Reliable Routing and Spectrum Allocation over Network Coding enabled Elastic Optical Networks

Xin Wang, Yuefeng Ji, Lin Bai
Beijing University of Posts and Telecommunications
Beijing, China
e-mail: xinwang@bupt.edu.cn; jyf@bupt.edu.cn; bailin@bupt.edu.cn

***Abstract*—As each optical link carries a huge amount of hybrid traffic requests, failure of any link may cause huge data loss. In this paper, we mainly discuss the reliable Routing and Spectrum Allocation (RSA) problem over network coding enabled Elastic Optical Network (EON) for hybrid types of traffic requests. As the link fails, a new routing will reconfigure to establish the backup-protection connection for the traffic request. The nodes capable of network coding over network coding enabled EON change the traditional RSA mechanism, which makes the routing processes more complex. To address this problem, we propose a mathematical model to formulate such problem, with the purpose of utilizing the minimal spectrum slots to serve the traffic requests. Besides, a heuristic algorithm called "Reliable Multipath RSA (RM-RSA)" is proposed to solve the model with multipath strategy. For different types of traffic requests, unicast or multicast requests, RM-RSA could provide different routing strategies. The simulation is conducted to verify the efficiency of the proposed RM-RSA, as the changes of average number of multicast receiver, network size, and number of traffic requests. Compared with the benchmark algorithm, the proposed RM-RSA shows more efficient in the spectrum utilization.**

Keywords-reliable RSA; hybrid services;multipath; network coding; EON.

I. INTRODUCTION

The tremendous bandwidth demand triggered by the new emerging high bandwidth services over the optical networks calls for a flexible and reliable network architecture [1]. Each spectrum link carries a large amount of data, and any link failure may cause data loss of 1Gb/s or 1 Tbit/s. How to guarantee the reliable and efficient transmission of service requests becomes urgent to solve, when the network breaks down. Network coding has the natural characteristic of reliable transmission by encoding and encrypting information. Network coding enabled Elastic Optical Network (EON) is the ideal support to accommodate the hybrid requests in the real optical networks [2][3].

We review recent research on the area of reliable and efficient RSA. A new survivable multipath provisioning scheme for unicast services is proposed in EON [4][5]. An Integer Linear Programming (ILP) model and a shared protection virtual optical network mapping algorithm based on different dynamic cost model is also proposed [6]. Single transmission type of service is considered in the research of reliable Routing and Spectrum Allocation (RSA) above. However, various types of services exist in the real optical networks. Survivable multipath routing of two types of traffic demands, anycast and unicast, is studied in EONs [7]. However, none of the research above is to accommodate hybrid services reliable and efficient in network coding enabled EON. The routing becomes more complex as the nodes capable of network coding, and narrow granularity of spectrum resource poses more challenge on spectrum allocation over network coding enable EON.

This paper mainly investigates the reliable RSA problem over network coding enabled EON for hybrid services. The rest of this paper is organized as follows. Section II describes the reliable RSA problem and presents the mathematical model for the problem. Section III proposes an efficient heuristic algorithm to solve the model. Section IV shows the simulation results and makes comparisons of the performances of different algorithms. Section V concludes the paper and presents the future work. The acknowledgement closes the article.

II. RELIABLE RSA PROBLEM

Network coding enabled EON could be a strong support network to provision the hybrid services of multicast and unicast reliable and efficient. This section mainly discusses the reliable RSA problem over network coding enabled EON. A mathematical model is proposed to formulate the problem. Table I shows the parameter definitions of the model. The network coding enabled EON is represented by $G(V,E)$. Given a set of hybrid services, multicast services $R_M^i = \{s_i, D_i, n_i\}, i \in nR_M$ and unicast services $R_U^i = \{s_i, d_i, n_i\}, i \in nR_U$, the object of the mathematical model is to accommodate the hybrid services in a reliable way with the minimal spectrum resources, considering the constraints.

