Incorporating Network Coding to Formulate Multicast Sessions in Elastic Optical Networks

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***Abstract*—In this paper, we leverage the Set-Cover problem to design the multicast-capable routing, modulation and spectrum assignment (MC-RMSA) algorithms that utilizes network coding (NC) to achieve efficient service provisioning in flexible-grid elastic optical networks (EONs). We use a realistic network model that considers the physical impairments from both transmission and light-splitting, and propose to serve each multicast request with a light-forest that includes one or more light-graphs[1] to improve spectrum efficiency. For each multicast request, the proposed algorithms firstly use a Set-Cover approach to select the destination subsets to cover all the destinations. Then, for each subset, we calculate the light-graph to cover all the destination in it. The proposed algorithms are evaluated with extensive simulations for dynamic service provisioning, and the simulation results indicate that they can achieve better performance on blocking probability than existing MC-RMSA algorithms.**

***Index Terms*—Multicast, Light-forest, Network coding, Elastic optical networks (EONs).**

I. Introduction

Nowadays, with the rapid development of inter-datacenter (inter-DC) networks, many bandwidth-intensive applications, such as DC backup and service migration, need to transfer huge amount of data to geographically distributed locations. Hence, to support these point-to-multiple-point communications efficiently, network operators have to establish multicast sessions in backbone networks [1, 2]. Meanwhile, optical networking provides a reliable physical-layer infrastructure that can support Petabyte-scale multicast transmissions efficiently. It is known that with multicast-capable optical cross-connects (MC-OXCs), light-trees with light-splitting (*i.e.*, forwarding an optical signal to multiple output ports) can be constructed [3]. Moreover, with the optical-electrical-optical (O/E/O) conversion based signal relay, multicast sessions can also be formulated in the overlay manner even when there are only multicast-incapable optical cross-connects (MI-OXCs) [4].

Recently, flexible-grid elastic optical networks (EONs) have been developed to make bandwidth allocation in the optical layer more efficient and adaptive. Specifically, by leveraging bandwidth-variable transponders (BV-Ts) and wavelength-selective switches (BV-WSS'), EONs can realize a lightpath with sub-wavelength bandwidth (*i.e.*, 12.5 GHz or less) and supper-channel at 400 GHz or beyond as well [5]. Hence, compared with the traditional fixed-grid wavelength-division multiplexing (WDM) networks, EONs are more promising for supporting dynamic traffics. In addition to the advantages, EONs also bring more challenges to the network control and management (NC&M). For instance, the routing and wavelength assignment (RWA) problem in WDM networks becomes the routing, modulation and spectrum assignment (RMSA), which is more sophisticated and needs to consider more constraints. More specifically, EONs need to allocate a few spectrally-contiguous frequency slots (FS') to a traffic demand, and the modulation format applied to these FS' should be chosen adaptively according to the quality-of-transmission (QoT) [5]. Basically, for a modulation format (*e.g.*, binary phase-shifted keying (BPSK), quadrature phase-shifted keying (QPSK), 8 quadrature amplitude modulation (8QAM) or 16QAM), there is a tradeoff between spectrum efficiency and receiver sensitivity.

When it comes to multicast in EONs, we need to consider multicast-capable RMSA (MC-RMSA). The MC-RMSA in EONs was firstly studied in [6], where two simple heuristics were proposed without considering QoT-aware modulation selection. In [7], we solved MC-RMSA with the help of layered auxiliary graphs and showed that our approach could outperform the algorithms developed in [6], but we also did not consider the QoT constraint. We addressed QoT-aware modulation selection for MC-RMSA in [1], but the network model was over-simplified and impractical, as it only included the transmission impairments but ignored the impact of light-splitting. It is known that light-splitting in MC-OXCs causes power loss and the subsequent re-amplification will introduce optical signal-to-noise-ratio (OSNR) degradation [8, 9].

