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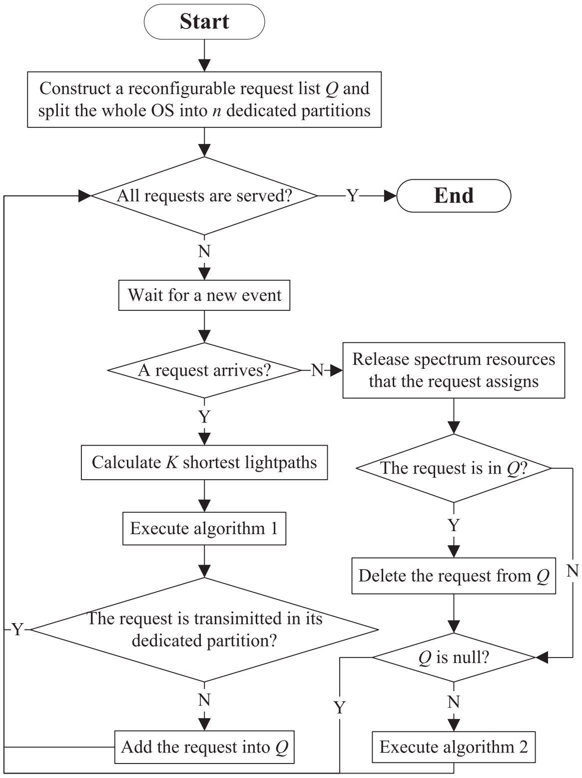

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Fragmentation-Avoiding Spectrum Assignment Strategy Based on Spectrum Partition for Elastic Optical Networks

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Abstract: A fragmentation-avoiding spectrum assignment strategy based on spectrum partition is proposed, which is used to resolve the spectrum fragmentation problem in elastic optical networks. For alleviating spectrum fragmentation, a spectrum partition policy, splitting the whole optical spectrum into several dedicated partitions, is presented. Based on this, a joint first-last-fit spectrum assignment policy is presented to enhance the probability of successful transmission of request and spectrum efficiency, where each partition is first used to transmit requests with the same rate in the first-fit policy; and other partitions are used to search available spectrum resources in the last-fit policy when there are no available spectrum resources in the dedicated partition. Meanwhile, a partition selection formula is designed to minimize the interference of spectrum resources during the last-fit spectrum assignment. Moreover, a reconfiguration mechanism, moving requests that are not transmitted in their dedicated partition to their dedicated partition, is also studied. The simulation results indicate that the proposed algorithm can reduce the bandwidth blocking probability and improve spectrum efficiency.

Index Terms: Elastic optical networks, fragmentation avoidance, spectrum partition, first-last-fit, reconfiguration.

1. Introduction

With the rapid development of the Internet, there have come into being a variety of bandwidth intensive applications, such as video conference, high definition television and cloud computing. Generally, there are some common characteristics: high burst, high bandwidth and low latency [1]. To efficiently serve and schedule these applications, it is urgent to need a network that can provide large capacity, scalability and high flexibility. In this context, by allowing the multiplexing of several wavelengths in a single fiber link, the wavelength division multiplexing (WDM) technology has brought great capacity to the network layer. Meanwhile, due to the use of intelligent optical cross-connect (OXC) and optical add-drop multiplexer (OADM), WDM networks have achieved high-speed storage-and-forwarding of signal in the physical layer [2]. However, in WDM networks, the optical spectrum (OS) is divided into several frequency slots of fixed width 50 GHz or 100 GHz [3], resulting in that high rate request (e.g., 400 Gbps and 1Tbps) consumes a large amount of guard-bands, while low rate request (e.g., under 50 Gbps) cannot fill full of the width. The WDM technology eventually makes network inflexible and wastes valuable bandwidth (spectrum) resources. Hence, in the case of limited bandwidth resources, how to serve request in an efficient and flexible way has become a research hotspot. In September 2008, the notion of spectrum-sliced elastic optical path network (SLICE) was first proposed by NTT of Japan [4]. Elastic optical networks (EONs) use much finer granularity (e.g., 12.5 GHz or even 6.25 GHz) and bandwidth-variable optical devices to establish lightpath [5], which significantly improves flexibility and efficiency of spectrum assignment in the optical layer. EONs resolves the shortage of WDM networks well, and is generally regarded as a promising better solution for next generation optical networks [6].

As similar to the routing and wavelength assignment (RWA) problem in WDM networks, spectrum resources assignment in EONs is also called the routing and spectrum assignment (RSA) [6], [7]. But the RSA needs to follow more rigid spectrum constraints—spectrum continuity, spectrum contiguity and spectrum non-overlapping [7], that is to say that a request can be successfully transmitted if and only if there are available common and contiguous spectrum resources that are not less than the bandwidth requirement of the request on all the links along the lightpath. Hence traditional RWA algorithms are not suitable for EONs, it is urgent to study a novel admission control mechanism under the constraints of EONs.

On the request aspect, mixed line rate requests usually coexist in EONs, spectrum resources required by high rate requests are usually times or even ten times as low rate requests [8]. Besides, on the spectrum assignment aspect, the establishment of lightpath is limited to the above spectrum constraints. Both of these factors have brought a new challenge to EONs, that is, spectrum fragmentation (SF) problem [7]–[9]—spectrum resources are cut into several discrete and different-sized SFs. As a consequence, compared with low rate requests, it is harder to find available spectrum resources for high rate requests, which reduces spectrum utilization ratio (SUR) and indirectly increases the probability of request blocked.

Based on the above background, this paper proposes a fragmentation-avoiding spectrum assignment (FASA) strategy based on spectrum partition (SP). For avoiding the spectrum fragmentation if possible, a spectrum partition policy considering the size and arrival rate of all requests is studied. Then, in order to minimize the interference of spectrum resources and to improve spectrum efficiency, two policies, first-last-fit (FLF) spectrum assignment policy and partition selection formula, are presented. Finally, we also present a reconfiguration mechanism (RM) of spectrum-interference avoidance to ensure spectrum contiguity.

