Received August 19, 2020, accepted August 29, 2020, date of publication September 1, 2020, date of current version September 14, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3021014

A Resource-Periodic-Arrangement Strategy for RMSA Problem in Elastic Optical Networks

SHURU LIU[1], QIANG GUO[2], JUNLING YUAN[1], AND QIKUN ZHANG[1]
[1]School of Computer and Communication Engineering, Zhengzhou University of Light Industry, Zhengzhou 450002, China
[2]PLA Zhengzhou Campus of Army Academy of Artillery and Air Defense, Zhengzhou 450000, China

Corresponding author: Junling Yuan (yuanjunling@foxmail.com)

This work was supported in part by the National Natural Science Foundation of China under Grant 61971380 and Grant 61772477, and in part by the Scientific and Technological Projects in Henan Province under Grant 182102210610.

ABSTRACT Elastic optical networks (EONs), which can flexibly assign spectrum resources to connection requests, have become the most promising technology for the next generation of optical core networks. Routing, modulation and spectrum assignment (RMSA) problem is one of the key issues in elastic optical networks. In the RMSA problem, spectrum resources in links are generally divided into frequency slices and connection requests with different capacities can use different numbers of frequency slices to transfer their data; however, this may lead to misalignment of idle frequency slices in links and then result in the increase of blocking probability of connection requests. In this article, we propose a resource-periodic-arrangement (RPA) strategy. The strategy partitions frequency slices into periodically arranged standard frequency blocks and each connection request exactly uses one or more standard frequency blocks. The RPA strategy can effectively reduce the misalignment of frequency slices. Furthermore, an RPA-based RMSA algorithm is designed, in which an enhanced-most-used policy is adopted to choose standard frequency blocks to connection requests. Simulation results show that the RPA-based RMSA algorithm can distinctly reduce blocking probability of connection requests, comparing with existing algorithms.

INDEX TERMS Elastic optical networks (EONs), routing modulation and spectrum assignment (RMSA), resource periodic arrangement (RPA), enhanced most used (EMU).

I. INTRODUCTION

In recent years, 5G communication technology has developed rapidly, which promotes the fast development of cloud computing, edge computing, mobile Internet, Internet of things, etc. In these application scenarios, connection requests always require large bandwidth and moreover, the required bandwidths by different connection requests are diverse with each other, which demands the underlying communication network to flexibly provide bandwidth for connection requests. Traditional wavelength division multiplexing (WDM) networks can only provide channels with fixed wavelengths, so they cannot satisfy the demand of bandwidth diversity. Elastic optical networks (EONs), which can flexibly assign frequency resources according to bandwidth requirements of connection requests, have become the most promising underlying technology for these application scenarios [1], [2]. In EONs, spectrum resources are generally divided into frequency slices (FSs) with fine granularity (for example 12.5 GHz or 6.25 GHz) and each connection request can use several contiguous frequency slices according to its bandwidth requirement [3].

Routing, modulation and spectrum assignment (RMSA) problem is one of the key issues in EONs. In the RMSA problem, we need to choose a path from the source to the destination of a connection request, select an adaptive modulation level according to length of the path, and assign an available frequency block composed by several contiguous frequency slices for the connection request according to its traffic capacity [4], [5]. The number of needed frequency slices of a connection request in a path can be calculated by the following formula [6]:

$$N_{FS} = \lceil \frac{C}{B_{slice} \cdot m} \rceil + N_g, \tag{1}$$

where C is traffic capacity of the connection request, B_{slice} is the bandwidth of each frequency slice, m is the adoptable

The associate editor coordinating the review of this manuscript and approving it for publication was Rentao Gu.

maximal modulation level of the path, and N_g is the number of guard frequency slices between connection requests.

In the RMSA problem, three constraints must be satisfied, namely spectrum non-overlapping constraint, spectrum continuity constraint and spectrum contiguity constraint [7]. The first constraint ensures that each frequency slice in a link can only be used by one connection at a time, the second constraint guarantees that the assigned frequency slices in all links of the source-destination path are with the same indexes, and the last constraint makes sure that the assigned frequency slices in each link are contiguous and form only one frequency block.

For connection requests with different data capacities, the numbers of needed frequency slices are distinct. Along with the frequent establishment and removal of connections, the remainder idle frequency slices in adjacent links would be misaligned with each other. Furthermore, the constraints of spectrum continuity and spectrum contiguity make the situation worse. The misalignment of idle frequency slices would lead to increase of blocking probability of connection requests. To decrease the blocking probability, several RMSA algorithms have been designed based on reducing the misalignment of frequency slices in recent years [8]. Some works even considered breaking the constraints of spectrum continuity and spectrum contiguity. Although the blocking probability has been reduced to a certain extent by these algorithms, it can be further lowered.