In this work, we investigate MC-RMSA that considers O/E/O conversion at certain intermediate nodes for network-coding-based relay, and considers the impairments from both transmission and light-splitting. Under this model, we propose to leverage linear network coding (NC) [10] and use a light-forest (one or more light-graphs) to serve a multicast request. The rationale behind this work is that it is well-known that NC provides an effective way to improve the throughput of multicast sessions [11], and with O/E/O conversion based signal relay, NC can be easily realized on intermediate nodes. Our simulation results indicate that the NC-based MC-RMSA can reduce blocking probability effectively.

The rest of the paper is organized as follows. We describe the network model and formulate the problem of MC-RMSA with NC in Section II. Section III discusses the proposed

[1] A light-graph is a light-tree or a structure that incorporates network coding.

algorithms. The simulation results are shown in Section IV, and finally, Section V summarizes the paper.

II. Problem Formulation

In this section, we formulate the MC-RMSA problem that considers the physical impairments from both transmission and light-splitting in EONs.

A. Network Model

We model the EON's physical topology as a directed graph $G(V, E)$, where V and E denote the sets of switch nodes and fiber links, respectively. We assume that each node $v \in V$ equips with an MC-OXC and each link $e \in E$ can accommodate F FS'. An FS is assumed to occupy a bandwidth of C GHz, which provides a capacity of C Gb/s when using BPSK as the modulation format [12]. We use m to represent the modulation-level and $m = 1, 2, 3,$ and 4 corresponds to BPSK, QPSK, 8QAM, and 16QAM, respectively. Hence, the capacity of an FS can be denoted as $m \cdot C$ Gb/s [12]. Here, for simplicity, we assume that the modulation format and spectrum assignment remain the same for all links on a light-graph [13].

On each light-graph, the length of the longest branch and the light-splitting times are the two main factors that affect its QoT performance [9], and hence should be considered in the QoT-aware modulation selection. We use the following equation to represent the relation among the longest branch length, modulation format and number of destinations (*i.e.*, light-splitting times) [8, 9], or **the TMD relation**.

$$S_{m,n} = \frac{S_{1,1}}{2^{m-1} \cdot (\log_{10}(n) + 1)}, \tag{1}$$

where $S_{1,1}$ denotes the transmission reach of a light-graph when it only consists of one destination (*i.e.*, unicast) and uses BPSK (*i.e.*, $m = 1$) as the modulation format. In this work, we set $S_{1,1} = 5,000$ km [12]. For a light-graph that uses modulation-level m and covers n destinations, the maximum transmission reach of its longest branch is calculated as $S_{m,n}$.

We denote a multicast session as $MR(s, D, B)$, where $s \in V$ is the source, $D \subseteq V \setminus s$ is the set of destinations, and B is the bandwidth requirement in terms of Gb/s. Based on the TMD relation, we set up a light-forest that contains one or more light-graphs to solve the MC-RMSA problem. Here, we assume that NC can be used in the light-graph, which means that when necessary, the optical signal can go through O/E/O conversion at certain intermediate nodes for NC-based relay.

B. Objective

Here, we consider dynamic network provisioning, which means that the multicast requests can come and leave on-the-fly. For each multicast request $MR(s, D, B)$, we first construct the light-forest. Then, for the t-th light-graph in the light-forest, we choose the highest possible modulation format m_t, and try to assign $\lceil \frac{B}{m_t \cdot C} \rceil$ contiguous FS' on all the links in the light-graph to it [14]. If the MC-RMSA failed, MR is blocked. The objective of the service provisioning is to minimize the request blocking probability.

III. NC-based MC-RMSA

In this section, we explain the detailed procedures of the proposed MC-RMSA algorithms that use NC.