The rest of this paper is organized as follows. Related works and main contributions of our work are introduced in the next section. The model of EONs and SF problem are described in Section 3. Then, Section 4 presents the overall procedure of the proposed algorithm. The numerical simulation setup and results for performance evaluation are discussed in Section 5. Finally, Section 6 summarizes the paper and looks ahead the future research works.

2. Related Works and Our Contributions

As an important problem for EONs, the RSA has recently attracted much attention. According to whether the request is known in advance, the RSA problem can be classified into both static and dynamic versions. For the static version of the RSA problem, the request matrix is known in advance, and the objective of this problem is to minimize the consumption of spectrum resources used to serve the request matrix in Integer Linear Programming (ILP) models [10], [11]. However, in [11], the RSA problem was demonstrated to be a NP-hard problem. Due to suffering from the huge computational complexity, ILP models are hard to obtain optimal results in an acceptable time for large networks. Thus researchers usually resorted to heuristic algorithm to obtain approximate results. The RSA problem was decoupled into routing sub-problem and spectrum assignment sub-problem, both of them were resolved separately [12], [13]. For the dynamic RSA version, it is uncertain for the bandwidth requirement and arrival time of each request, the objective of the dynamic RSA problem is to minimize the bandwidth blocking probability. Researchers usually used heuristic or meta-heuristic algorithms to tackle this problem.

In dynamic EONs, the SF is generally considered as a serious problem. There are two methods to tackle the SF problem. One is fragmentation avoidance. The study in [14] first used lightpath of heavy SF in the step of routing, which makes SF be used to transmit new request as much as possible and then improves SUR. The works in [15], [16] designed metrics to capture and evaluate the SF. Considering the use of spectrum resources in the step of spectrum assignment, the above two works allocated a spectrum block (SB) of the least SF for request, which avoids the generation of SF in advance. A spectrum consumption model concerning the size and holding time of request was also studied in [17]. Although these literatures can alleviate the impacts of the SF on the network performance to some extent, it is difficult to find a large available SB to transmit high rate requests with the increase of the network load. The other is defragmentation. When the set condition was satisfied, network carried out defragmentation policy to concentrate requests on one side of spectrum axis [18]. The authors of [19] introduced an interference graph technique to accommodate the dynamic time-varying request, while minimizing the network reconfiguration cost. Although defragmentation policy can improve the network performance significantly, its complexity is really high.

To utilize SFs as much as possible, the multi-path approach, splitting a high rate request into several low rate requests and transmitting them separately, was studied in [20]. Nevertheless, the way only concerns the success of request transmission and does not take extra cost into account, such as guard-band and transponder consumptions. By considering the size of requests, the authors of [21], [22] introduced the method, splitting the whole OS into several dedicated partitions, to eliminate the spectrum contiguity constraint. However, because of the randomness and bursty behavior of requests, this method cannot make full use of spectrum resources when the network load is low.

In summary, although these literatures are expected to reduce SF and improve the network performance with respect to different perspectives, most of which only consider the SF problem in terms of the inherent continuity of the spectrum and ignore the fact that there exists a close relationship between the SF and request attributes (e.g., the size and arrival rate of requests). Therefore, based on the shortcomings of existing works, we in this paper comprehensively investigate the SF problem in EONs with mixed line rate requests. The major contributions of our work are the following. i) By considering the size and arrival rate of all requests, we propose a novel spectrum partition policy; each partition is first used to transmit requests with the same rate in the first-fit (FF) spectrum assignment policy. ii) We propose a last-fit (LF) spectrum assignment policy having a temporary loan to other partitions, and design a partition selection formula, which enhance the probability of successful transmission of request and reduce SF. iii) A reconfiguration mechanism, moving these requests that are not transmitted in their dedicated partition to their dedicated partition, is also studied. The simulation results demonstrate that the proposed spectrum allocation strategy can reduce the bandwidth blocking probability and improve spectrum utilization efficiency.

3. Model of EONS and Spectrum Fragmentation Problem

In this section, we describe the network model that is used to investigate the proposed algorithm, and then discuss the SF problem in EONs.

3.1 Network Model

The physical topology of EONs can be modeled as an undirected graph $G(V, E, S)$, where V denotes the set of optical nodes and E is the set of fiber links, S shows the state of frequency slots on all the links, each link can accommodate the capacity of B in terms of frequency slot (FS). $r = \{r_1, r_2, \ldots, r_n\}$ is the set of request types, where r_i is the size of the i-th request type; the size of r is n. $p = \{p_1, p_2, \ldots, p_n\}$ is the set of traffic intensity of request, in which p_i represents the traffic intensity of the i-th request type. In EONs, a request that demands a lightpath with the bandwidth requirement of b from source node s to destination node d is denoted as $R(s, d, b)$. When a request R_i arrives at the network in dynamic scenario, the request is either blocked or established with a lightpath $P^{R_i}_{s_i,d_i}$ from node s_i to node d_i with an available SB [f_s, f_e] by the control plane, in which the size of the SB is equal to b_i, and f_s and f_e are the index of start FS and end FS of the SB, respectively.

Due to its high cost and complexity, we assume that there is no spectrum converter in EONs. Therefore, the spectrum assignment must follow the following three constraint conditions.

Spectrum contiguity constraint:

$$\prod_{j=f_s}^{f_e} WP^{R_i}_{e,j}=1,\ \ \forall e \in P^{R_i}_{s_i,d_i} \tag{1}$$

where $WP^{R_i}_{e,j}$ is a boolean variable that equals 1 if the j-th FS is available on the link e, and 0 otherwise.