In this article, we propose a resource-periodic-arrangement (RPA) strategy to reduce the misalignments of both occupied and idle frequency slices, and then design an RPA-based RMSA algorithm to assign spectrum resources to connection requests. The contributions of this article are triple:

1) A resource-periodic-arrangement (RPA) strategy is proposed. The strategy partitions frequency slices into periodically arranged standard frequency blocks and stipulates that each connection can use one or more standard frequency blocks. The strategy can decrease the misalignment of frequency slices in adjacent links.
2) An RPA-based RMSA algorithm is designed. In the algorithm, the RPA strategy is used to arrange frequency slices and an enhanced-most-used (EMU) policy is used to search available standard frequency blocks for connection requests. The EMU policy can further decrease the misalignment of standard frequency blocks in adjacent links.
3) Simulations are done to show the performance of the proposed algorithm. First some simulations are done to show the impact of number of candidate paths and then simulations are done to compare the proposed algorithm with three existing algorithms. Simulation results show that the proposed algorithm outperforms the existing ones in terms of blocking probability.

The rest of this article is organized as follows. In Section II the related works are summarized. In Section III the proposed resource-periodic-arrangement strategy and the RPA-based RMSA algorithm are introduced in detail. In Section IV simulations are done to evaluate performance of the RPA-based RMSA algorithm. At last, a brief conclusion is drawn in Section V.

II. RELATED WORKS

The RMSA problem in EONs is similar to the routing and wavelength assignment (RWA) problem in WDM networks, so several classical RWA algorithms are converted for the RMSA problem in early years [9], [10], such as the Random-Fit algorithm, the First-Fit algorithm, the Last-Fit algorithm, the First-Exact-Fit algorithm, etc. In recent years, the characteristics of RMSA problem are specifically studied and dozens of RMSA algorithms are designed for various scenarios of EONs [11]. Next, we first introduce the algorithms based on the idea of aligning frequency slices in links, and then summarize RMSA algorithms for several special scenarios in EONs.

A. ALIGNMENT-BASED RMSA ALGORITHMS

Fragmentation of spectrum is a big disadvantage for RMSA problem in EONs, which would affect the utilization efficiency of frequency slices and lead to increase of blocking probability. One of the main causes of fragmentation is misalignment of frequency slices in different links. To reduce blocking probability, several RMSA algorithms are designed from the point of reducing misalignment of frequency slices.

Fadini *et al.* designed an RMSA algorithm named First-Last-Fit in 2014 [12]. In their algorithm, frequency slices are partitioned into even number of partitions; when searching spectrum resources for a connection request, the First-Fit policy is used in odd partition and the Last-Fit policy is used in even partition; at last, the available frequency block with the minimum distance to boundary of the corresponding partition is selected. For two adjacent partitions, the First-Last-Fit algorithm can concentrate the occupied frequency slices on sides and let frequency slices at the center of the partitions idle. The strategy can decrease the misalignment of frequency slices and then decrease blocking probability of connection request. Simulation results show that the First-Last-Fit algorithm outperforms all algorithms converted from RWA algorithms [13].

Fukuda *et al.* designed an RMSA algorithm named Block-Assignment in 2015 [14]. In their algorithm, frequency slices are divided into frequency blocks with sizes of $2^0, 2^1, 2^2, \cdots$. Concretely, frequency slices are divided into frequency blocks with size 16 (block-16) first, each block-16 is divided into two frequency blocks with size 8 a (block-8), each block-8 is further divided into two frequency blocks with size 4 (block-4), and so on. The frequency blocks with different sizes are multilevel-nested. For a connection request needing n frequency slices, the algorithm would only check the blocks with size $2^{\lceil \log n \rceil}$. For example, if $n = 7$, then $\lceil \log 7 \rceil = \lceil 2.81 \rceil = 3$ and $2^{\lceil \log n \rceil} = 8$; thus the algorithm would only check blocks with size 8. The Block-Assignment algorithm can make the occupied and idle frequency slices in all links more aligned.

Yuan *et al.* proposed an RMSA algorithm named Tradeoff-RnI in 2018 [15]. In their algorithm, the idea of first-last-fit is extended to K candidate paths. The lengths of different candidate paths are distinct, which leads to different maximal modulation levels in different candidate paths. For the same connection request, numbers of needed frequency slices in different paths are distinct. The algorithm tries to minimize two indexes of the available frequency block for each connection request, namely consumed resources (R) and interval between boundary (I). If the indexes cannot be minimized at the same time, a tradeoff would be made between them. The Tradeoff-RnI algorithm can make the occupied and idle frequency slices more aligned in all candidate paths.