A. Solving NC-based MC-RMSA with Set-Cover

Due to the TMD relation in Eq. (1), we may not be able to find a feasible MC-RMSA solution for MR, which only uses one light-graph. Basically, the length of the longest branch in the light-graph is restricted by the modulation format and the number of destinations. Therefore, a light-forest that consists of multiple light-graphs needs to be considered, when we want to use a relatively high modulation-level and/or the number of destinations is large. Here, we propose an NC-based MC-RMSA algorithm by leveraging the Set-Cover problem. Firstly, we transform the MC-RMSA to a Set-Cover problem by treating the destination set D as the universe, and defining all the feasible subsets of the universe D as the family, *i.e.*, A. Note that when determining the family A, the TMD relation should be obeyed (as shown in Table I).

TABLE I
Longest Branch Length of a Light-Graph (km)

$S_{m,n}$	$n = 1$	$n = 2$	$n = 3$	$n = 4$	...
BPSK ($m = 1$)	5000.0	3843.1	3385.0	3121.0	...
QPSK ($m = 2$)	2500.0	1921.6	1692.5	1560.5	...
8QAM ($m = 3$)	1250.0	960.8	846.2	780.2	...
16QAM ($m = 4$)	625.0	480.4	423.1	390.1	...

Algorithm 1 shows the procedure to leverage the Set-Cover problem to determine the destination subsets for each light-graph in the light-forest. Here, we use T to store the selected subsets. *Lines* 2-12 obtain the family $A = \{A_{m,n}\}$ based on the TMD relation. Specifically, for each destination, as long as the shortest path length from the source to it is not longer than the maximum transmission reach $S_{m,n}$ for a specific modulation-level m and destination number n, we insert it in $A_{m,n}$, in which any n destinations can be covered with a light-graph that uses modulation-level m. *Lines* 13-33 use Set-Cover to find the subsets that can cover all the destinations in D. Note that in order to include more destinations in each subset, we only search the subsets $A_{m,n}$ with $n \geq 2$ here. The invalid subsets that do not have enough destinations in it (*i.e.*, $|A_{m,n}| < n$) are first deleted with *Lines* 15-18. *Line* 19 determines the number of subsets that can be selected out from an $A_{m,n}$. *Lines* 20-31 put the subsets into T one by one. Here, we use *Lines* 22-27 to ensure that the longest branch length of the light-tree that covers the selected destination subset D_{temp} is not longer than $S_{m,n}$, *i.e.*, satisfying the TMD relation. Finally, if there are still certain destinations that have not been covered by the selected subsets, we use *Lines* 34-39 to cover them one by one with unicast lightpaths.

B. Network Coding for Subsets

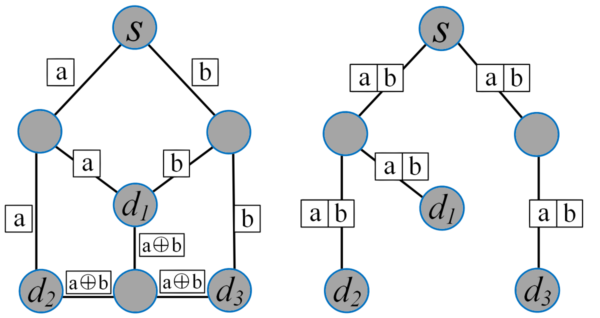
For each subset that is obtained with *Algorithm* 1, we need to cover all the destinations in it with a light-graph that uses NC. Meanwhile, the TMD relation should be satisfied. Note that here, to realize NC, the optical signal can go through O/E/O conversion at certain intermediate nodes.

Algorithm 1: Get destination subsets with Set-Cover

input : Multicast request $MR(s, D, B)$, the TMD relation $\{S_{m,n}\}$, physical topology $G(V, E)$.
output: T, destination subsets to cover D.

