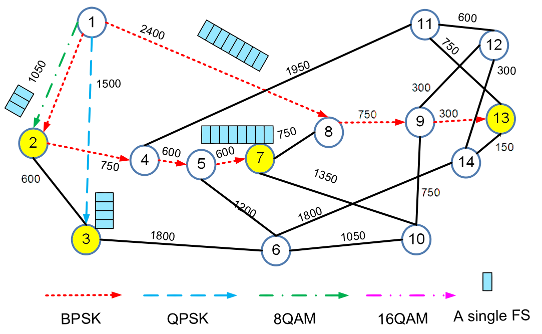

Fig. 1: An example of OL-M-SPT in NSFNET.

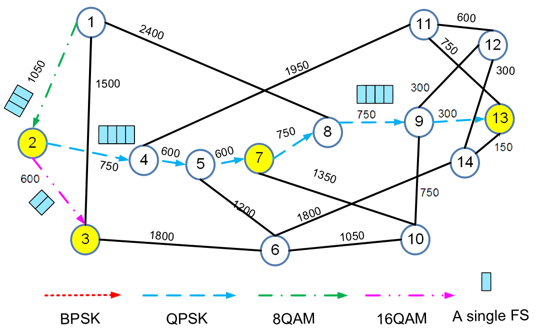

Fig. 2: An example of OL-M-SFMOR in NSFNET.

work, we apply a simple modulation-level assignment scheme that a transmitter selects the modulation-level based on the transmission distance of its lightpath [5]. We assume that the transmission reaches of QPSK, 8QAM and 16QAM are 2500 km, 1250 km, 625 km, respectively. When the lightpath is longer than 2500 km, only BPSK can be used. When the transmission reach permits, a transmitter always selects the highest modulation-level. Then, we have

$$n_{i,j} = \lceil \frac{B_i}{C_{FS}} \rceil, \tag{1}$$

where $n_{i,j}$ is the number of FS' to be assigned on $p_{i,j}$. Finally, we perform spectrum assignment for all lightpaths in P_i.

III. OVERLAY MULTICAST SCHEMES FOR MI EONS

A straight-forward method to achieve OL-M is to set up a lightpath from s_i to each $d_{i,j}$ in D_i with the shortest-path routing. Therefore, all lightpaths in P_i are from s_i. We then select the modulation-level for each $p_{i,j}$ and assign $n_{i,j}$ contiguous FS' on it with the first-fit scheme. We refer to this OL-M scheme as "OL-M with shortest-path tree" (OL-M-SPT). Fig. 1 shows an example of OL-M-SPT. Given the multicast request $R_i = \{1, \{2, 3, 7, 13\}, 100\ Gb/s\}$, we have $P_i = \{1 \rightarrow 2, 1 \rightarrow 3, 1 \rightarrow 2 \rightarrow 4 \rightarrow 5 \rightarrow 7, 1 \rightarrow 8 \rightarrow 9 \rightarrow 13\}$ and the modulation-levels of the four lightpaths are 8QAM, QPSK, BPSK and BPSK, respectively. Then, to carry the 100 Gb/s capacity, we need to assign 3, 4, 8, and 8 FS' on the four lightpaths. If we count an occupied FS on a link as one used FS, OL-M-SPT needs 23 FS' to serve R_i.

The major drawback of OL-M-SPT is that if two or more lightpaths in P_i have common links, redundant spectrum resources are allocated. For instance, in Fig. 1, the same data is transmitted twice on link $1 \rightarrow 2$. Moreover, since all $p_{i,j}$ are set up independently, when a $d_{i,j}$ is far from s_i in the topology, we can only use a low modulation-level on $p_{i,j}$ and more spectra and energy resources are wasted. It is known that higher modulation-level can provide higher energy-efficiency in terms of W/Gb/s for the O-OFDM transmitters [9].

To overcome the drawbacks of OL-M-SPT, we propose a spectrum-efficient OL-M scheme that relies on spectrum-flexible member-only relay. Specifically, we construct a light-tree $\mathcal{T}_i$ for R_i, and segment it into lightpaths under the constraint that each lightpath can only start and end at the member nodes, i.e., $M_i = \{s_i, D_i\}$. If one or more lightpaths start from a member node, we call it a "relay-node". The relay-nodes receive the multicast data and equip transmitter(s) to perform necessary optical-to-electrical-to-optical (O/E/O) conversions. Note that the modulation-level selected by a transmitter in the relay-node can be different from that of the lightpath ending at it. Therefore, spectrum-flexible relay can be achieved. We refer to this OL-M scheme as "OL-M with spectrum-flexible member-only relay" (OL-M-SFMOR).

