Fragmentation-Aware Routing and Spectrum Allocation Scheme Based on Distribution of Traffic Bandwidth in Elastic Optical Networks

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***Abstract*—Empowered by multirate transmission and bandwidth-variable switching technology, elastic optical networks (EONs) enhance spectrum utilization efficiency and increase network capacity to satisfy the rapid growth of Internet traffic. Routing and spectrum allocation (RSA) is one of the key elements in realizing EONs. However, previous RSA schemes with superior performance have had the drawback of high computational complexity. In this work, we focus on achieving superior RSA performance with reduced computational complexity. We first propose a dynamic network resource evaluation method that takes into account both the distribution of traffic bandwidth and the spectrum blocks' carrying capability. Based on this, we introduce traffic-based fragmentation-aware concepts into the RSA steps. In the routing step, we propose a low-complexity fragmentation-aware load-balanced shortest path routing scheme and a modified fragmentation-aware load-balanced *k*-shortest-path routing scheme. In the spectrum allocation step, we propose an efficient traffic-based fragmentation-aware spectrum allocation scheme. Simulation results prove that the proposed RSA schemes can reduce the computational complexity significantly and provide network accommodation that is comparable to and traffic blocking probability that is similar to existing dynamic RSA schemes.**

***Index Terms*—Elastic optical network; Routing and spectrum allocation.**

I. Introduction

Due to emerging services such as high-definition video distribution, cloud computing services, mobile applications, and data centers, the IP traffic volume is continually increasing by around 40% per year [1]. It will be a continuous challenge for optical transport networks to serve this huge and heterogeneous volume of traffic in a cost-effective and scalable way [2]. To cater to this explosive growth of capacity requirements, wavelength division multiplexing (WDM) systems [3] have been fully studied and deployed in backbone networks. With advanced modulation formats and digital equalization technologies, WDM networks are able to provide 40 Gb/s, 100 Gb/s, and even higher rates per channel with improved transmission distance.

However, WDM networks strictly follow the rigid International Telecommunication Union (ITU-T) grids (typically 50 or 100 GHz) [4] and operate at the same granularity level, resulting in underutilization of spectrum resources and severe granularity mismatch. Specifically, a wavelength channel may be assigned to a traffic demand smaller than the capacity of a whole wavelength even if traffic grooming is performed. As a result, the fixed-grid spectrum allocation of WDM networks with coarse spectrum granularity lowers spectrum utilization efficiency and must be changed to improve network throughput.

To reduce spectrum wastage, optical orthogonal frequency division multiplexing (O-OFDM) [5–7] and Nyquist WDM [8,9] have been introduced. These technologies utilize multicarrier transmission and provide much finer granularity (e.g., 12.5 GHz) than the ITU-T WDM grid (50 or 100 GHz). Empowered by these technologies, elastic optical networks (EONs) [10,11] provide an efficient way to support variable traffic demands from the subwavelength level to the superwavelength level by allocating an arbitrary number of finer granularity carriers to traffic demands. Flexible network resource allocation enables EONs to accommodate heterogeneous traffic demands in a much more spectrum-efficient [12] way than WDM networks.

Such a technological advance for EONs introduces challenges to resource allocation at the networking level. For an incoming traffic demand, the control plane of the EON needs to find a routing path and allocate enough consecutive spectrum slots on all the fiber links along the path to establish an end-to-end lightpath. This problem is called the routing and spectrum allocation (RSA) problem [13–15]. As an upgrade of the traditional routing and wavelength allocation (RWA) [16,17] problem in WDM networks, the RSA problem brings new constraints: 1) the same spectrum portion along the routing path between the source node and the destination node should be occupied, and 2) the entire bandwidth of the connection must be contiguously allocated. These two constraints are called the spectrum continuity constraint and the spectrum

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contiguity constraint. Due to these constraints, conventional RWA solutions cannot be applied directly in EONs. Furthermore, bit-error-rate (BER)-adaptive modulation-level selection schemes [18] should be considered to increase the spectrum efficiency and extend the RSA problem into a routing, modulation-level, and spectrum-allocation (RMSA) [19] problem. However, these schemes cannot be employed at the incipient stage due to the increased cost and complexity, so we consider only the RSA problem in this paper. Meanwhile, our proposed RSA schemes can be easily upgraded to RMSA schemes.

We focus on the heuristic schemes for a dynamic scenario of the RSA problem, in which traffic demands arrive at and depart from the EONs dynamically in a random manner. Because of the flexible bandwidth allocation for nonuniform traffic demands, the dynamic set-up and tear-down of links will fragment the available spectrum resources and induce the spectrum fragmentation problem [14]. Without all-optical spectrum convertors, the spectrum fragmentation leads to spectrum underutilization and seriously increases the traffic blocking probability. Therefore, dynamic RSA schemes should aim to find a sufficient contiguous spectrum to accommodate the traffic demands, while reducing the spectrum fragmentation to increase the probability of accommodating as many potential future traffic demands as possible.

In this paper, we propose several RSA schemes for different network scenarios, which require different computational complexity and blocking performance. First, we propose an evaluation method to assess the accommodation capability of spectrum resources for incoming traffic demands. This evaluation method is based on the relationship between the spectrum blocks' carrying capability and the traffic bandwidth's distribution. By utilizing this evaluation, corresponding algorithms are introduced in both the routing step and the spectrum-allocation step to increase RSA efficiency and the accommodation capability of the EONs.

The rest of this paper is organized as follows. Related works and the core idea of our work are introduced in Section II. We explain the considered EON model and the RSA problem in Section III. The evaluation method of the spectrum block's carrying capacity based on the spectrum fragmentation is proposed as the basis of our RSA scheme in Section IV. Based on this evaluation method, our routing schemes and spectrum allocation scheme are proposed in Section V and Section VI, respectively. Simulation results of proposed RSA schemes are presented in Section VII. Section VIII concludes the paper.

II. Related Works and Our Contributions

As one of the most important problems for EONs, the RSA problem has been widely investigated. To efficiently solve the dynamic RSA problem, we decompose the problem into two subproblems: routing and spectrum allocation. For each subproblem, we review previous schemes and present our opinions.

A. Routing Subproblem

The routing subproblem is about how to find a routing path from the source node to the destination node. The routing schemes collect the network resource information and select routing paths with available spectrum resources. To solve this problem efficiently, several aspects have to be taken into consideration.

1) Minimizing the optical loss of the routing path: The routing schemes should minimize the routing paths' hop number and length to achieve better BER performance and reduce the cost of the optical amplifier. This is called shortest-path routing (SPR), by which the RSA schemes allocate the routing paths with the least routing hop/length for traffic demands.

2) Load balancing: In optical transport networks with mesh topologies, some links may be used more frequently, so these links will bear much higher load than other links. Network resources can be allocated more effectively if the routing schemes take the load situation into consideration and avoid links with high loads.