$T = \emptyset$;
for $m = 1$ *to* M **do**
  for $n = 1$ *to* $|D|$ **do**
    $A_{m,n} = \emptyset$;
    for *each* $d \in D$ **do**
      obtain $l_{s,d}$ as the shortest path length for $s \rightarrow d$;
      if $l_{s,d} \le S_{m,n}$ **then**
        insert d into $A_{m,n}$;
      end
    end
  end
end
for $m = M$ *to* 1 **do**
  for $n = |D|$ *to* 2 **do**
    if $|A_{m,n}| < n$ **then**
      $A_{m,n} = \emptyset$;
      continue;
    end
    $i = \left\lfloor \frac{|A_{m,n}|}{n} \right\rfloor$;
    for $j = 1$ *to* i **do**
      select n destinations that have the shortest path length to s;
      record selected destinations in D_{temp};
      calculate a light-tree to cover all the destinations in D_{temp};
      store the longest branch length in l_b;
      if $l_b > S_{m,n}$ **then**
        continue;
      end
      $D = D \setminus D_{temp}$;
      $T \leftarrow D_{temp}$;
      delete D_{temp} from A;
    end
  end
end
if $D \neq \emptyset$ **then**
  for $m = M$ *to* 1 **do**
    put each element in $A_{m,1}$ in T;
    delete $A_{m,1}$ from A;
  end
end

Fig. 1 shows an illustrative example on the difference between the light-graphs with and without NC, where we assume that the multicast request is $MR(s, \{d_1, d_2, d_3\}, B)$. For the NC case in Fig. 1(a), we divide the original traffic into two sub-streams a and b, and send out them from two different output ports of s. It can be seen that if we perform NC-based relay at d_1, d_2 and d_3 receive $\{a, a \oplus b\}$ and $\{b, a \oplus b\}$, respectively. Therefore, all the three destinations can decode to get the original traffic correctly. In this case, the total bandwidth resource that is consumed by the multicast session is $9_{hop} \cdot \frac{B}{2} = 4.5B$. However, for the case without NC in Fig. 1(b), we can see that the light-graph is essentially a classic light-tree. Hence, if we want to make sure that all the destinations receive the original traffic, we need to send it on all the links in the light-tree. Hence, the total used bandwidth resource is $5_{hop} \cdot B = 5B$. Apparently, the NC case consumes less bandwidth resource.



(a) Light-graph with NC. (b) Light-graph without NC (light-tree).

Fig. 1. Examples on light-graph.

The work in [15] indicated that NC-based multicast can be achieved with the following two steps:

- Construct a light-graph in the physical topology for NC.
- Find the NC nodes on the light-graph and perform corresponding algebraic operations on them.

Meanwhile, it is also known that the NC nodes and associated algebraic operations will exist as long as the light-graph can be obtained [16]. Therefore, we focus on finding the light-graph in the following discussion.

To find the light-graph for NC, we first calculate K ($K \ge 2$) shortest and link-disjoint paths from source node s to each destination in D. If the K paths can be found, we can merge them together to get the light-graph and transmit $\frac{1}{K}$ original traffic on each path. Meanwhile, we also check the light-graph without NC (*i.e.*, the light-tree that uses a Steiner tree) to see whether the NC case can save bandwidth resource. If no, we will just use the light-graph without NC.

Algorithm 2 illustrates the detailed procedure for finding the light-graph to cover each selected destination subsets. *Line* 1 is for initialization. *Lines* 2-11 try to find all the paths for the light-graph with NC. Here, we set $K = 2$ and try to find two shortest and link-disjoint paths from s to each destination node in the selected destination subset D_{sub}. *Lines* 7-10 check whether the length of the second path is longer than $S_{m,n}$. If yes, we mark $flag = 1$, which means that a light-graph for NC cannot be found. We calculate a Steiner tree with the shortest-path tree (SPT) algorithm or the minimum-spanning tree (MST) algorithm in *Line* 12 to cover all the destinations in

Algorithm 2: Find the light-graph to cover a selected destination subset

input : Source node s, a selected destination subset D_{sub} and its corresponding $S_{m,n}$, $G(V, E)$.
output: A light-graph to cover all the destinations in D_{sub}.