Fig. 2 illustrates an example of OL-M-SFMOR. The multicast request is the same as that in Fig. 1. We have $P_i = \{1 \rightarrow 2, 2 \rightarrow 3, 2 \rightarrow 4 \rightarrow 5 \rightarrow 7, 7 \rightarrow 8 \rightarrow 9 \rightarrow 13\}$, and assign their modulation-levels as 8QAM, 16QAM, QPSK, and QPSK. We allocate 1, 2, and 1 transmitter(s) at relay-nodes 1, 2, and 7, respectively, for R_i. Therefore, the number of transmitters required for R_i is still 4, which is the same as that in OL-M-SPT. However, since OL-M-SFMOR pushes some of the transmitters closer to the destinations, its average lightpath length is shorter than that of OL-M-SPT. As a result, OL-M-SFMOR only needs 13 FS' to serve R_i.

In order to achieve efficient multicast-routing for OL-M-SFMOR, we propose an algorithm to build the light-tree based on the member-only approach in [10] and the definition below.

Definition 1: For two node sets $V_1 \subseteq V$ and $V_2 \subseteq V$ in a topology $G(V, E)$, we calculate the shortest-path from $v_1 \in V_1$ to $v_2 \in V_2$ and denote it as sp_{v_1,v_2}. Then, the shortest-path from V_1 to V_2 is the one that is the shortest among $\{sp_{v_1,v_2},\ \forall v_1 \in V_1, \forall v_2 \in V_2\}$.

Algorithm 1 shows the detailed procedures for the multicast-routing. *Lines* 1-3 are for the initialization, and we divide the member nodes into two node sets V_{in} and V_{out}. Then, *Lines* 5-13 construct $\mathcal{T}_i$ and move nodes from V_{out} to V_{in} one-by-one, until all member nodes are in V_{in}. Note that *Algorithm* 1 is different from the member-only algorithm in [10]. More specifically, the algorithm in [10] was for all-optical multicast (AO-M) in networks with sparse MC node placements, while *Algorithm* 1 is for OL-M in networks without any MC nodes.

IV. PERFORMANCE EVALUATIONS

We consider both static network planning and dynamic network provisioning in the performance evaluations. Two core network topologies are tested, i.e., the 14-node NSFNET and the 28-node US Backbone [11]. To generate the multicast requests, we set the average size of the multicast groups (i.e., $\overline{|D_i|}$) as 4, determine the member nodes with the assumption that each node in the topology has equal probability to be included, and then select the source node randomly from the

Algorithm 1: Build Light-Tree for OL-M-SFMOR

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input  : Physical topology $G(V, E)$, multicast request
         $R_i\{s_i, D_i, B_i\}$.
output: Multicast light-tree $\mathcal{T}_i$.
$M_i = \{s_i, D_i\}$, $\mathcal{T}_i = \emptyset$;
$V_{in} = \{s_i\}$;
$V_{out} = D_i$;
$j = 1$;
while $V_{in} \neq M_i$ do
    calculate the shortest-path from $V_{in}$ to $V_{out}$;
    store the path in $sp$;
    insert $sp$ into $\mathcal{T}_i$;
    store the end node of $sp$ as $d_{i,j}$;
    $V_{out} = V_{out} \setminus \{d_{i,j}\}$;
    $V_{in} = V_{in} \cup \{d_{i,j}\}$;
    $j = j + 1$;
end
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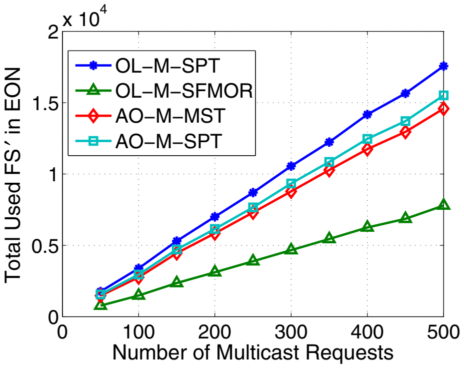

Fig. 3: Network spectrum-utilization in NSFNET.

member nodes. The size of a multicast group can vary from 1 (unicast) to $|V|-1$ (broadcast). The bandwidth requirement B_i is uniformly distributed within $[25, 100]$ Gb/s. We also implement the all-optical multicast (AO-M) schemes in [6] as the benchmark algorithms, and denote them as AO-M-SPT and AO-M-MST. Therefore, we can compare OL-M in MI EONs to AO-M in MC EONs. Note that for AO-M, the modulation-level and spectrum assignments on the links in a physical light-tree are the same, since the signals are all from the same transmitter in the source node s_i. Hence, the modulation-level of the physical light-tree is determined according to the longest path from s_i to a $d_{i,j}$ in D_i.