Spectrum continuity constraint:

$$WP^{R_i}_{e,j} = WP^{R_i}_{e',j} = 1, \forall e, e' \in P^{R_i}_{s_i,d_i},\ \ j \in [f_s, f_e] \tag{2}$$

Spectrum non-overlapping constraint:

$$WP^{R_i}_{e,j} = 1, \forall e \in P^{R_i}_{s_i,d_i},\ \ j \in [f_s, f_e] \tag{3}$$

To increase profit, network service providers prefer to accommodate as many requests as possible. Hence the main objective of dynamic RSA problem is to find a lightpath to transmit new request as possible, i.e., to minimize the bandwidth blocking probability (BBP). BBP is defined as

$$BBP = \frac{\sum_{i\in R} a_i \cdot b_i}{\sum_{i\in R} b_i} \tag{4}$$

where a_i is a boolean variable that equals 1 and 0 otherwise if request R_i is blocked. $\sum_{i\in R}$ represents the total number of requests in simulation.

3.2 Spectrum Fragmentation Problem

In dynamic EONs, the setting up and tearing down of lightpaths over time can lead to a large amount of SFs in both the spectral and spatial dimensions [7]. When a contiguous SB is used to transmit a request and then split into two smaller SBs, the SF in the spectral dimension arises. And the SF in the spatial dimension is that the FS is effectively available but misaligned in the neighboring links. Since the SF problem in the spatial dimension has been studied in WDM networks, this paper only studies the spectrum fragmentation problem in the spectral dimension which is unique to EONs.

Owing to these facts that the spectrum assignment in EONs is subject to more rigid constraint conditions, and the size and arrival rate of all requests are uneven, it is very easy to induce the SF of the spectral dimension over time if both facts are not considered in the process of the RSA. It will finally undermine spectrum efficiency and frequently block high rate requests. Fig. 1 shows the generation process of the SF. It is assumed that there are only two kinds of requests in the network, i.e., $r = \{2, 3\}$. At time t_1, there exist three requests: R_1(A, E, 2 FS), R_2(C, F, 3 FS) and R_3(B, F, 3 FS); the spectrum state of the C-D link is shown. We assume that the request R_2 has the shortest holding time, and its occupied spectrum resources are first released at time t_2. At time t_3, the request R_4(B, D, 2 FS) arrives, and is successfully transmitted in the traditional FF policy [12]. However, since this policy does not take the size of requests into account, there leaves one FS that cannot be used by any request on the C-D link.

It can be clearly seen that whether a SB is SF depends on the size of requests in the network. Hence, in order to avoid the SF caused by mixed line rate requests provisioning if possible, this paper considers the relationship between the SF and request from the point of view of the size and arrival rate of requests, and aims to seek a novel spectrum assignment strategy.

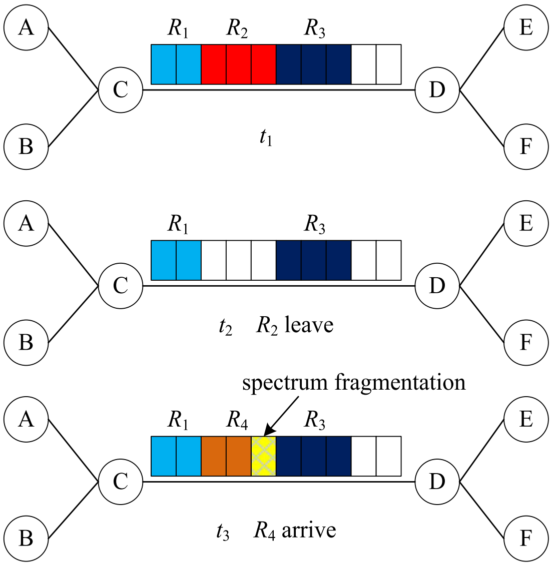

Fig. 1. Generation process of spectrum fragmentation.

4. Fragmentation-Avoiding Spectrum Assignment Strategy

In this section, a fragmentation-avoiding spectrum assignment strategy based on spectrum partition is described in detail. How to split the OS into several dedicated partitions is first explained; then, on the basis of spectrum partition, the first-last-fit (FLF) spectrum assignment policy and reconfiguration mechanism are subsequently introduced.

4.1 Spectrum Partition Policy

In order to reduce different-sized SFs, the idea of memory partition in computer system [23] is introduced. The basic idea is to split the whole OS into n dedicated partitions according to the size and arrival rate of requests, each partition is used to transmit requests with the same rate in priority. The size of each partition is calculated by using (5).

$$M = \left\lfloor \frac{B}{\sum_{i=1}^{n} r_i \cdot p_i} \right\rfloor, \; Zs_i = M \cdot r_i \cdot p_i \tag{5}$$

where M and Zs_i represent the maximum number of channels allocated simultaneously in each partition and the size of the dedicated partition of the i-th request type, respectively. It can be seen that there are a part of spectrum resources that do not belong to any partition when the remainder is not zero. In this case, we assume that the remaining spectrum resources will be allocated to the last partition.

Fig. 2 highlights the advantage of spectrum partition policy compared with the traditional FF policy based on spectrum sharing. We assume that there are two types of requests $r = \{2, 3\}$ with the same traffic intensity (i.e., the value of p_i is the same for all request types) in the network with four nodes (A, B, C, D) and three links (e_1, e_2, e_3), each link configures 10 FSs. Therefore, the OS is split into two partitions, each of which is 4 and 6, respectively. As shown in Fig. 2, five requests arrive one by one. For the FF policy, since it only considers the spectrum assignment of the current request and does not the future requests into account, so that there are a large amount of SFs in the network. Finally, although there are many available spectrum slots on the lightpath linking A to D, there is no continuous and common spectrum block, so that request R_5 is blocked. On the contrary, for the case of spectrum partition, due to the fact that the OS is split into two dedicated partitions and each type of request is transmitted in a predefined partition, request R_5 is therefore

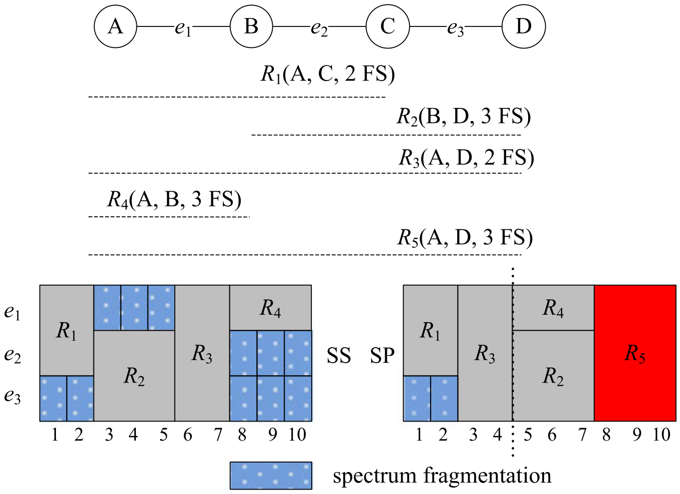

Fig. 2. Spectrum sharing (SS) *vs* spectrum partition (SP).

successfully transmitted. Note that the OS is also fragmented by using spectrum partition policy, but the SFs have higher chances to be used.