In this article, we would propose a resource-periodic-arrangement strategy and design an RBA-based RMSA algorithm. The algorithm uses an enhanced-most-used policy to assign frequency slices to connection requests. Both the resource-periodic-arrangement strategy and the enhanced-most-used policy can make the occupied and idle frequency slices more aligned. Since our algorithm is based on the resource-alignment idea, we would compare it with the existing alignment-based RMSA algorithms.

B. RMSA ALGORITHMS FOR SPECIAL SCENARIOS

The above RMSA algorithms are based on ordinary scenario of EONs, in which the required spectrum resources of connection requests need to be assigned immediately and the constraints of spectrum continuity and spectrum contiguity must be met. Besides the ordinary scenario, the RMSA problems for special scenarios of EONs are also widely investigated in recent years. Next we introduce these works in brief.

Some works considered the multi-path or multi-flow RMSA problem in EONs [16]–[23], in which the constraint of spectrum contiguity is broken. In ordinary RMSA problem, frequency slices for a connection request must be contiguous or equivalently can only compose one frequency block. In the multi-flow RMSA algorithms, if no frequency block is available for a connection request, its traffic can be split into multiple flows and each flow is regarded as a separate connection request. The strategy of splitting connection requests to multiple flows can make some fragmentary resources available and then increase the success probability of connection requests. However, since the strategy breaks the constraint of spectrum contiguity, processing complexity of network is higher than that of ordinary case.

Some works investigated the multi-hop RMSA problem in EONs [24]–[27], in which the constraint of spectrum continuity is broken. In ordinary RMSA problem, frequency slices for a connection request must be the same in all links of the source-destination path. However in the multi-hop based works, if no frequency block is available in all links of the source-destination path, different frequency blocks can be selected in different links; at nodes who joint two links using different frequency blocks, the signal must be converted at electric domain. It seems that the source-destination path is cut into multiple sub-paths by the converting nodes and each sub-path is an all-optical hop. The multi-hop strategy would increase the processing complexity of network either.

Some works studied the RMSA problem for advance reservation (AR) requests in EONs [28]–[37]. In ordinary RMSA problem, the required frequency slices of connection requests must be assigned immediately and the holding times of connections are unknown. It means that the occupied frequency slices of a connection cannot be assigned to other connection requests until the ending of current connection. In the RMSA problem for AR requests, beginning time of each connection request can be delayed for a time interval; the holding time of the connection is known at its arriving time, which means that the release time of each connection can be pre-calculated. Hence frequency slices can be reserved in advance to different connections by the manner of time division multiplexing.

Some other works researched the RMSA problem for malleable reservation (MR) requests in EONs [38]–[45]. The RMSA problem for MR requests can be regarded as an extension of the problem for AR requests. In the RMSA problem for MR requests, the volume of data of each connection request is known at its arriving time, yet both the number of needed frequency slices and holding time of the connection request are changeable. Resource reservation for an MR request has more freedom than that for AR requests.

In works for different scenarios of EONs, the basic settings are different from each other, so the algorithms for different scenarios are non-universal. Specially, the settings in special scenarios are different from those in the ordinary scenario, and thus the algorithms for special scenarios are not suitable for the ordinary RMSA problem. In this article, we design an RMSA algorithm for ordinary scenario. Hence, we do not compare our algorithm with the algorithms for special scenarios of EONs.

The above-mentioned works are based on traditional optimization methods. In the last two or three years, several works studied the RMSA problem based on artificial intelligence (AI) methods [46]–[52], which can generally get a better performance than traditional ones. However, the AI-based algorithms are usually with high computation complexity, so we do not compare our algorithm with them either.

III. THE PROPOSED RPA-BASED RMSA ALGORITHM

The proposed RPA-based RMSA algorithm has two innovation measures, namely the Resource-Periodic-Arrangement (RPA) strategy and the Enhanced-most-used (EMU) policy. The RPA strategy is used to partition frequency slices into standard frequency blocks, while the EMU policy is used to select adaptive standard frequency blocks for connection requests. In this section, we first introduce the RPA strategy and the EMU policy in detail, then describe procedure of the proposed algorithm, and finally analyze computation complexity of the algorithm.

A. THE RESOURCE-PERIODIC-ARRANGEMENT (RPA) STRATEGY

In order to reduce the misalignment of frequency slices in different links, we partition frequency slices into frequency blocks with standard sizes. In our strategy, three kinds of standard frequency blocks (SFBs) are used, namely standard frequency block 1 (SFB_1), standard frequency block 2 (SFB_2) and standard frequency block 4 (SFB_4). An SFB_1 is composed by only one frequency slice, an SFB_2 is composed by two contiguous frequency slices, and an SFB_4 is composed by four coutiguous frequency slices. For the sake of intuition, structures of different kinds of standard frequency blocks are shown in Figure 1. We stipulate that each standard frequency block must be used as a whole. In other words, all the frequency slices within a standard frequency block must be used by the same connection.