3) Maximizing the available spectrum resources on routing path: The available spectrum resources on the routing path highly depend on the link load and the distribution of spectrum resources. The routing schemes aim to find a routing path that has the maximum possibility of accommodating the traffic requests.

In previous works, different routing schemes have been proposed for different scenarios. SPR schemes were used in [20] and precalculated k-shortest-path routing (KSPR) schemes were used in [20–25]. The modified shortest-path (MSP) [15] scheme and the spectrum-constraint path vector searching (SPV) [26] scheme were proposed to find the routing paths with more spectrum resources. These two schemes improved SPR schemes with extra constraints. Entire path searching (EPS) [27] and polynomial-time discrete spectrum scan routing (DSSR) [28] were proposed as greedy schemes with high computational complexity. The routing scales have been sequentially increased to enhance the spectrum utilization efficiency, while the computational complexity has also been increased. As far as we know, the DSSR scheme provides the best performance among all previous works. However, this scheme has a high computational complexity of $\mathbf{O}(m \times n^2)$ (m is the spectrum slot number and n is the node number), and it is not suitable for centralized large-scale EONs.

B. Spectrum Allocation Subproblem

The spectrum allocation subproblem is about how to select a spectrum pattern (i.e., consecutive fraction of available spectrum slots). Among all the available spectrum resources on the routing path(s), the spectrum allocation schemes select a preferable one while maximizing the possibility for the rest of the resources to satisfy future incoming traffic. For EONs, the spectrum allocation schemes should consider several factors to wisely select a spectrum pattern.

1) Minimizing the spectrum slots' sequence number: Spectrum fragmentation has great influence on network blocking performance in EONs. A simple way to reduce spectrum fragmentation is to allocate the spectrum slots with the smallest possible sequence numbers to the traffic requests. This method will concentrate the traffic demands on one side of the spectrum axis so that the traffic will preferentially occupy the fragmented spectrum. An example is that the first-fit (FF) RSA scheme performs much better than the random-fit RSA scheme in EONs.

2) Minimizing spectrum fragmentation and maximizing network capability: The selection among different available spectrum blocks will influence the spectrum fragmentation and the ability of the remaining spectrum blocks to accommodate future incoming traffic. Therefore, the RSA scheme should make full use of fragmented spectra and try to avoid separating spectrum blocks if possible.

In previous works, different schemes have been proposed to improve the performance of spectrum allocation. The FF [20–24] scheme with low computational complexity and time delay has been used in most works. Fragmentation-aware RSA schemes [29,30] have been proposed to improve the performance of the spectrum allocation scheme. In these works, parameters are defined to quantify spectrum fragmentation (e.g., link fragmentation ratio [29], possible accommodation states [25]). Based on these parameters, weighted resource selective schemes [25] were then proposed to improve blocking performance.

C. Our Contributions

In summary, some previous works have focused on the dynamic RSA in EONs. However, the distribution of traffic bandwidth (DoTB) and the incoming traffic bandwidth have not been considered in the routing step. Also, the fragmentation-aware algorithms are not adjustable for different DoTBs in the spectrum allocation step. In this work, we separate the RSA process into 3 steps: network resource evaluation, routing, and spectrum allocation. For each step, the major contributions of our work are the following.

1) Network resource evaluation step: We separate this step from the RSA process individually to dynamically evaluate the network resource. For the first time, to the best of our knowledge, we introduce the DoTB into the evaluation. The DoTB, which is variable in different scenarios, significantly influences the spectrum fragmentation. Therefore, the DoTB needs to be considered for a more efficient routing scheme. We propose a fragmentation-based network resource evaluation method based on the DoTB to probabilistically qualify resource capabilities. The centralized controller periodically monitors the DoTB information collected by IP routers, and adjusts the resource evaluation step for the network accordingly. The simulation results show that the proposed scheme is more stable with a better blocking performance.

2) Routing step: This step highly influences the RSA's performance and its computational complexity. We propose two modified routing schemes based on conventional dynamic SPR and KSPR schemes to achieve low computational complexity. Meanwhile, the proposed routing algorithms have efficiencies similar to previous high-complexity schemes owing to our proposed evaluation method.

3) Spectrum allocation step: We take into consideration both the sequence number of spectrum slots and the accommodation capability of spectrum blocks, i.e., traffic concentration and spectrum fragmentation. An optimized weighted spectrum allocation algorithm is proposed based on the trade-off between minimizing the spectrum slot sequence number and maximizing the anticipated network capability.

The simulation results show that all the proposed methods can improve network blocking performance. The proposed RSA schemes achieve similar RSA performance as that of the DSSR algorithm (i.e., the best performing RSA scheme we know of), while keeping the computational complexity similar to k-path routing, which is especially beneficial for centralized EONs.

III. Model of EONs and the RSA Problem

In this section, we briefly present the model of EONs and the RSA problem. First, we introduce the parameters used in this EON model. In this paper, $G(N,E)$ represents the network topology, in which N denotes the set of nodes and E denotes the set of fiber links. The length of each fiber link is D_e, $e \in E$. All the fiber links have the same spectral window with the spectrum slot number m per fiber, i.e., the set of spectrum slots is $M = \{1,2,3,\ldots,m\}$. The spectrum slot occupied status is $f_{\text{Link}}(e,j)$, where $e \in E$ and $j \in M$. $f_{\text{Link}}(e,j) = 1$ means the spectrum slot is occupied while $f_{\text{Link}}(e,j) = 0$ means the spectrum slot is available. EONs support multi-line-rate traffic demands, whose spectral width is represented as B_{Req} and distribution is represented as P_{Req}. For example, $B_{\text{Req}} = \{12.5, 25, 37.5, \ldots, 100\ \text{GHz}\}$ and $P_{\text{Req}} = \{0.1, 0.1, 0.1, \ldots, 0.1\}$. A traffic demand that requests a lightpath with a spectral width of b_{sd} from source node s to destination node d is denoted as $\text{TD}(s,d,b_{sd})$.

In the model of EONs, traffic demands with unpredictable arrival times (e.g., *Poisson* process) and holding times (e.g., negative exponential distribution) randomly arrive at the network in on-line scenarios. When a traffic demand $\text{TD}(s,d,b_{sd})$ arrives at the EONs, the control plane must find a RSA solution immediately, i.e., a feasible path P_R from node s to node d with sufficient spectrum bandwidth $S_R = (s_{\text{start}}, s_{\text{end}}), s_{\text{end}} - s_{\text{start}} \geq b_{sd}$. Specifically, the same continual portions of all spectrum slots $j_{\text{start}} - j_{\text{end}}$ must be available all along the routing path without any spectrum overlap, i.e., $f_{\text{Link}}(e,j) = 0$, where $e \in P_R$ and $j_{\text{start}} \leq j \leq j_{\text{end}}$.