4.2 First-Last-Fit Spectrum Assignment Policy

Although the spectrum partition technology can alleviate the spectrum fragmentation caused by the spectrum contiguity constraint in the spectral domain, this technology cannot make full use of spectrum resources. Hence, in order to obtain a tradeoff between SUR and SF, we propose a FLF spectrum assignment policy based on spectrum partition. The idea is: on the basis of spectrum partition, request is transmitted through the way that the dedicated SB[1] is first chosen on all the lightpaths in the FF policy. When the request is not successfully transmitted in its dedicated partition, the spectrum resources of other partitions will be searched in the right-to-left direction from end of each partition on each lightpath until the request is successfully transmitted, that is LF policy. Moreover, when there are several available partitions during the LF policy, we design a partition selection formula (6) to minimize spectrum interference through ensuring the number of the available dedicated SBs. It is noteworthy that the spectrum resources that are assigned by the LF policy are just a temporary loan for other partitions, and will be released when these requests will have been expired. Therefore, the LF policy is an effective way for fragmentation avoidance. The pseudo-code process is shown in algorithm 1.

$$\text{Minimize}\left\{\frac{FSNum_i - b_i}{r_i}\,\middle|\, r_i \in r\right\} \tag{6}$$

where $FSNum_i$ is the number of vacant FSs of the i-th partition.

Fig. 3 shows the advantage of the proposed FLF spectrum assignment policy. We assume that there are total 18 FSs and three types of requests $r = \{1, 2, 3\}$ with the same traffic intensity in the network, and the spectrum state is shown as Fig. 3(a). Two requests R_1 and R_2 that demand 2 FS arrive one by one. For request R_1, the dedicated SB is searched with the FF policy in the second partition (Zs_2), and the dedicated SB [8], [9] is used to transmit request R_1, as shown in Fig. 3(b). For request R_2, it can be seen that there is no available dedicated SB in its dedicated partition, thus the LF policy is used to search available SBs, and there are two partitions that can be used to transmit this request. Finally, the SB [17], [18] is used to transmit the request R_2 according to (6). Hence, compared with just using the FF policy, the FLF spectrum assignment policy may have

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[1] The dedicated SB: It is assumed that the start FS index and end FS index of the ith partition are l and m, respectively, so the dedicated SBs are $[l, l + r_i - 1], [l + r_i, l + 2r_i - 1], \ldots, [m - r_i + 1, m]$.

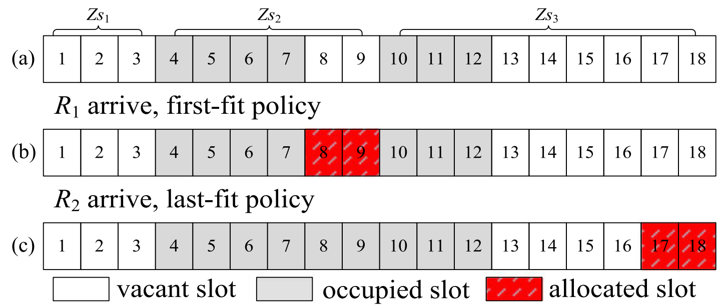


Fig. 3. Example of first-last-fit spectrum assignment policy.

Algorithm 1: First-last-fit spectrum assignment algorithm.

```
Input: $G(V, E, S)$, $R_i(s_i, d_i, b_i)$ and the $K$ candidate shortest lightpaths linking $s_i$ to $d_i$.
Output: RSA status $F$.
Identify the dedicated partition of this request;
for each candidate lightpath do
    Calculate the available dedicated SB in its dedicated partition;
    if the available SB is found then
        Execute the FF policy and assign spectrum resources in its dedicated partition;
        return $F = SUCCESS$;
    end if
end for
while the request is not successfully transmitted do
    for each candidate lightpath do
        Calculate available SBs from right to left in other partitions;
        if there are several partitions that have available SB then
            Apply formula (6) to obtain the minimum spectrum-interference partition;
            Execute the LF policy and assign spectrum resources in this partition;
            return $F = SUCCESS$;
        else if there is only a available partition then
            Execute the LF policy and assign spectrum resources in this partition;
            return $F = SUCCESS$;
        end if
    end for
end while
return $F = FAILURE$;
```

a temporary loan to other partitions when there are no available dedicated spectrum resources in the dedicated partition, which enhances the probability of successful transmission of request and spectrum efficiency.

4.3 Reconfiguration Mechanism of Spectrum-Interference Avoidance

When network has run for some time, the spectrum resources of dedicated partition are fragmented by the LF policy, and then the advantage of partition is weakened. Hence, to ensure the contiguity of spectrum resources, we propose a reconfiguration mechanism of spectrum-interference avoidance.