In the routing stage, the nodes capable of network coding change the routing process for multicast service. Compared with routing in EON of establishing one end-to-end path for each source and destination node pair, at least two link-disjoint paths should be established from the source node to each destination node in multicast group [8]. Figure 1 shows the topology of reliable routing for multicast over network coding enabled EON, and multipath transmission strategy is adopted to accommodate multicast services. For each source and destination node pair $(s_i, d_{i,k})$, $w(w=2)$ link-disjoint parallel paths are established as the working path $P_{d_{i,k}}$, representing as the solid lines. Each working path should be provided with a link-disjoint backup protection path, representing as the dotted lines. Note that it has been proved that the best spectrum utilization can be realized only as the number of link-disjoint parallel paths for each source and destination node pair is less than 3 [5]. Thus, w is set as 2 in the proposed model. Besides, it is reasonable to limit the value of w, so as to establish the network coding based multicast tree in the topology. Figure 2 shows the reliable routing topology of unicast over network coding enabled EON. The unicast service is transmitted through multiple paths P_{d_i} and P_{d_i} is provided a link-disjoint backup protection path set $\overline{P_{d_i}}$.

In the spectrum allocation stage, narrow granularity of spectrum resources requires spectrum contiguity constraint and non-overlapping spectrum constraint. Note that we consider the guard band as a default in the spectrum requirement of service request, and guard band constraint is not constrained in the model.

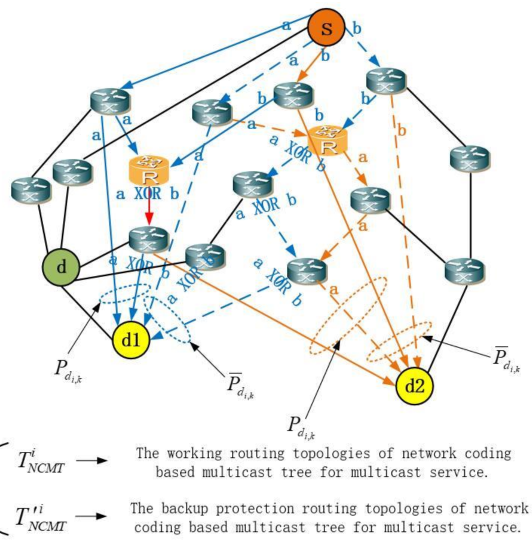

Figure 1. The topology of reliable routing for multicast over network coding enabled EON.

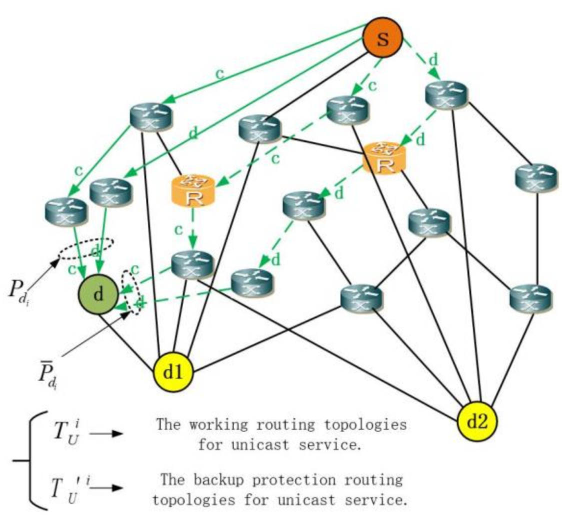

Figure 2. The topology of reliable routing for unicast over network coding enabled EON.

TABLE I. THE PARAMETER DEFINATION OF THE MATHEMATICAL MODEL

Parameter	***Description***
$G(V,E)$	The physical topology of EON.
V	The node set of EON.
E	The edge set of EON.
nR_M	The index set of multicast requests.
nR_U	The index set of unicast requests.
$R_M^i=\{s_i,D_i,n_i\}$	The i-th multicast request set.
$R_U^i=\{s_i,d_i,n_i\}$	The i-th unicast request set.
s_i	The source node of the i-th request.
$d_{i,j}$	The j-th destination node of multicast D_i.
$P_{d_{i,j}}$	The working path set from s_i to $d_{i,j}$.
$\overline{P_{d_{i,j}}}$	The backup protection path set from s_i to $d_{i,j}$.
$p^k_{d_{i,j}}$	The k-th path in path set.