The proposed RSA scheme can be applied to any centralized controlled EON. For example, an application of our RSA scheme in a software-defined-network (SDN)-controlled EON is shown in Fig. 1. The SDN-based control plane can provide much better and more convenient support for our RSA scheme: 1) the SDN system collects the abstracted information from both the IP and optical layers to the path computation element (PCE) for the RSA process, and 2) the allocation process for both optical cross connects and IP routers can be executed by the SDN with unified control.

All network resources are assigned by the centralized PCE and controller. As shown in Fig. 1, the red marks are the traffic reservation and lightpath set-up process based on the SDN [31,32] controller, and the green marks are the RSA process. This resource allocation process can be implemented in any optical network with centralized PCEs with the network resource information stored in the traffic engineering databases (TEDs), so that the network resources can be scheduled in a high-efficiency way. To reduce computational complexity, the TEDs store the network topology, the resource information, and some intermediate variables that can be reused for future incoming traffic, e.g., the link weights.

IV. Evaluation Method of Spectrum Block Carrying Capacity Based on Spectrum Fragmentation

The basic units in our proposed evaluation method are spectrum blocks. We define the carrying capacity Λ of a spectrum block as the expected spectral bandwidth of possible traffic. In EONs, Λ depends on not only the available spectrum slots' number in the spectrum block, but also the DoTB, i.e., the extent of fragmentation. We quantify Λ of each spectrum block and each link representing their capacities. Therefore, Λ and its variation $\Delta\Lambda$ during RSA process can provide a criterion of selective priority.

In this section, we propose a method to evaluate a spectrum block's Λ, i.e., Λ_{SB}. Meanwhile, Λ_{Link} stands for the Λ of a link, which is defined as the sum of all the Λ_{SB} in the link, i.e., $\sum \Lambda_{\mathrm{SB}}$. The calculation process of Λ_{SB} strongly relies on the granularity of the basic EON spectrum grid, the granularities of incoming traffic requests, and their distribution (DoTB). For simplicity, the following calculation part of this section is based on a 12.5 GHz basic spectrum grid, and $B_{\mathrm{Req}} = 1$–8 spectrum slot traffic granularity (i.e., 12.5–100 GHz) with their distribution P_{Req}. For other spectrum grids and DoTBs, similar results can be inferred.

The definition of Λ_{SB} is the accommodated traffic spectral bandwidth $\sum b_{sd}$ in a spectrum block before it fails to satisfy incoming traffic. Λ_{SB} does not linearly grow as the spectrum bandwidth increases due to spectrum fragmentation. Because the spectrum allocation process always concentrates the traffic to the spectrum slots with lower sequence numbers (FF), the calculation process of Λ_{SB} is from one side of a spectrum block to the other. Given the DoTB P_{Req}, we are able to calculate $\Lambda_{\mathrm{SB}}(x)$ of a spectrum block with x spectrum slots as

$$\Lambda_{\mathrm{SB}}(x) = \sum_{i=0}^{i\le x} P_{\mathrm{Block}}(x,i)\times i, \tag{1}$$

$$P_{\mathrm{Block}}(x,x) = \begin{cases} 1, & x=0; \\ P_{\mathrm{Req}}(1), & x=1; \\ \sum_{k=0}^{k<x} P_{\mathrm{Block}}(k,k)\times P_{\mathrm{Req}}(x-k), & \text{others}, \end{cases} \tag{2}$$

$$P_{\mathrm{Block}}(x,y) = P_{\mathrm{Block}}(y,y)\times \sum_{k>x-y} P_{\mathrm{Req}}(k), \qquad x>y, \tag{3}$$

where $P_{\mathrm{Block}}(i,j)$ is the probability that a spectrum block that has total i spectrum slots fails to accommodate incoming traffic while j spectrum slots have been used.

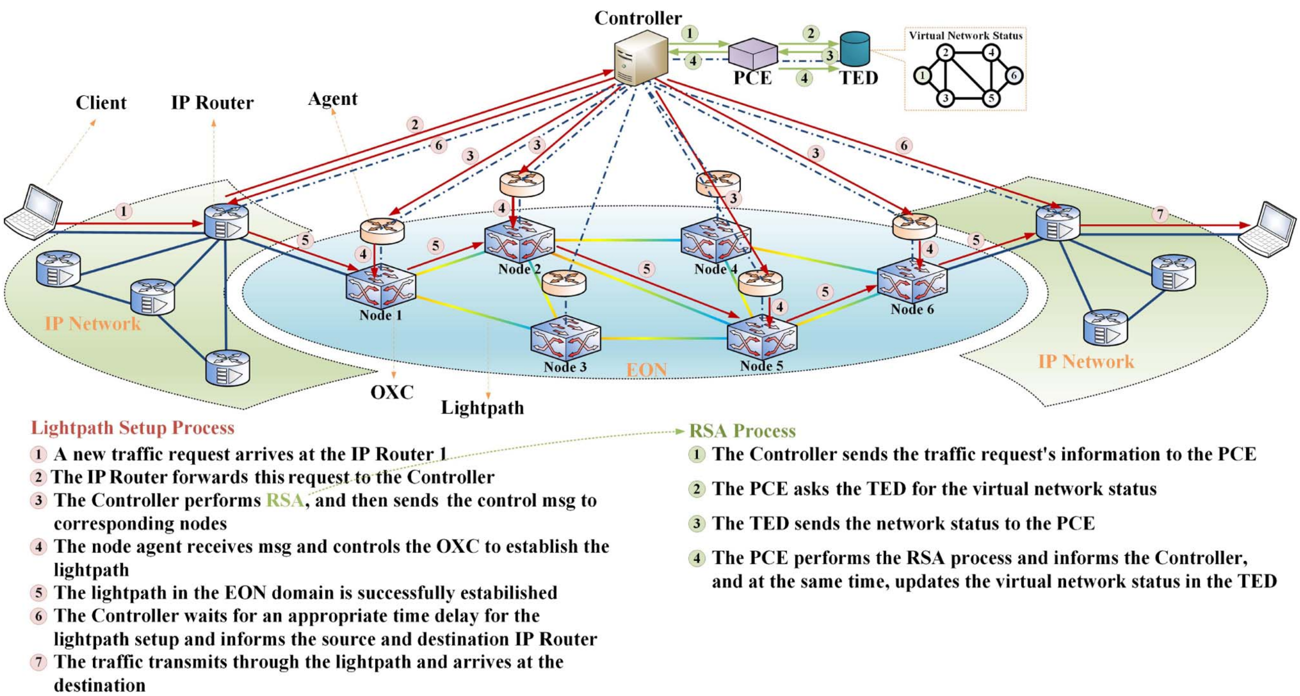

Fig. 1. Network model of EONs and formulation of traffic request.