1 $flag = 0$;
2 **for** *each* $d \in D_{sub}$ **do**
3   obtain $p^1_{s,d}$ as the shortest path for $s \to d$ in G;
4   delete $p^1_{s,d}$ in G;
5   obtain $p^2_{s,d}$ as the shortest path for $s \to d$ in G;
6   store the path length of $p^2_{s,d}$ in $l^2_{s,d}$;
7   **if** $l^2_{s,d} > S_{m,n}$ **then**
8         $flag = 1$;
9   **break;**
10   **end**
11 **end**
12 calculate a Steiner tree as the light-tree to cover all the destinations in D_{sub};
13 **if** $flag = 0$ **then**
14   merge $p^1_{s,d}$ and $p^2_{s,d}$ to get the light-graph for NC;
15   **if** *the light-graph for NC consumes less bandwidth than the light-tree* **then**
16   select the light-graph for NC;
17   **else**
18   select the light-tree without NC;
19   **end**
20 **else**
21   select the light-tree without NC;
22 **end**

D_{sub}, which corresponds to the classic light-tree without NC. *Lines* 13-22 select the light-graph for D_{sub} based on $flag$ and the bandwidth consumptions of the light-graphs.

C. Dynamic Provisioning with NC-based MC-RMSA

Algorithm 3 illustrates the overall procedure for dynamic service provisioning with NC-based MC-RMSA. In this work, we do not allow partial provisioning for the destinations in a multicast session, and hence, if there is no sufficient bandwidth resource to provision a multicast request, it will be blocked.

IV. Performance Evaluation

In this section, we evaluate the proposed algorithms for NC-based MC-RMSA. We consider two physical topologies, *i.e.*, the 14-node NSFNET and the 28-node US Backbone [1].In the EONs, the C-band is deployed on the fiber links, and hence there are 358 FS' on each link and each FS has a bandwidth of $C = 12.5$ GHz. We use the Poisson traffic model to generate the dynamic multicast requests. Specifically, the requests' arrivals follow the Poisson process whose average arrival rate is λ and the holding time of each request is in a negative exponential distribution with an average of $\frac{1}{\mu}$. Hence, the traffic load can be quantified as $\frac{\lambda}{\mu}$ in Erlangs. For each

Algorithm 3: Dynamic provisioning with NC-based MC-RMSA

while *the EON is operational* **do**
    for *each arrived* $MR(s, D, B)$ **do**
        release the bandwidth resource of expired multicast requests;
        apply *Algorithm* 1 to select the destination subsets to cover D;
        for *each destination subset* **do**
            apply *Algorithm* 2 to get a light-graph;
            assign FS' to the light-graph with first-fit;
            if *spectrum assignment is failed* **then**
                mark MR as blocked;
                break;
            end
        end
    end
end

$MR(s, D, B)$, we select the source node and destination nodes randomly, and set the average number of destinations as 4 while the bandwidth requirement is within $[75, 150]$ Gb/s. For the benchmark algorithms, we use SPT and MST based MC-RMSA, which means that in *Algorithm* 2, we fix $flag = 1$ all the time to only consider the classic light-tree without NC and the light-tree is calculated with SPT or MST. Meanwhile, we refer to the proposed NC-based MC-RMSA algorithms as SPT-NC and MST-NC, depending on the algorithms used to calculate the light-graph in *Algorithm* 2.