- Minimize:

$$\sum_{i\in nR_M}\sum_{\substack{p\in P_{d_{i,j}}\\ j\in[1,|D_i|]}}\sum_{e\in E}\sum_{f\in[1,F]}O_p^f\cdot\sigma_p^e\cdot\theta_i^p+\sum_{i\in nR_M}\sum_{\substack{p\in \overline{P}_{d_{i,j}}\\ j\in[1,|D_i|]}}\sum_{e\in E}\sum_{f\in[1,F]}O_p^f\cdot\sigma_p^e\cdot\theta_i^p+\sum_{i\in nR_U}\sum_{p\in P_{d_i}}\sum_{e\in E}\sum_{f\in[1,F]}O_p^f\cdot\sigma_p^e\cdot\theta_i^p+\sum_{i\in nR_U}\sum_{p\in \overline{P}_{d_i}}\sum_{e\in E}\sum_{f\in[1,F]}O_p^f\cdot\sigma_p^e\cdot\theta_i^p \tag{1}$$

Equation (1) represents the objective function of the mathematical model, aiming to minimize total spectrum slots of hybrid services occupied on both working paths and backup protection paths. There are some variables needed to be defined. Where O_p^f is the boolean variable, and if the f-th spectrum slot is occupied by path p, O_p^f =1; otherwise, O_p^f =0. σ_p^e is the boolean variable, and if the link e is used by the path p, σ_p^e =1; otherwise, σ_p^e =0. θ_i^p is the boolean variable, and if the path p is used to serve the reqeust R_i, θ_i^p =1; otherwise, θ_i^p =0.

- Constraints:

Equations (2) and (3) ensure the establishment constraints of network coding based multicast tree (NCMT) for multicast request R_M^i. Note that, the number of link-disjoint parallel paths for $(s_i, d_{i,j})$ should be less than 3 so as to achieve the most optimal resource utilization [5]. The number of multiple link-disjoint parallel paths w is set to 2 in this paper, represented as (2).

$$\sum_{p \in P_{d_{i,j}}, \overline{P_{d_{i,j}}}} \theta_i^p = w, \forall i \in nR_M \quad (2)$$

$$\sigma_{p_m}^e \cdot \sigma_{p_n}^e \leq 0, \forall p_m, p_n \in P_{d_{i,j}} \cup \overline{P_{d_{i,j}}}, \forall e \in E \quad (3)$$

Equations (4) and (5) ensure the routing constraints for unicast request R_U^i, and the source node and destination node is connected with w link-disjoint paths. Here, w is set to 2.

$$\sum_{p \in P_{d_i}, \overline{P_{d_i}}} \theta_i^p = w, \forall i \in nR_U \quad (4)$$

$$\sigma_{p_m}^e \cdot \sigma_{p_n}^e \leq 0, \forall p_m, p_n \in P_{d_i} \cup \overline{P_{d_i}}, \forall e \in E \quad (5)$$

Equations (6) and (7) ensure that the spectrum contiguity constraint [4] on the working paths and backup protection paths for the multicast and unicast requests, respectively.

$$\sum_{f' \in [f+2, F]} O_{p_{d_{i,j}}^k}^{f'} \leq \left(O_{p_{d_{i,j}}^k}^{f} - O_{p_{d_{i,j}}^k}^{f+1} - 1 \right) \cdot (-F),$$
$$\forall p_{d_{i,j}}^k \in P_{d_{i,j}}, \overline{P_{d_{i,j}}}, j \in [1, |D_i|], \forall f \quad (6)$$

$$\sum_{f' \in [f+2, F]} O_{p_{d_i}^k}^{f'} \leq \left(O_{p_{d_i}^k}^{f} - O_{p_{d_i}^k}^{f+1} - 1 \right) \cdot (-F),$$
$$\forall p_{d_i}^k \in P_{d_i}, \overline{P_{d_i}}, \forall f \quad (7)$$

Equations (8) and (9) ensure the non-overlapping spectrum constraint [4] on the working paths and backup protection paths for the multicast requests and the unicast requests, respectively. Where λ_p^f is the boolean parameter, and if the f-th spectrum slot is occupied on every link of path p, λ_p^f=1; otherwise, λ_p^f=0.