As an example shows in Fig. 2, Λ_{SB} of a spectrum block with three spectrum slots is calculated. The traffic requests are allocated next to each other until the incoming traffic cannot be put in the rest of the spectrum. There are four different possible final states of the spectrum block and their intermediate states are shown in the figure. For example, $P_{\text{Block}}(3,3)$ may come from the initial state, the intermediate state $P_{\text{Block}}(1,1)$, or $P_{\text{Block}}(2,2)$. The probability from each state to another is shown in Fig. 2, as well.

At the routing step, Λ_{Link}, as a sum of all the Λ_{SB} in the link, can be used to evaluate each link's load. At the spectrum-allocation step, when we assign a traffic request in a spectrum block, we will make a spectrum block smaller or separate it into two small ones. Accordingly, $\Delta\Lambda_{\text{Link}}$ can be used to evaluate this assignment behavior. The Λ of the remaining blocks differ from each other with different size combinations. This evaluation considers both the spectrum block's bandwidth and the DoTB. Compared with previous works, this evaluation method is more valid and suitable for EONs. From all we mentioned above, we introduce Λ_{Link} into the routing step and $\Delta\Lambda_{\text{Link}}$ into the spectrum allocation step to propose DoTB-based fragmentation-aware RSA schemes.

V. Λ-Based Routing Process for EONs

In this section, we explain how the parameter Λ is used in the routing algorithm. We propose a modified SPR algorithm and a KSPR algorithm based on Λ as introduced in the previous section. With a much lower computational complexity ($\mathbf{O}(n^2)$ and $\mathbf{O}(k \times n^2)$), the proposed routing algorithm can achieve blocking performance similar to that of the DSSR algorithm.

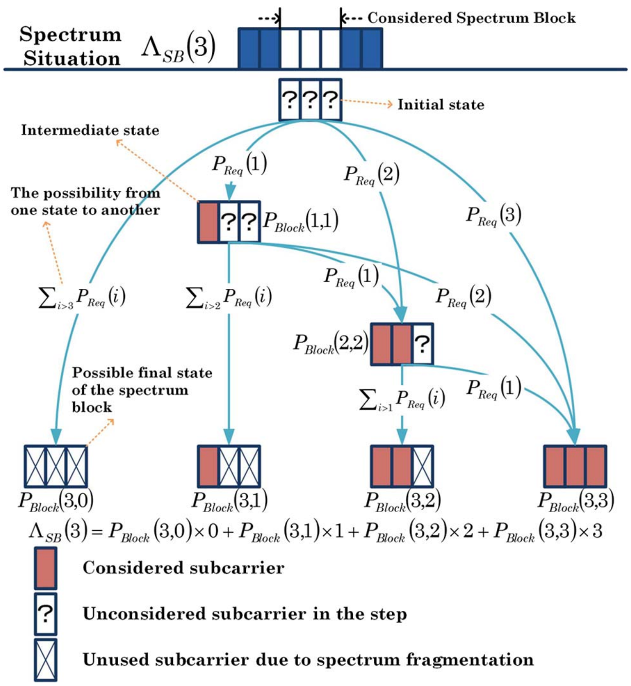

Fig. 2. Example of the calculation process of $\Lambda_{\text{SB}}(3)$.

A. *Fragmentation-Aware Load-Balanced SPR Based on Traffic Distribution*

We propose a fragmentation-aware load-balanced SPR (FL-SPR) scheme. This scheme is based on a weighted SPR (e.g., Dijkstra) algorithm to maintain low computational complexity ($\mathbf{O}(n^2)$). Meanwhile, we use M/Λ_{Link} as the link's weight to increase the routing efficiency. This algorithm performs better than conventional SPR and load-balanced SPR (LB-SPR) algorithms based on the available spectrum slot ratio in our simulation.

Algorithm 1 Fragmentation-Aware Load-Balanced SPR

Input: *Topology* $G(N,E)$; *spectrum slot number* M; *demand* (s,d,b_{sd}); *spectrum utilization* $f_{Link}(e,j)$, $e \in E$, $j \in M$ (1 *means occupied*, 0 *means available*); *traffic bandwidth granularity* B_{Req} with its distribution P_{Req};
Output: *Routing path* P_R; *available spectrum* S_R;
1. ***Λ calculation and*** L_e ***initialization***
  Calculate Λ_{SB} based on B_{Req} and P_{Req};
  for every link: $e \in E$ **do**
    $J \leftarrow$ **find** 1 **in** $f_{Link}(e)$; *//mark spectrum blocks (SBs)*
    $J_s \leftarrow (0,J)$; $J_e \leftarrow (J, M+1)$; *with location*
    $I_v \leftarrow J_e - J_s - 1$; *and bandwidth*
    $H \leftarrow$ **find** $I_v \geq 1$; *//available spectrum blocks*
    Link weight $L_e \leftarrow \frac{M}{\sum_{h\in H} \Lambda_{SB}(I_v(h))}$;
  end for
2. ***RSA process for incoming traffic***
  2.1. ***Λ-weighted shortest path routing***
    $P_R \leftarrow SPR(G(N,E), L, s, d)$; *//weighted SPR*
  2.2. ***First-fit spectrum allocation***
    Pattern state record: $F_{MIN} \leftarrow \infty$;
    for every pattern layer: $p = 1$ **to** $m - b_{sd} + 1$ **do**
      Pattern state $F_{Pattern} \leftarrow \sum_{e\in P_R} \sum_{i=p}^{i<p+b_{sd}} f_{Link}(e,i)$;
      if $F_{Pattern} = 0$ **then** *//All resource available*
        $S_R \leftarrow (p, p+b_{sd}-1)$, $F_{MIN} \leftarrow 0$;
        Go to *Step 2.3*.
      end if
    end for
  2.3. ***Response traffic request***
    if $F_{MIN} < \infty$ **then**
      Return (P_R, S_R);
    Else
      Return Blocking;
    end if
  2.4. ***Λ calculation and database updating***
    for every link: $e \in P_R$ **do**
      Calculate Link Weight L_e as ***Step 1***;
    end for
  Go to *Step 2*.

We use a virtual link-weight database and update the variations of Λ after every RSA process to streamline the calculation process. In addition, this kind of routing scheme provides a chance to verify the correctness of Λ.