In order to ensure the effectiveness and success of reconfiguration, the remaining holding time and size of request are jointly considered in the step of reconfiguration. The idea is: firstly, if there is a request that is not transmitted in its dedicated partition, the request is added into a reconfigurable

Algorithm 2: Reconfiguration mechanism of spectrum-interference avoidance.

```
while network is running do
    for each request that is transmitting in other partition do
        Add the request into $Q$;
    end for
    Sort $Q$ in descending order of $EF$;
    for each request in $Q$ do
        Calculate $K$ candidate shortest lightpaths;
        for each candidate lightpath do
            Calculate the available dedicated SB in its dedicated partition;
            if the available SB is found then
                Move the request to its dedicated partition in the FF policy;
                Delete the request from $Q$;
            end if
        end for
    end for
end while
```

request list Q, and the *effective factor* (EF) of the request is calculated by using (7). Then, all reconfigurable requests are sorted in descending order of EF. In the end, if there is a request being released, the reconfigurable request list Q will be checked to see whether any request can be moved to its dedicated partition. The pseudo-code process of the reconfiguration mechanism is shown in algorithm 2.

$$EF = \frac{\text{the departure time of request } R_i}{r_i} \tag{7}$$

where the departure time of request R_i is equal to the sum of the arrival time and the holding time. The bigger the EF value of request is, the greater the revenue from the reconfiguration of the request is.

4.4 The Overall Process of FASA-SP-FLF-RM

Fig. 4 is the overall flow chart of the proposed FASA-SP-FLF-RM algorithm (these acronyms of FASA-SP-FLF-RM are presented in the end of introduction section). The operation of spectrum partition and construction of a reconfigurable request list Q are first executed. Then waiting for a new event, if it is the case that a request arrives, algorithm 1 is executed for this request; else, network releases the spectrum resources that the expired request assigns, and algorithm 2 is executed when the list Q is not null.

The time complexity of FASA-SP-FLF algorithm is mainly determined by the used routing and spectrum assignment algorithms. The first step is to find K shortest lightpaths from source to destination. For this we use the KSP [24] whose time complexity is $O(K \times (|E| + |N| \times \log |N|))$, where $|\ |$ returns the number of element(s) in the set. But this paper uses off-line computational method, thus its complexity may be neglected. As a consequence, the time complexity of FASA-SP-FLF is mainly determined by the spectrum assignment policy. Where, the time complexity of the FF and LF policy are $O(K \times |E| \times M)$ and $O(K \times |E| \times B)$, respectively. The time complexity of FASA-SP-FLF is therefore polynomial.

5. Performance Evaluation

To evaluate the effectiveness and universality of the proposed algorithm, the 14-node NSFNET [8] and 24-node USNET [15] are employed in our simulations. According to the average degree

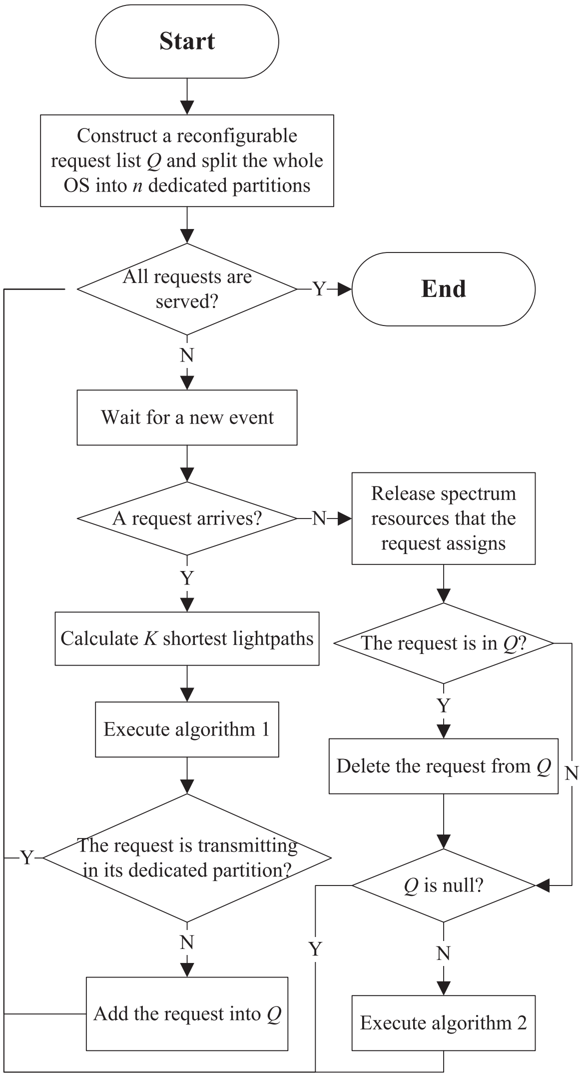


Fig. 4. Flow chart of FASA-SP-FLF-RM algorithm.

of each network topology, the K shortest lightpaths are 3 and 4, respectively. Each link is bidirectional fiber. Each fiber is constituted by 360 FSs and each slot occupies 12.5 GHz. The size of all requests is randomly distributed in the set of mixed line rate requests $r = \{40 \text{ Gbps}, 100 \text{ Gbps}, 400 \text{ Gbps}, 1 \text{ Tbps}\}$. Considering that the transponders apply the common DP-QPSK (Dual Polarization Quadrature Phase Shift Keying) in EONs, the requests use, including the guard-band: 3, 4, 7 and 16 FS respectively. The requests are uniformly distributed among all pairs of nodes and arrive according to a Poisson distribution; the holding time follows a negative exponential distribution. In our simulations, the two scenarios with different traffic intensity of requests are investigated. 10^6 requests are generated in each simulation.

The metrics that are used to evaluate the performance of algorithms are BBP and SUR. Since there is a direct relationship between BBP and SF, we only evaluate the BBP performance. The proposed FASA-SP-FLF-RM algorithm is tested, in comparison with two algorithms: the SETA algorithm in [17] and Zone Based (ZB) algorithm proposed in [22]. To show the contribution of each component to the overall performance improvement, the FASA-SP and FASA-SP-FLF algorithms are also simulated.