$$\lambda_{p_{d_{i,j}}^k}^f \cdot O_{p_{d_{i,j}}^k}^f \leq 0, \forall f, \forall p_{d_{i,j}}^k \in P_{d_{i,j}}, \overline{P_{d_{i,j}}}, j \in [1, |D_i|] \quad (8)$$

$$\lambda_{p_{d_i}^k}^f \cdot O_{p_{di}^k}^f \leq 0, \forall f, \forall p_{d_i}^k \in P_{d_i}, \overline{P_{d_i}} \quad (9)$$

As we research some related references, most mathematic models of RSA problem are formulated over the EON [4][7]. A new survivable multipath provisioning scheme is proposed and an ILP model is developed for the scheme in [7]. However, the proposed model just considers one type of service, unicast. Although an ILP model of survivable multipath routing is proposed for hybrid services of anycast and unicast traffic, multicast services are not served over the EON. Due to that the routing process is quite different in network coding enabled EON, as demonstrated in Equations (2)-(5), these models can not be applied into our problems. Although the model of hybrid services efficient provision problem in [2] is proposed in network coding enabled EON, reliable connection is not guaranteed as link failure occurs. In our proposed model, reliable of RSA over network coding enabled EON is formulated for hybrid services of unicast and multicast services.

III. PROPOSED ALGORITHMS

A. Reliable Multipath RSA

Due to that the mathematical model is not efficient to solve the reliable RSA in large networks, an efficient heuristic algorithm, called "Reliable Multipath Routing and Spectrum Allocation (RM-RSA)", is proposed. The detailed procedures of RM-RSA are shown below.

Step 1: To initialize the NCMT set T_{NCMT}^i, the backup protected NCMT set $T_{NCMT}'^i$ for multicast service R_M^i, unicast routing set T_U^i, backup protected unicast routing set $T_U'^i$ for unicast service R_U^i, layered graph set $U^p(V^p, E^p)$, and total occupied spectrum slots $Nfstotal$.

Step 2: According to transmission types of unicast or multicast, clarifying the hybrid services into $R_U^i, i \in nR_U$ and $R_M^i, i \in nR_M$;

Step 3: Adopting multicast priority strategy, to process the service request one by one;

Step 4: Subject to the spectrum contiguity constraint of (6), and non-overlapping spectrum constraint of (8), adopting the layered graph approach [9] to establish $U^p(V^p, E^p)$, which meets with the spectrum requirement of R_M^i;

Step 5: Based on $U^p(V^p, E^p)$ obtained in Step 4, utilizing the Warshall-Floyd algorithm [10] to establish w(w=2) link-disjoint parallel paths for each $(s_i, d_{i,j})$ of R_M^i as the working paths, subject to the constraints of (2) and (3);

Step 6: To mark the usage status of occupied spectrum slots in B0 as used, and set the weight of occupied link as *Inf*;

Step 7: To establish the backup protection structure of each working path for each $(s_i, d_{i,j})$ of R_M^i as Step 5, and set the spectrum usage status in B0 as reserved;

Step 8: To calculate total occupied number of spectrum slots saved as $Nfstotal$, and initialize the weight matrix of $G(V, E)$;

Step 9: Repeating from Step 4 to Step 8, establishing the reliable NCMT until all the destination nodes $d_{i,j}$, $j \in [1, |D_i|]$ are connected to s_i;

Step 10: To save the established NCMT as T_{NCMT}^i and backup protected NCMT as $T_{NCMT}'^i$ and calculate total spectrum utilization saved as $Nfstotal$;

Step 11: Repeat from Step 4 to Step 10, until all $R_M^i, i \in nR_M$ are processed;

Step 12: Subject to the spectrum contiguity constraint of (7), and non-overlapping spectrum constraint of (9), adopting the layered graph approach [9] to establish $U^p(V^p, E^p)$, which meets with the spectrum requirement of R_U^i;

Step 13: Based on the obtained $U^p(V^p, E^p)$ in Step 12, utilizing the Warshall-Floyd algorithm [10] to establish *w*(*w*=2) link-disjoint parallel paths for (s_i, d_i) of R_U^i as the working paths, subject to the constraints of (4) and (5);

Step 14: To mark the usage status of occupied spectrum slots in B0 as used, and set the weight of occupied link as Inf;