An example is shown in Fig. 3. The network topology and spectrum occupation situation is shown in Fig. 3(a). A traffic demand is coming from node 1 to node 6. As Fig. 3(b)

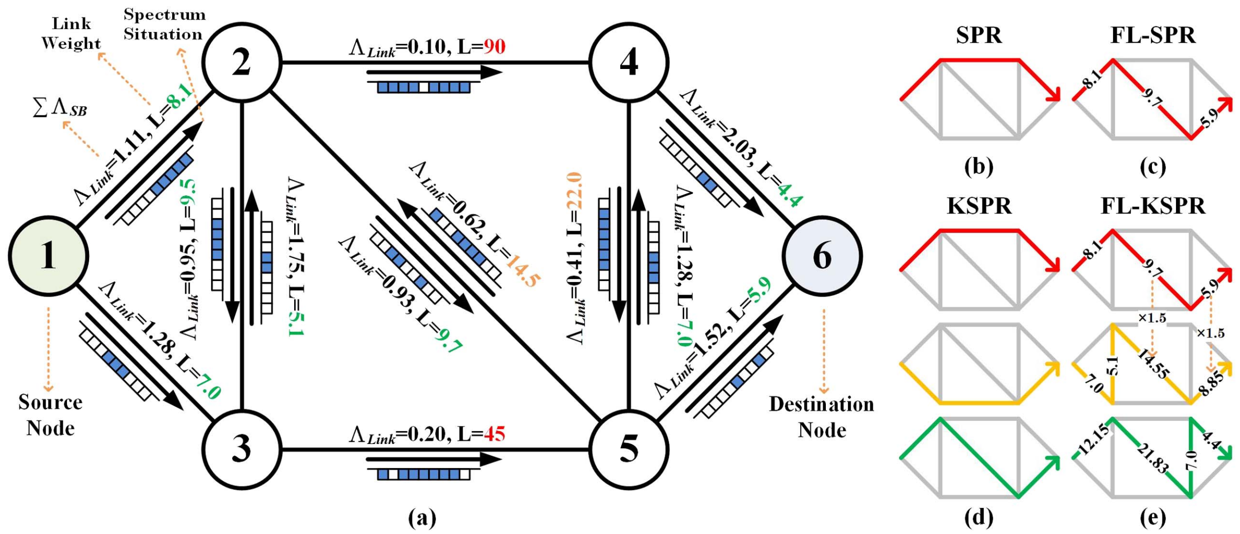

Fig. 3. Example of different routing schemes: (a) network topology and spectrum situation, (b) SPR scheme, (c) FL-SPR scheme, (d) KSPR scheme, and (e) FL-KSPR scheme ($k = 3$).

shows, the SPR scheme finds the routing path with the shortest distance (we set every link's length as 1). In this case, SPR finds routing path $1 \to 2 \to 4 \to 6$ as the candidate routing path. On the other hand, the proposed FL-SPR scheme calculates the $\sum\Lambda$ of every link and the corresponding link weight L. With a weighted SPR algorithm, FL-SPR finds routing path $1 \to 2 \to 5 \to 6$ and avoids high load links $2 \to 4$ and $3 \to 5$.

B. Fragmentation-Aware Load-Balanced KSPR Based on Traffic Distribution

For better blocking performance, we propose an optimized fragmentation-aware load-balanced KSPR (FL-KSPR) scheme. The k-path routing algorithm is based on the link's weight M/Λ_{Link}. The kth routing path is generated by magnifying the weight of links used in the $(k-1)$th routing path β times (the scheme performs best when $\beta = 1.5$, according to our simulation).

Algorithm 2 Fragmentation-Aware Load-Balanced KSPR

Input: Same as ***Algorithm 1***;
Output: Same as ***Algorithm 1***;
1. *Λ calculation and L_e initialization*
  Same as ***Algorithm 1***, ***Step 1*;**
2. *RSA process for incoming traffic*
  2.1. *Λ-weighted k-shortest-path routing*
    for routing selection $R = 1$ **to** k **do**
      $P_R \leftarrow SPR(G(N,E), L, s, d)$; *//weighted SPR*
      for routing link $L_r \in P_R$
        $L_r = L_r \times \beta$; *//magnify the used links' weight*
      end for
    2.2. *First-fit spectrum allocation*
      Same as ***Algorithm 1***, ***Step 2.2***;
    end for
  2.3. *Response traffic request*
    Same as ***Algorithm 1***, ***Step 2.3***;
  2.4. *Λ calculation and database updating*
    Same as ***Algorithm 1***, ***Step 2.4***;
  Go to *Step 2*.

As Fig. 3(d) shows, the KSPR scheme finds the routing path with the shortest distance (we set every link's length as 1 and $k = 3$). In this case, KSPR finds routing paths

$$1 \to 2 \to 4 \to 6, \quad 1 \to 3 \to 5 \to 6, \quad 1 \to 2 \to 5 \to 6.$$

This is a hop-minimized routing selection for a blank network or a load-balanced network. However, in the network considered, this routing scheme cannot avoid high load links. The high load links (i.e., $2 \to 4$ and $3 \to 5$) are randomly used in the routing results.

On the other hand, the proposed FL-SPR scheme finds the following routing paths, as shown in Fig. 3(e):

$$1 \to 2 \to 5 \to 6,$$
$$1 \to 3 \to 2 \to 5 \to 6,$$
$$1 \to 2 \to 5 \to 4 \to 6.$$

These routing paths avoid high load links $2 \to 4$ and $3 \to 5$. Compared with KSPR, FL-KSPR is more efficient and provides better blocking performance in our simulation.

VI. Λ-Based Spectrum Allocation Process for EONs

In this section, we explain how $\Delta\Lambda$ is used as the criterion of selective priority and propose a weighted traffic-based fragmentation-aware spectrum allocation (TFSA) scheme. The main idea of our scheme is to maximize the $\sum\Lambda$ of the rest of the spectrum. To achieve better performance, the weight of spectrum slots takes into account both Λ and the spectrum slots' sequence numbers to alleviate the spectrum fragmentation in a narrow spectrum range while centralizing traffic requests in the entire spectrum range. With the linearly weighted parameter μ (about 0.05 in our simulation), the TFSA algorithm is introduced as below.

Algorithm 3 Traffic-Based Fragmentation-Aware Spectrum Allocation

Input: Same as ***Algorithm 1***;
Output: Same as ***Algorithm 1***;
1. *Λ calculation and L_e initialization*
  Same as ***Algorithm 1***, ***Step 1;***
2. *RSA process for incoming traffic*
  2.1. *Routing*
    Pattern state record: $F_{MIN} \leftarrow \infty$; *//Initialization*
    Same as ***Algorithm 1 or 2***, ***Step 2;***
  2.2. *TF spectrum allocation*
    for available SBs: $h \in H$ **do**
      for patterns in SB_h: $p = J_s(h)$ **to** $J_e(h) - b_{sd} + 1$ **do**
        $F_{Pattern} \leftarrow \sum_{e \in P_R}[\mu \times p + \Lambda_{SB}(I_v(h))$
        $-\Lambda_{SB}(p - J_s(h)) - \Lambda_{SB}(J_e(h) - p - b_{sd} + 1)]$;
        if $F_{Pattern} < F_{MIN}$ **then** *// Min. weighted pattern*
        $S_R \leftarrow (p, p + b_{sd} - 1)$, $F_{MIN} \leftarrow F_{Pattern}$;
        end if
      end for
    end for
  2.3. *Response traffic request*
    Same as ***Algorithm 1***, ***Step 2.3***;
  2.4. *Λ calculation and database updating*
    Same as ***Algorithm 1***, ***Step 2.4***;
  Go to *Step 2.*

TFSA examples are shown in Fig. 4. An incoming traffic request with $b_{sd} = 1$ has four different choices: RSA_1 to RSA_4.