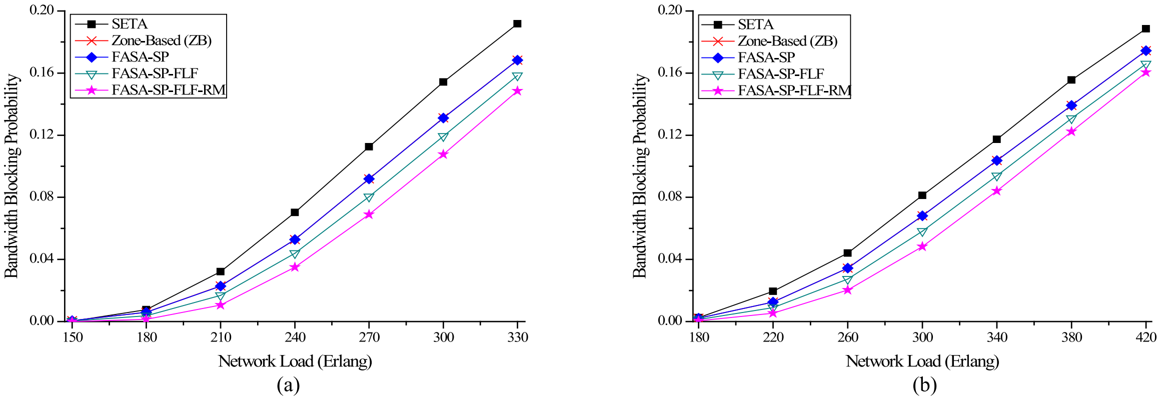


Fig. 5. BBP performance under uniform distribution scenario. (a) NSFNET. (b) USNET.

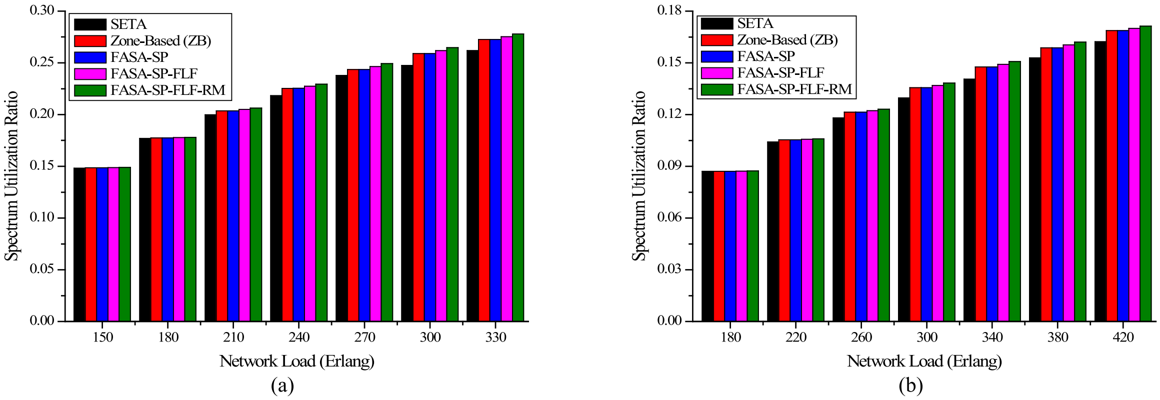
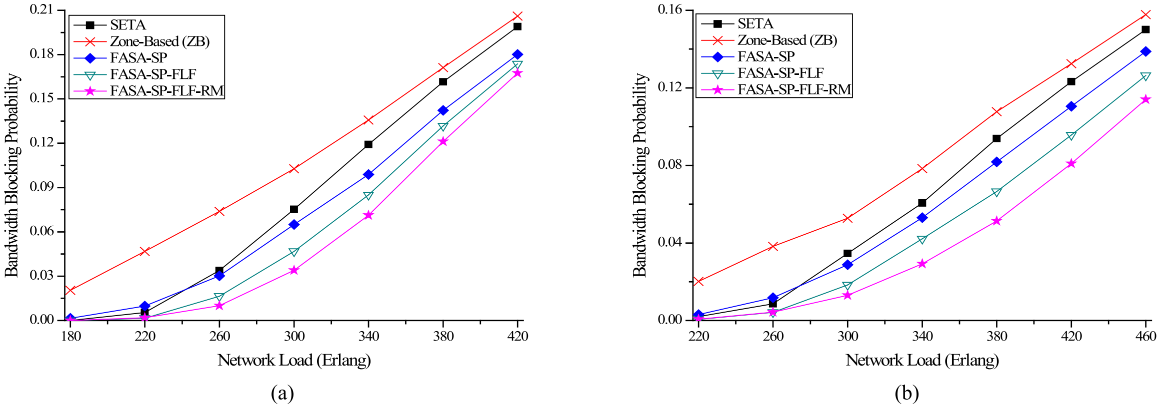


Fig. 6. SUR performance under uniform distribution scenario. (a) NSFNET. (b) USNET.