In static network planning, all multicast requests are known *a priori*. We accommodate all of them in the network and do not consider request blocking. For fair comparisons, the request sets are the same for all algorithms, which serve the requests in each set with the same order. Figs. 3-4 show the results on network spectrum-utilization (i.e., the total number of used FS' in the EON). It can be seen that among the four algorithms, OL-M-SPT requires the most FS' to serve the same number of requests. This is because of the spectrum wastage mentioned above. The AO-M algorithms achieve savings on the used FS' over OL-M-SPT, since the redundant lightpaths can be avoided in the light-trees. OL-M-SFMOR is the most spectrum-efficient one among the four algorithms and achieves significant reduction on the spectrum-utilization when compared with the other three. This is because with the member-only relay, OL-M-SFMOR also avoids setting up the redundant lightpaths and makes higher modulation-levels possible by pushing some of the transmitters closer to their destinations. Figs. 5-6 show the average values of the maximum path-difference, which is defined as the maximum difference between the path-lengths of any two s_i-$d_{i,j}$ pairs in a multicast group. We observe that OL-M-SFMOR provides the largest path-differences among the four in both topologies. This is because with the member-only branching constraint, OL-M-SFMOR has to use longer paths for certain destinations. Therefore, OL-M-SFMOR has to sacrifice certain performance on path-difference to ensure higher spectrum-efficiency.

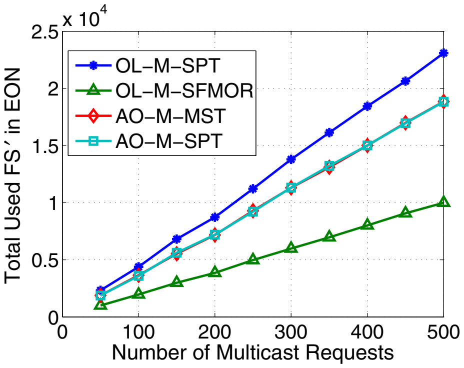

Fig. 4: Network spectrum-utilization in US Backbone.

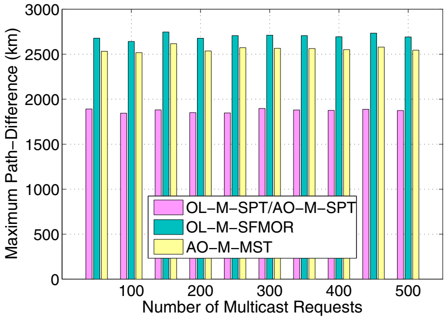

Fig. 5: Average maximum path-difference in NSFNET.

We also investigate the total power consumption of the O-OFDM transmitters and receivers for the two OL-M schemes. Applying the model in [9], we define w_{FS} as the power consumption per FS for a pair of transmitter/receiver. When the modulation-level is BPSK, QPSK, 8QAM, and 16QAM, w_{FS} is 112.4, 133.4, 154.5, and 175.5 W, respectively [9]. Then, for a multicast request R_i, the total power consumption of its transmitters and receivers is,

$$W_{R_i} = \sum_{j=1}^{|D_i|} w_{FS}^{(j)} \cdot n_{i,j} \tag{2}$$

where $w_{FS}^{(j)}$ denotes the power consumption per FS for the modulation-level on path $p_{i,j}$ in light-tree $\mathcal{T}_i$, and $n_{i,j}$ is the number of FS' assigned on $p_{i,j}$. Table I shows the simulation results. We can see that OL-M-SFMOR always consumes less power than OL-M-SPT, since both of them use the same number of transmitter/receiver pairs but OL-M-SFMOR tends

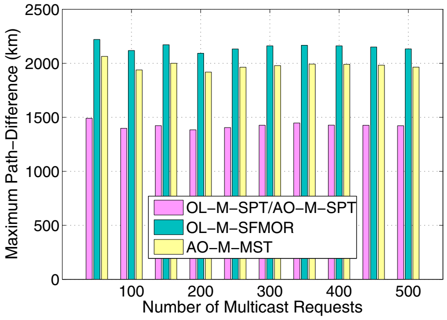

Fig. 6: Average maximum path-difference in US Backbone.

TABLE I: Power Consumption of Transmitter/Receiver Pairs (kW)

# of Requests	NSFNET Topology		US Backbone Topology	
	SFMOR	SPT	SFMOR	SPT
100	**128.3**	161.5	**126.4**	147.8
200	**264.1**	333.8	**248.3**	293.1
300	**399.2**	502.9	**388.4**	460.2
400	**537.4**	676.9	**512.5**	607.5
500	**667.3**	840.0	**643.5**	762.9

to apply higher modulation-levels that provide higher energy-efficiency in terms of W/Gb/s.