1) Selection between RSA_1 and RSA_2: They are two nearby spectrum patterns in the same routing path. In RSA_1, spectrum blocks {3, 4} are used and transformed to spectrum blocks {2, (1, 2)}. In RSA_2, spectrum blocks {1, 2} are used and transformed to spectrum blocks {0, 1}. Compared with F_{RSA1}, F_{RSA2} is smaller and ends up with a higher remaining Λ, so TFSA chooses RSA_2 for the traffic.

2) Selection between RSA_1 and RSA_3: They are two remote spectrum patterns in the same routing path. The spectrum block scenario of RSA_3 is the same as that of RSA_2; however, the sequence number of RSA_3 (30) is much larger than that of RSA_2 (6). The benefit brought by $\sum \Delta\Lambda$ of RSA_3 cannot cover the cost of traffic decentralization, so TFSA chooses RSA_1 for the traffic.

3) Selection between RSA_1 and RSA_4: They are two spectrum patterns in different routing paths. In RSA_4, spectrum blocks {2, 1, 1} are used and transformed to spectrum blocks {1, 0, 0}. Even though RSA_4 chooses a longer routing path, F_{RSA4} is smaller than F_{RSA1}. So TFSA chooses RSA_4 for the traffic. This method is mainly a selection among different spectrum blocks. It also influences the routing selection when spectrum fragmentation is high.

VII. Simulation and Discussion

In EONs, bandwidth blocking probability (BBP) is employed to evaluate the blocking performance of routing, modulation, and spectrum allocation schemes. For nonuniform bandwidth (or mixed line rate) traffic requests in EONs, BBP is defined as

$$\mathrm{BBP} = \frac{\sum_{i \in B_{\mathrm{Req}}} B_i \times A_i}{\sum_{i \in B_{\mathrm{Req}}} B_i}, \qquad (4)$$

where B_i is the capacity of the demands with bandwidth i, and A_i is its blocking probability.

The simulation is conducted on the 14-node and 21-link NSFNET network. We assume that connection requests are established with randomly selected source–destination node pairs. The fiber capacity is set with 128 spectrum slots. The generation of connection requests follows a Poisson process and the holding time for each connection follows a negative exponential distribution. The traffic granularity is 12.5 to 100 GHz with average distribution. A spectrum slot guardband (12.5 GHz) has been added between spectrum-adjacent superchannels. At least 10^6 connection requests are simulated in each scenario. The parameters used in the proposed RSA schemes are tested in different scenarios. Then the BBP performances of the proposed FL-SPR, FL-KSPR, and TFSA schemes are tested, in comparison with some previous schemes.

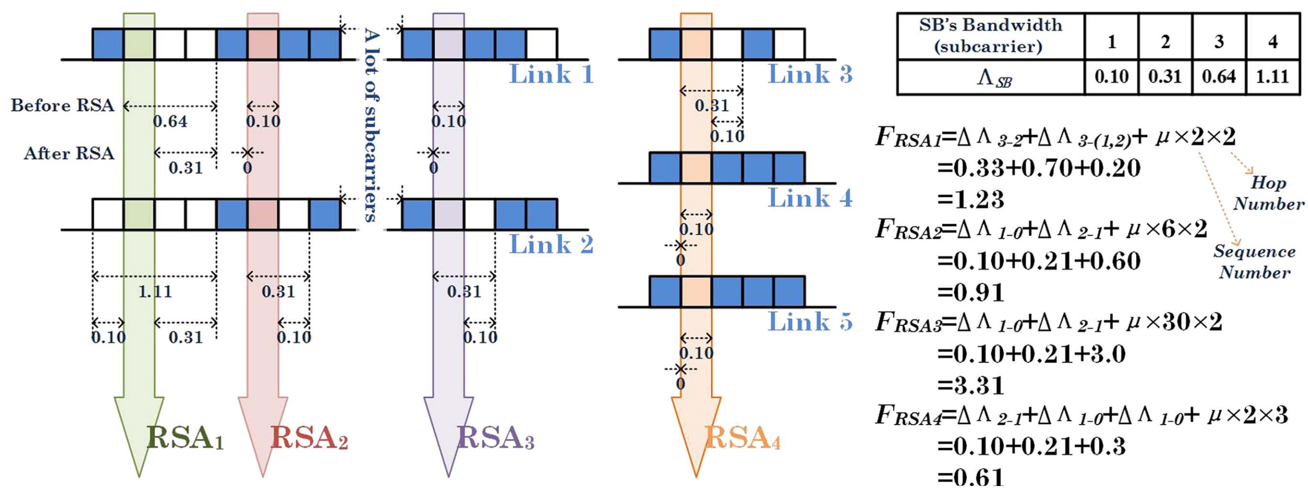

Fig. 4. Example of different spectrum allocation scenarios.

A. Parameter Test of μ for TFSA

Parameter μ introduced in Section VI influences the performance of TFSA. In this section, we investigate the BBP performance of scenarios with different μ values. As shown in Fig. 5, when μ equals 0, the BBP will be very high. At this point, the spectrum allocation scheme considers only the $\Delta\Lambda$ and ignores the spectrum slots' locations. When μ increases, the scheme tends to allocate the resource to one side of the spectrum with high concentration. When μ is large enough (e.g., 2 or larger), the algorithm evolves to FF. We test different values and select the one with the best BBP performance (e.g., 0.05 in the figure).

B. Parameter Test of β for FL-KSPR

Parameter β introduced in Section V influences the performance of the KSPR + FL-KSPR scheme. In this section we investigate the BBP performance of scenarios with different β values. When β equals 1, KSPR schemes will evolve to SPR schemes with low performance. When β increases, the schemes have higher possibilities to use new links with higher load. The performance of all schemes are different from each other and depend on the network topology. For a better understanding, we simulate both KSPR and FL-KSPR. As shown in Fig. 6(a), $\beta = 1.5$ obtains the best BBP performances in both schemes.

C. Parameter Test of k for FL-KSPR

Parameter k introduced in Section V influences not only the performance of k-path routing schemes, but also the computational complexity. As k increases, the performance of routing schemes is improved with increasing cost. A trade-off should be made between BBP performance and computational complexity. For example, we simulate both KSPR and FL-KSPR. As shown in Fig. 6(b), we can determine that when k is larger than 5, the BBP performance starts to level off. To reduce the computational complexity, we set $k = 5$ for NSFNET in our simulation.