5.1 Scenario 1

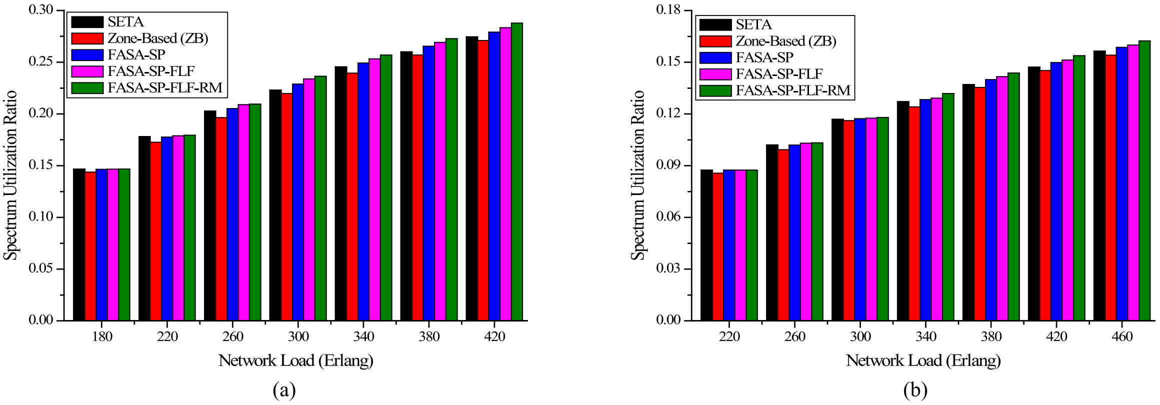
In scenario 1, the requests follow uniform distribution, and the proportion of four types of requests is set as 1:1:1:1. Fig. 5 shows the BBP of different algorithms obtained from the two topologies. The BBP of all algorithms increases with the network load. This is because there are no adequate spectrum resources that can be used to transmit all requests with the increase of the network load. Since the requests follow uniform distribution, our SP policy is the same as ZB. So FASA-SP and ZB obtain the same BBP results. But the proposed FASA-SP-FLF and FASA-SP-FLF-RM can always outperform SETA and ZB. The reason is that FASA-SP-FLF can adopt the LF policy to transmit requests when these requests are not successfully transmitted in their dedicated partition, which increases the probability of successful transmission of request. In addition, FASA-SP-FLF-RM also adopts reconfiguration mechanism to ensure the contiguity of spectrum resources of dedicated partitions, which avoids the generation of SFs as much as possible. FASA-SP-FLF-RM therefore obtains the best BBP performance. It can be seen that ZB obtains the suboptimal BBP performance by means of spectrum partition policy, which testifies that spectrum partition policy can alleviate the SF caused by mixed line rate requests provisioning. What is more, the network performance of USNET is always better than the NSFNET. The reason is that the connectivity of the former is better. USNET has more chance to establish lightpath for request, and then can accommodate more requests. So that network service providers will win more profit.

Fig. 6 reflects spectrum utilization ratio for three algorithms. In all topologies, the proposed FASA-SP-FLF-RM algorithm obtains the best SUR due to transmitting more requests, whereas SETA obtains ineffective spectrum utilization efficiency with the contrary reason. When the network load is low, FASA-SP-FLF-RM obtains slight improvement. This is the reason that all algorithms



(a) (b)

Fig. 7. BBP performance under non-uniform distribution scenario. (a) NSFNET. (b) USNET.



(a) (b)

Fig. 8. SUR performance under non-uniform distribution scenario. (a) NSFNET. (b) USNET.

prefer to select the shortest lightpath to transmit requests, and requests are not almost blocked. However, when the network load is more and more high, FASA-SP-FLF and FASA-SP-FLF-RM can improve spectrum utilization efficiency to some extent. This is because FASA-SP-FLF and FASA-SP-FLF-RM make the best use of spectrum resources by means of the LF policy. Furthermore, by applying spectrum partition and reconfiguration policy, FASA-SP-FLF-RM can reduce SFs and ensure the spectrum contiguity effectively, and then indirectly increase the probability of successful transmission of requests. Although the spectrum utilization ratio performance of USNET is relatively lower compared with NSFNET, its bandwidth blocking probability performance is much better.

5.2 Scenario 2

To highlight the advantage of the proposed spectrum partition policy, we also simulate the scenario 2 that the requests follow non-uniform distribution. Generally, there are many low rate requests in EONs [25]. Thus the proportion of four types of requests is set as 2:2:1:1. Fig. 7 shows the BBP performance of different algorithms under non-uniform distribution scenario. It is interesting to note that ZB obtains the worst BBP compared with other algorithms. The reason is that ZB only considers the size of requests and ignores another observable attribute, arrival rate of requests, to spectrum partition, which causes that the spectrum resources that are reserved for high rate requests cannot be made full use. However, for our spectrum partition policy, not only the size of requests but also the arrival rate of requests is considered, FASA-SP therefore obtains better performance compared with ZB. More importantly, the first-last-fit spectrum assignment policy can make full use of spectrum resources, and the reconfiguration mechanism of spectrum-interference avoidance largely ensures the contiguity of spectrum resources. Therefore, the proposed FASA-SP-FLF-RM algorithm can also obtain the best BBP performance under non-uniform distribution scenario.

Fig. 8 shows the simulation results on SUR of different algorithms under non-uniform distribution scenario. It can be seen that the proposed algorithm always obtains the best SUR for all cases, which further proves the effectiveness and universality of the proposed FASA-SP-FLF-RM algorithm. For SETA, the change of SUR can be explained by its BBP curve.

6. Conclusion

In this paper, we investigate the spectrum fragmentation problem caused by mixed line rate requests provisioning for EONs. To efficiently resolve the spectrum fragmentation problem, we first present a novel spectrum partition policy to alleviate fragmentation. Then, on the basis of spectrum partition, we present a joint first-last-fit spectrum assignment policy and formulate a partition selection formula to improve spectrum efficiency. Furthermore, we present a reconfiguration mechanism to ensure the contiguity of spectrum resources. The simulation results show that the proposed spectrum partition policy is better than the existing spectrum partition policy that only considers the size of requests in dynamic scenario. What is more, FASA-SP-FLF-RM can always yield the best bandwidth blocking probability and spectrum utilization ratio performance in whatever scenario, and the first-last-fit policy is a very effective spectrum assignment policy to obtain a tradeoff between spectrum fragmentation and spectrum utilization ratio.

In recent years, Soft Defined Networking (SDN) has made great development. Thus the future research is to make this strategy combination with SDN and use the logically centralized software controller to optimize the global network performance.

References

[1] R. V. Fávero, L. B. Bonani, and M. L. F. Abbade, “Spectral reallocation in lightpaths encompassing the most fragmented link of elastic optical networks,” in *Proc. 2016 IEEE 18th Int. Conf. Commun. Transparent Opt. Netw.*, Jul. 2016, pp. 1–4.

[2] N. Bao, G. Su, and J. Chen, “Recovery-time aware hybrid path protection algorithm in optical networks,” *J. Chongqing Univ. Posts Telecommun.*, vol. 29, no. 3, pp. 313–319, Jun. 2017.