Step 15: To establish the backup protection path for the working path of (s_i, d_i) according to the method in Step 13;

Step 16: To calculate total occupied number of spectrum slots saved as $Nfstotal$, and initialize the weight matrix of $G(V, E)$;

Step 17: To obtain T_U^i and backup protected structure $T_U'^i$ and calculate total spectrum utilization saved as $Nfstotal$;

Step 18: Repeat from Step 12 to Step 17, until all $R_U^i, i \in nR_U$ are processed;

IV. SIMULATION RESULTS

In this section, we conducted simulations to evaluate the performance of the proposed algorithms. Two commonly used algorithms select as the benchmark algorithms, which are K shortest paths-first fit algorithm (KSP-FF) and K shortest paths-random fit (KSP-RF). Note that, we considered the reliable routing path for each working path, and the benchmark algorithms become Reliable-KSP-FF (RKSP-FF) and Reliable-KSP-RF (RKSP-RF).

We use the tools of MATLAB to realize the simulation. The spectrum resources over the network coding enabled EON are deployed on the C band, and the total capacity of spectrum link is 4.475THz. The spectrum granularity is assumed as 12.5GHz, and the corresponding number of spectrum slots on each spectrum link provides 358 at most. The index number of source and destination nodes are random selected in the range of $[1, N]$. The number of parallel link-disjoint paths are set as 2. The total occupied number of spectrum slots $Nfstotal$ consider as only parameter to evaluate the spectrum utilization of the proposed algorithm. The performance of the proposed algorithm is evaluated in the test networks of random networks. The impacts of different parameters of average receiver number, network size, and number of hybrid requests are evaluated on the performance of the proposed algorithm in the following. Besides, as serving multicast requests, the performances of the proposed algorithm considering network coding or not are compared.

A. *Impact of average receiver number*

Figures 3 and 4 show that RM-RSA consumes the least number of spectrum slots to accommodate the hybrid services of same scale and different scales among other benchmark algorithms, respectively. As the average receiver number (nD) increases, RM-RSA considering network coding outperforms RM-RSA in the performance of spectrum utilization, and the average spectrum utilization is improved by about 9.8%. This is reasonable because under the layered graph approach, spectrum allocation considers firstly, and routing is established based on a set of layered graph meeting with the spectrum requirement. Besides, network coding could also improve the spectrum utilization of link.

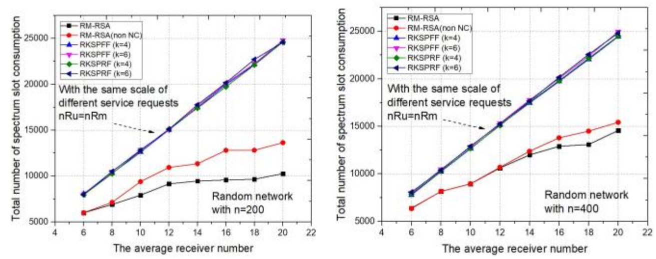

Figure 3. As serving same scale of hybrid requests in the random networks of (a) n=200; (b) n=400, the impact of nD on the spectrum utilization of RM-RSA.

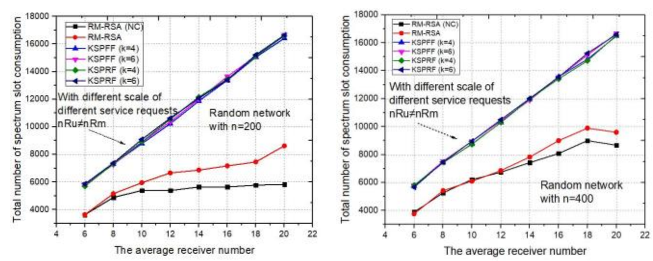

Figure 4. As serving different scales of hybrid requests in the random networks of (a) n=200; (b) n=400, the impact of nD on the spectrum utilization of RM-RSA.

B. *Impact of network size*

As the random network size n increases, the proposed algorithm RM-RSA shows the best spectrum utilization performance among other benchmark algorithms in both random networks of small size and large size shown in Figures 5 and 6. As serving same scale of hybrid services, RM-RSA reduces the average spectrum resources consumption by about 29.64% among other benchmark algorithms. Moreover, RM-RSA shows more efficient, especially in large random networks than in small random networks.