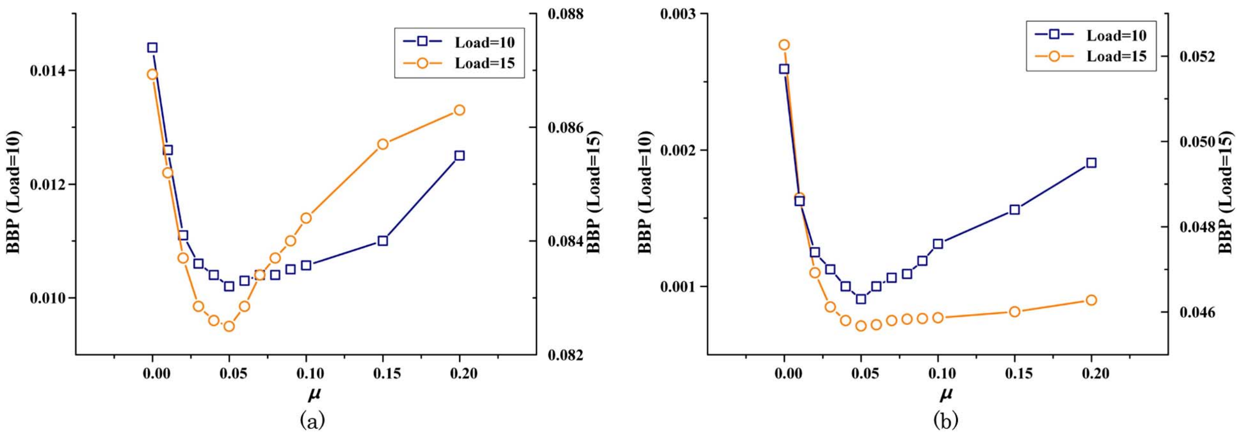

Fig. 5. BBP performance of TFSA with different values of μ: (a) BBP vs. μ for SPR scheme; (b) BBP vs. μ for FL-SPR scheme.

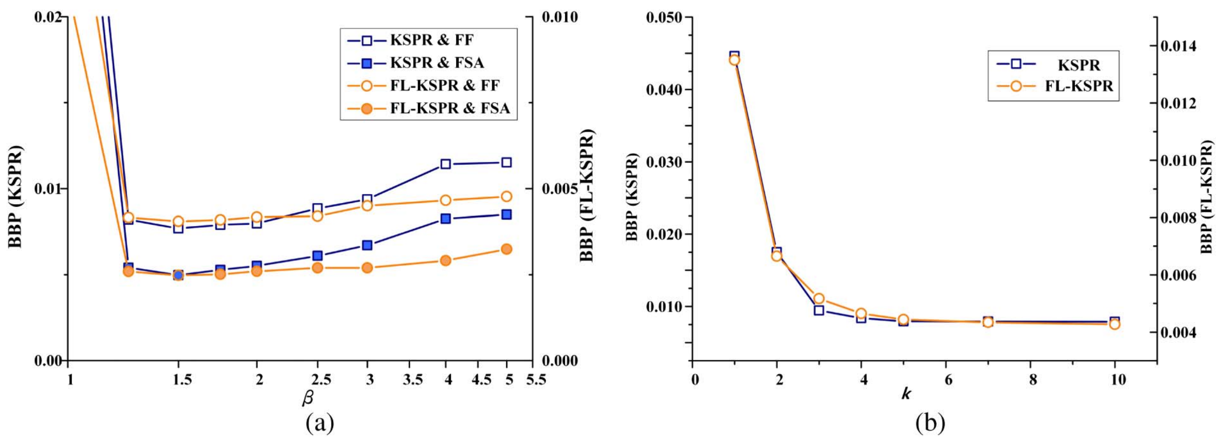

Fig. 6. Parameter test for k-path routings: (a) BBP performance of k-path routing schemes with different β values; (b) BBP performance of k-path routing schemes with different β values.

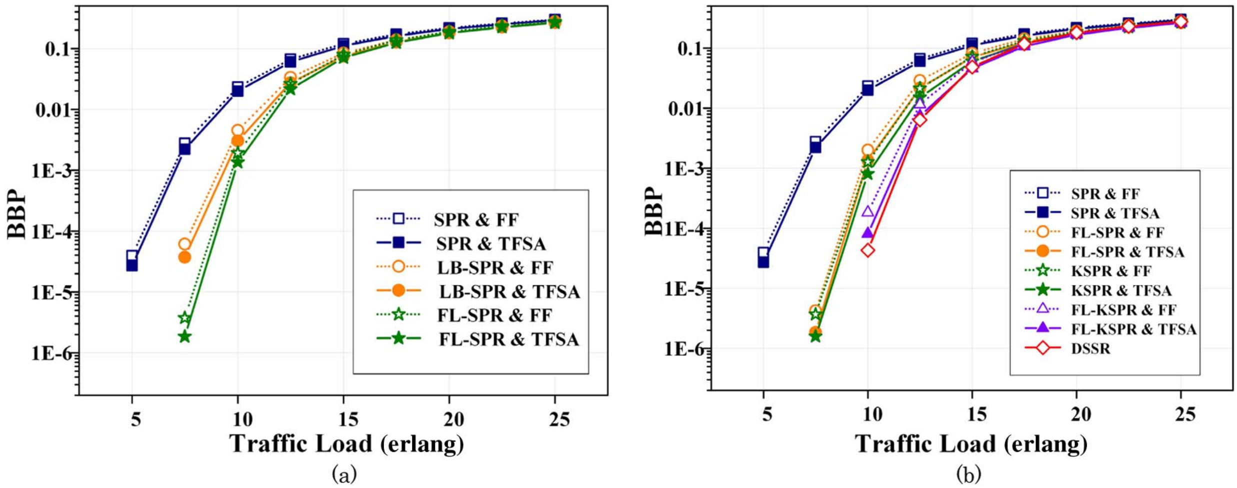

Fig. 7. Simulation results: (a) BBP of different SPR schemes; (b) BBP of different RSA schemes.

D. Performance of FL-SPR and TFSA

In this section, we investigate the performance of the FL-SPR + TFSA scheme. For comparison, we also investigate the BBP of LB-SPR based on the available spectrum slot ratio. As shown in Fig. 7(a), FL-SPR has about $1/10^3$ the BBP of the SPR scheme when traffic load is low (7.5 erlang). At the same time, the BBP of FL-SPR is 1/10 of LB-SPR. For RSA schemes with only one alternate routing path, the proposed FL-SPR + TFSA scheme shows a significant reduction of BBP compared with previous routing algorithms with the same level of computational complexity.

E. Performance of FL-KSPR + TFSA

We investigate the performance of the FL-KSPR + TFSA scheme, and compare it with the KSPR and DSSR schemes. As shown in Fig. 7(b), FL-KSPR provides a BBP that is about 1/10 that of the KSPR scheme when traffic is low (10 erlang). Compared with the DSSR scheme, the proposed FL-KSPR + TFSA scheme shows similar BBP performance.