[3] H. Liu, Q. Fang, and F. Lei, “Analysis of multicast traffic grooming algorithms in WDM mesh networks,” *J. Chongqing Univ. Posts Telecommun.*, vol. 24, no. 3, pp. 269–277, Jun. 2012.

[4] M. Jinno *et al.*, “Demonstration of novel spectrum-efficient elastic optical path network with per-channel variable capacity of 40 Gb/s to over 400 Gb/s,” in *Proc. 2008 IEEE 34th Eur. Conf. Opt. Commun.*, Sep. 2008, pp. 1–2.

[5] N. G. Anoh, M. Babri, A. D. Kora, R. M. Faye, B. Aka, and C. Lishou, “An efficient hybrid protection scheme with shared/dedicated backup paths on elastic optical networks,” *Digit. Commun. Netw.*, vol. 3, no. 1, pp. 11–18, Feb. 2017.

[6] M. Hadi and M. R. Pakravan, “Spectrum-convertible BVWXC placement in OFDM-based elastic optical networks,” *IEEE Photon. J.*, vol. 9, no. 1, Jan. 2017, Art. no. 7801312

[7] Y. Yin *et al.*, “Spectral and spatial 2D fragmentation-aware routing and spectrum assignment algorithms in elastic optical networks,” *IEEE/OSA J. Opt. Commun. Netw.*, vol. 5, no. 10, pp. A100–A106, Oct. 2013.

[8] R. Wang and B. Mukherjee, “Spectrum management in heterogeneous bandwidth optical networks,” *Opt. Switch. Netw.*, vol. 11, pp. 83–91, Jan. 2014.

[9] H. Liu, B. Zhou, and Y. Chen, “Spectrum allocation based on spectrum integration and re-routing for elastic optical networks,” *IET Optoelectron.*, vol. 10, no. 5, pp. 179–183, Oct. 2016.

[10] 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 IEEE Int. Conf. Comput. Commun.*, Apr. 2011, pp. 1503–1511.

[11] K. Christodoulopoulos, I. Tomkos, and E. A. Varvarigos, “Elastic bandwidth allocation in flexible OFDM-based optical networks,” *IEEE/OSA J. Lightw. Technol.*, vol. 29, no. 9, pp. 1354–1366, May 2011.

[12] H. Zhou, S. Mao, and P. Agrawal, “Optical power allocation for adaptive transmissions in wavelength-division multiplexing free space optical networks,” *Digit. Commun. Netw.*, vol. 1, no. 3, pp. 171–180, Aug. 2015.

[13] Y. Wang, X. Cao, Q. Hu, and Y. Pan, “Towards elastic and fine-granular bandwidth allocation in spectrum-sliced optical networks,” *IEEE/OSA J. Opt. Commun. Netw.*, vol. 4, no. 11, pp. 906–917, Nov. 2012.

[14] A. Horota, L. Reis, G. Figueiredo, and N. L. S. Fonseca, “Routing and spectrum assignment algorithm with most fragmented path first in elastic optical networks,” *IEEE Latin Amer. Trans.*, vol. 14, no. 6, pp. 2980–2986, Jun. 2016.

[15] H. Chen *et al.*, “Time-spectrum consecutiveness based scheduling with advance reservation in elastic optical networks,” *IEEE Commun. Lett.*, vol. 19, no. 1, pp. 70–73, Jan. 2015.

[16] X. Chen, J. Li, P. Zhu, R. Tang, Z. Chen, and Y. He, “Fragmentation-aware routing and spectrum allocation scheme based on distribution of traffic bandwidth in elastic optical networks,” *IEEE/OSA J. Opt. Commun. Netw.*, vol. 7, no. 11, pp. 1064–1074, Nov. 2015.

[17] Y. Qiu, Z. Fan, and C. K. Chan, “Efficient routing and spectrum assignment in elastic optical networks with time scheduled traffic,” *Opt. Fiber Technol.*, vol. 30, pp. 116–124, Jul. 2016.

[18] S. Ba, B. C. Chatterjee, S. Okamoto, N. Yamanaka, A. Fumagalli, and E. Oki, “Route partitioning scheme for elastic optical networks with hitless defragmentation,” *IEEE/OSA J. Opt. Commun. Netw.*, vol. 8, no. 6, pp. 356–370, Jun. 2016.

[19] S. Shakya, X. Cao, Z. Ye, and C. Qiao, “Spectrum allocation in spectrum-sliced elastic optical path networks using traffic prediction,” *Photon. Netw. Commun.*, vol. 30, no. 1, pp. 131–142, Aug. 2015.

[20] H. Liu, M. Zhang, and Y. Chen, “Shared Path protection through reconstructing sharable bandwidth based on spectrum segmentation for elastic optical networks,” *Opt. Fiber Technol.*, vol. 32, pp. 88–95, Dec. 2016.

[21] S. Sugihara, Y. Hirota, S. Fujii, H. Tode, and T. Watanabe, “Routing and spectrum allocation method for immediate reservation and advance reservation requests in elastic optical networks,” in *Proc. 2015 IEEE Int. Conf. Photon. Switch.*, Sep. 2015, pp. 178–180.

[22] R. S. Tessinari, B. Puype, D. Colle, and A. S. Garcia, “Zone based spectrum assignment in elastic optical networks: a fairness approach,” in *Proc. 2015 IEEE Opto Electron. Commun. Conf.*, Jul. 2015, pp. 832–834.

[23] M. S. Johnstone and P. R. Wilson, “The memory fragmentation problem: Solved?,” *Proc. 1st Int. Symp. Memory Manage.*, vol. 34, no. 3, pp. 26–36, Mar. 1998.

[24] N. Katoh, T. Ibaraki, and H. Mine. “An efficient algorithm for *K* shortest simple paths,” *Networks*, vol. 12, no. 4, pp. 411–427, Oct. 1982.

[25] Y. Qiu, “Group-based spectrum assignment in dynamic flex-grid optical networks,” *Opt. Fiber Technol.*, vol. 19, no. 5, pp. 437–445, Oct. 2013.