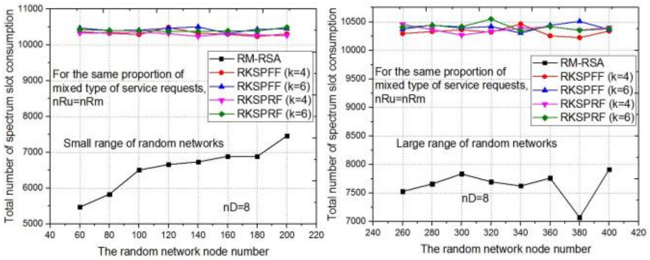

Figure 5. As serving same scale of hybrid requests in the random networks of (a) small size; (b) large size, the impact of n on the spectrum utilization of RM-RSA.

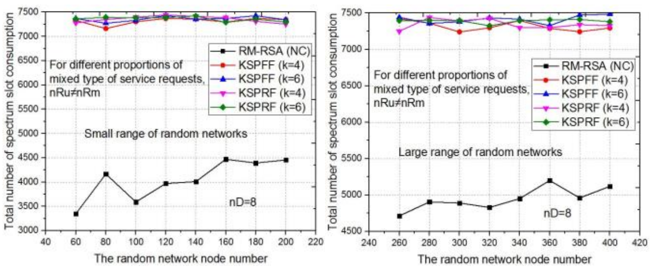

Figure 6. As serving different scales of hybrid requests in the random networks of (a) small size; (b) large size, the impact of n on the spectrum utilization of RM-RSA.

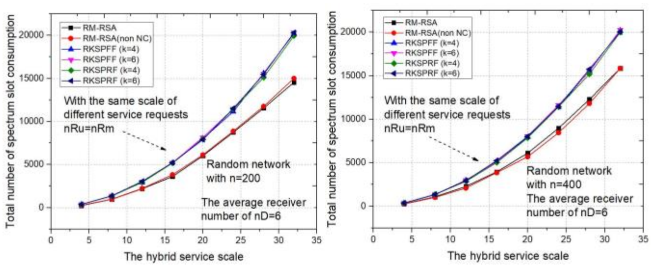

Figure 7. As serving same scale of hybrid requests in the random networks of (a) n=200; (b) n=400, the impact of nR on the spectrum utilization of RM-RSA.

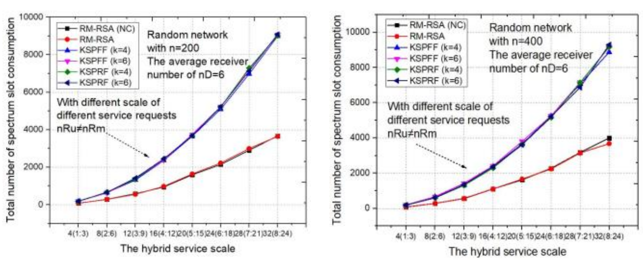

Figure 8. As serving different scales of hybrid requests in the random networks of (a) n=200; (b) n=400, the impact of nR on the spectrum utilization of RM-RSA.

C. Impact of number of hybrid requests

As the number of hybrid requests increases, RM shows the best spectrum utilization among other algorithms in both random networks in Figures 7 and 8. Note that, the simulation results above are obtained under the specific simulation conditions, as serving the limited size of hybrid requests.

V. CONCLUSION AND FUTURE WORK

In this paper, we mainly investigate reliable multipath RSA for hybrid services of unicast and multicast over network coding enabled EON. We formulate a mathematical model and propose an efficient heuristic algorithm “Reliable Multipath RSA (RM-RSA)”. Simulation results show that the proposed algorithm RM-RSA shows the best spectrum utilization among other benchmark algorithms in random networks, as different parameters of average receiver number, network size, and number of hybrid requests change. A large number of simulations need to evaluate the impact of large-scale request services on the performance of the algorithm in the future work. Due to that free space optical (FSO) communication networks have high requirement for reliable transmission, the application of the proposed scheme into the FSO can be a good choice.

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