F. Service Fairness of Traffic With Different Granularity

In this section, the service fairness of traffic with different granularity is discussed. The BBP of different granularity traffic demands is investigated. The normalized blocking probability of different granularity n is denoted as $\tilde{p_n}$, and the fairness index (***FI***) [33] is defined as

$$\tilde{p_n} = 1 - \sqrt[n]{1 - p_n}, \tag{5}$$

$$\boldsymbol{FI} = \frac{\left(\sum_{i=1}^{N} \tilde{p_i}\right)^2}{N \times \left(\sum_{i=1}^{N} \tilde{p_i}^2\right)}, \tag{6}$$

where p_n is the blocking ratio of traffic demands with granularity n and the traffic granularity is 1 to N. Note that ***FI*** is a number between 0 and 1 and the closer to 1, the better the service fairness is. The ***FI*** of different RSA schemes is shown in Table I.

As we can see, the service fairness of the proposed scheme follows the trend of conventional RSA schemes. The RSA scheme that provides more efficient or a greater number of alternative network resources will improve the BBP performance, but reduce the ***FI*** at the same time. However, because the TFSA scheme provides no more alternative resources than the FF scheme, but a better selection priority, the ***FI*** of the TFSA scheme in every scenario is better than the corresponding FF scheme.

G. Network Accommodation and Computational Complexity

To evaluate the performance of different RSA schemes, we introduce the network accommodation (NA) as the highest traffic load when BBP is lower than 0.1%. First, we investigate the performance of the FL-SPR + TFSA algorithm. As shown in Fig. 8(a), the NAs are normalized by that of the DSSR scheme. The conventional SPR + FF

TABLE I
SERVICE FAIRNESS

		Traffic Load (erlang)		
FI		10	17.5	25
SPR	FF	0.586	0.719	0.800
	TFSA	0.654	0.779	0.847
FL-SPR	FF	0.387	0.599	0.709
	TFSA	0.429	0.648	0.753
KSPR	FF	0.342	0.523	0.631
	TFSA	0.371	0.552	0.656
FL-KSPR	FF	0.310	0.507	0.616
	TFSA	0.332	0.533	0.642
DSSR		0.245	0.448	0.245

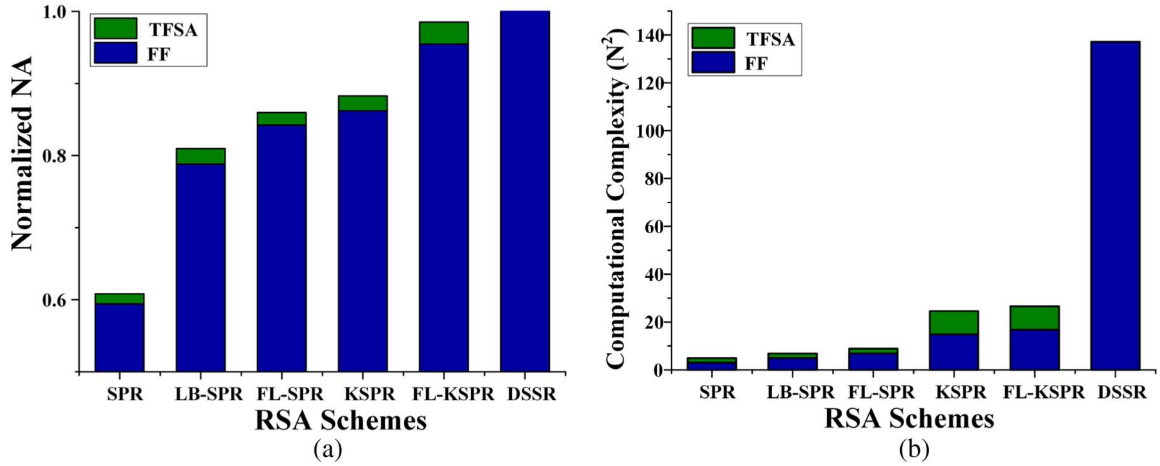

Fig. 8. Simulation results: (a) NNA of different RSA schemes; (b) computational complexity of different RSA schemes.

scheme can provide only 59.42% of the NA of the DSSR scheme. The proposed FL-SPR can provide 24.78% improvement of NA compared with the SPR scheme. For each routing algorithm, the TFSA increases the NA by 1.40% to 1.75%. Overall, the FL-SPR + TFSA scheme brings about 26.53% improvement of NA comparing with the SPR + FF scheme. It should be noted that most of the improvement is made by the routing step (FL-SPR and FL-KSPR) providing more efficient alternative network resources for the traffic demand. The improvement made by the spectrum allocation step is limited because this step does not provide any extra resources but provides better selecting priorities.

The computational complexity is shown in Fig. 8(b), including the routing step and the spectrum allocation step. The computation process of the resource evaluation step (including the tests of parameters μ and β) is performed when network status or traffic distribution changes. This process is independent of the RSA part. Therefore, the computational complexity of the RSA scheme is not impacted by the resource evaluation step. We can determine that the FL-SPR + TFSA scheme remains the same level of computational complexity ($\mathbf{O}(n^2)$) compared with conventional schemes.

Second, we investigate the performance of the FL-KSPR + TFSA scheme. As shown in Fig. 8(a), the proposed FL-KSPR can provide 9.25% improvement of NA compared with the KSPR scheme. For each routing algorithm, the TFSA brings about 2.05% and 3.05% NA improvement. Overall, the FL-KSPR + TFSA scheme brings about 12.30% improvement of NA compared with the KSPR + FF scheme. Compared with the DSSR scheme, the NA of the proposed scheme decreases by only 1.48%. The computational complexity is shown in Fig. 8(b). We can determine that the FL-KSPR + TFSA scheme remains the same level of computational complexity ($\mathbf{O}(k \times n^2)$) compared with conventional KSPR schemes, while the complexity is much lower than the DSSR scheme.

VIII. Conclusion

In this paper, we study fragmentation-aware RSA combined with the traffic profile for an EON. We propose several different schemes for each step of the RSA process to increase RSA efficiency and reduce computational complexity. In the network resource evaluation, both the DoTB and the bandwidth of the incoming traffic have been taken into consideration. Therefore, optimized FL-SPR and FL-KSPR schemes are proposed that have blocking performance similar to previous high-complexity schemes, but with much lower computational complexity. TFSA schemes are proposed that take into account both traffic centralization and spectrum fragmentation. The proposed schemes can utilize spectrum fragments more efficiently and accommodate ingress traffic more effectively. Our simulation results show that this proposal can achieve 39.09% network accommodation improvement and only 1.48% less than DSSR, while greatly reducing the computational complexity (about 80%).

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