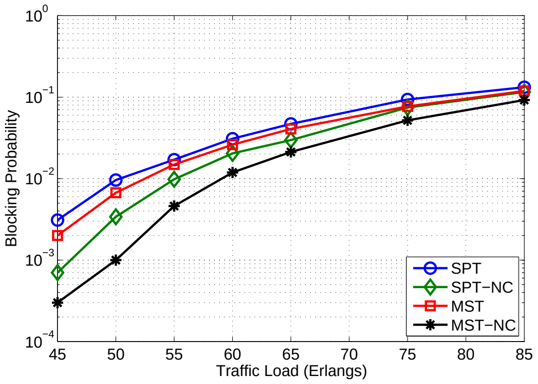
Fig. 2 shows the simulation results on blocking probability in NSFNET and US Backbone topologies. We can observe that both SPT-NC and MST-NC achieve better blocking performance than those without NC, and MST-NC performs the best in both NSFNET and US Backbone topologies. However, in Fig. 2(b), it can be seen that the performance gap between the approaches with and without NC becomes smaller in US Backbone topology. This can be explained with the results shown in Figs. 3 and 4. Note that, in the two figures, W/O NC represents light-graphs without using NC, and W/ NC represents that using NC. Basically, for both SPT-NC and MST-NC, the actual proportions of NC cases used in US Backbone topology is less than that in NSFNET topology. Since NC requires on O/E/O conversion, the actual proportion of NC cases becomes an important metric to evaluate the operational cost of the NC-based MC-RMSA. Fortunately, in Figs. 3 and 4, we can observe that the actual proportion of NC cases is relatively small ($\leq 12\%$). Note that even though in SPT-NC and MST-NC, the majority of the multicast sessions do not use NC, the blocking performance still gets improved effectively, which is really meaningful and promising.

V. Conclusion

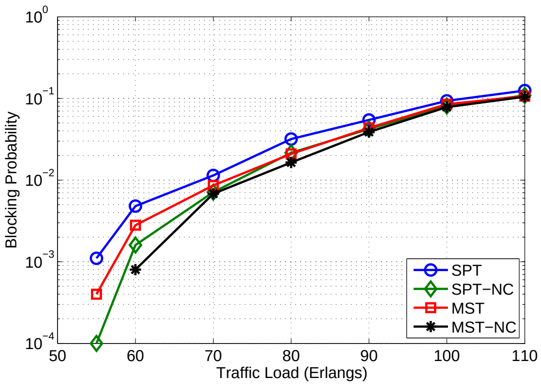
In this paper, we leveraged the Set-Cover problem to design NC-based MC-RMSA algorithms to formulate multicast sessions in EONs. The MC-RMSA algorithms considered the impairments from both transmission and light-splitting, and utilized a light-forest that consists of one or more light-graphs to serve each multicast request. The proposed algorithms were evaluated with extensive simulations for dynamic service provisioning, and the simulation results indicated that they could achieve better performance on blocking probability than existing MC-RMSA algorithms.

ACKNOWLEDGMENTS

This work was supported in part by the NSFC Project 61371117, the Fundamental Research Funds for the Central Universities (WK2100060010), Natural Science Research Project for Universities in Anhui (KJ2014ZD38), the Strategic Priority Research Program of the CAS (XDA06011202), the state key laboratory of advanced optical communication systems networks, China, and key lab of optical fiber sensing and communications (UESTC), Ministry of Education, China.

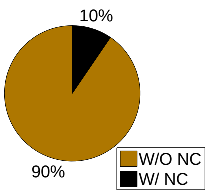


(a) Results with the NSFNET topology.

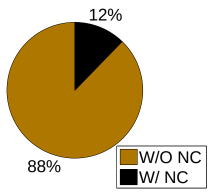


(b) Results with the US Backbone topology.

Fig. 2. Simulation results on blocking probability.

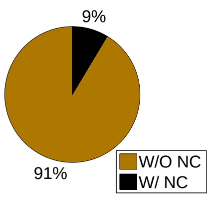


(a) SPT-NC algorithm.

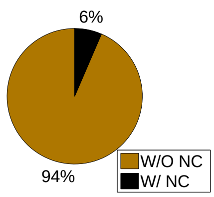


(b) MST-NC algorithm.

Fig. 3. Simulation results on actual proportion of NC cases in NSFNET.



(a) SPT-NC algorithm.



(b) MST-NC algorithm.

Fig. 4. Simulation results on actual proportion of NC cases in US Backbone.

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