In dynamic network provisioning, the requests arrive according to the Poisson process. The average arrival rate is λ requests per time unit, while the holding time of a request follows the negative exponential distribution with a mean value of $\frac{1}{\mu}$. Hence, the traffic load is quantified with $\frac{\lambda}{\mu}$ in Erlangs. We determine the source, destinations, and the bandwidth requirement of a multicast request with the same method as in the static network planning. We assume that there are 358 FS' on each fiber link, corresponding to the 4.475 THz spectrum in C-band. Figs. 7-8 show the results on blocking probability. With its high spectrum-efficiency, OL-M-SFMOR also provides the lowest blocking probabilities, while the other three perform similarly.

V. CONCLUSION

We investigated overlay multicast (OL-M) in multicast-incapable EONs, and proposed a spectrum-efficient OL-M scheme that relies on the spectrum-flexible member-only relay (OL-M-SFMOR). Simulation results indicated that in static network planning, OL-M-SFMOR achieved significant savings on spectrum-utilization over the other schemes, including the all-optical multicast schemes in multicast-capable EONs, while in dynamic network provisioning, OL-M-SFMOR also provided the lowest blocking probabilities.

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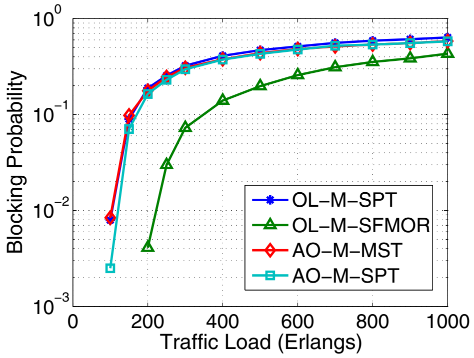

Fig. 7: Blocking probability in NSFNET.

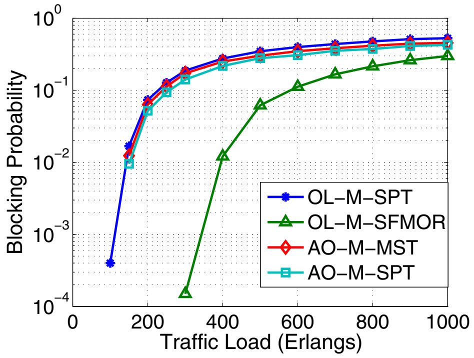

Fig. 8: Blocking probability in US Backbone.

REFERENCES

[1] O. Gerstel *et al.*, "Elastic optical networking: a new dawn for the optical layer?" *IEEE Commun. Mag.*, vol. 50, no. 2, pp. S12–S20, Apr. 2012.

[2] P. Colbourne and B. Collings, "ROADM switching technologies," in *Proc. 2011 OFC*, pp. 1–3.

[3] K. Christodoulopoulos, I. Tomkos, and E. Varvarigos, "Elastic bandwidth allocation in flexible OFDM-based optical networks," *J. Lightw. Technol.*, vol. 29, no. 9, pp. 1354–1366, May 2011.

[4] Y. Wang, X. Cao, and Y. Pan, "A study of the routing and spectrum allocation in spectrum-sliced elastic optical path networks," in *Proc. 2011 INFOCOM*, pp. 1503–1511.

[5] L. Gong *et al.*, "A two-population based evolutionary approach for optimizing routing, modulation and spectrum assignments (RMSA) in O-OFDM networks," *IEEE Commun. Lett.*, vol. 16, no. 9, pp. 1520–1523, Sept. 2012.

[6] Q. Wang and L. Chen, "Performance analysis of multicast traffic over spectrum elastic optical networks," in *Proc. 2012 OFC*, pp. 1–3.

[7] W. Hu and Q. Zeng, "Multicasting optical cross connects employing splitter-and-delivery switch," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 970–972, Jul. 1998.

[8] A. Gadkar, J. Plante, and V. Vokkarane, "Multicast overlay for high-bandwidth applications over WDM networks," *J. Opt. Commun. Netw.*, vol. 4, pp. 571–585, Aug. 2012.

[9] J. Vizcaino *et al.*, "On the energy efficiency of survivable optical transport networks with flexible-grid," in *Proc. 2012 ECOC*, p. P5.05.

[10] X. Zhang, J. Wei, and C. Qiao, "Constrained multicast routing in WDM networks with sparse light splitting," *J. Lightw. Technol.*, vol. 18, no. 12, pp. 1917–1927, Dec. 2000.

[11] Y. Xiong and L. Mason, "Restoration strategies and spare capacity requirements in self-healing ATM networks," *IEEE/ACM Trans. Netw.*, vol. 7, no. 1, pp. 98–110, Feb. 1999.