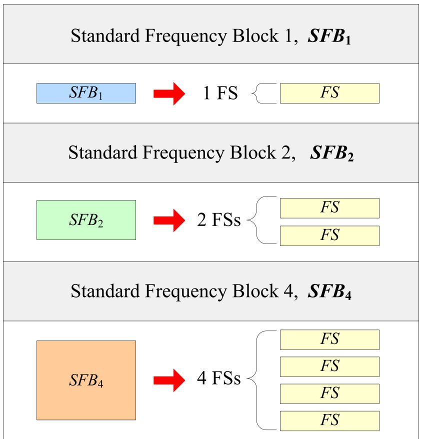


FIGURE 1. Structures of different kinds of standard frequency blocks.

Supposing that frequency slices are partitioned into P periods and the number of standard frequency blocks within each period is B, then the b-th standard frequency block of the p-th period can be denoted as $SFB(p, b)$. Specially, the b-th standard frequency block of the p-th period in link e can be denoted as $SFB_e(p, b)$. Further supposing that K candidate paths are used for each source-destination pair and the k-th candidate path between source s and destination d is $P_{sd,k}$, then the b-th standard frequency block of the p-th period in path $P_{sd,k}$ can be expressed as $SFB_{sd,k}(p, b)$.

In general, states of spectrum resources are expressed by the states of frequency slices. However in the resource-periodic-arrangement strategy, the frequency slices are partitioned into standard frequency blocks and standard frequency blocks are periodically arranged, so the states of spectrum resources can be expressed by the states of standard frequency blocks. Concretely, the state of $SFB_e(p, b)$ can be expressed by the following formula:

$$S_e(p, b) = \begin{cases} 1, & \textit{All FSs in } SFB_e(p, b) \textit{ are idle;} \\ 0, & \textit{Any FS in } SFB_e(p, b) \textit{ is busy.} \end{cases} \tag{2}$$

Furthermore, the state of $SFB_{sd,k}(p, b)$ can be determined by the following formula:

$$S_{sd,k}(p, b) = \prod_{e \in E(P_{sd,k})} S_e(p, b). \tag{3}$$

In which, $E(P_{sd,k})$ is the link set of path $P_{sd,k}$. The formula implies that, if the $SFB_e(p, b)$'s in all links of path $P_{sd,k}$ are commonly idle, $SFB_{sd,k}(p, b)$ is idle in path $P_{sd,k}$, and if $SFB_e(p, b)$ in any link of the path is occupied, $SFB_{sd,k}(p, b)$ is busy in the path.

The purpose of partitioning frequency slices into standard frequency blocks is to make the occupied and idle frequency slices more aligned. Hence, the standard frequency blocks must be carefully arranged so that connection requests can conveniently use them. In the resource-periodic-arrangement strategy, the arrangement order of standard frequency blocks within each period is as follows:

$$\mathcal{S}_{SFB} = (SFB_2, SFB_4, SFB_1, SFB_2, SFB_2, SFB_4, SFB_4, SFB_1). \tag{4}$$

The sequence can be briefly denoted as 24122441. For the sake of intuition, the partition result of frequency slices is shown in Figure 2. In the partition pattern, each period contains eight standard frequency blocks composing by twenty

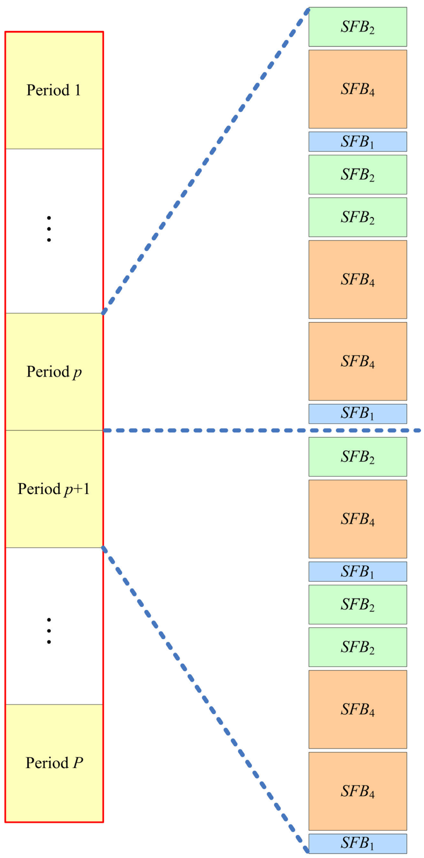


FIGURE 2. Method of partitioning frequency slices to periodically arranged standard frequency blocks.

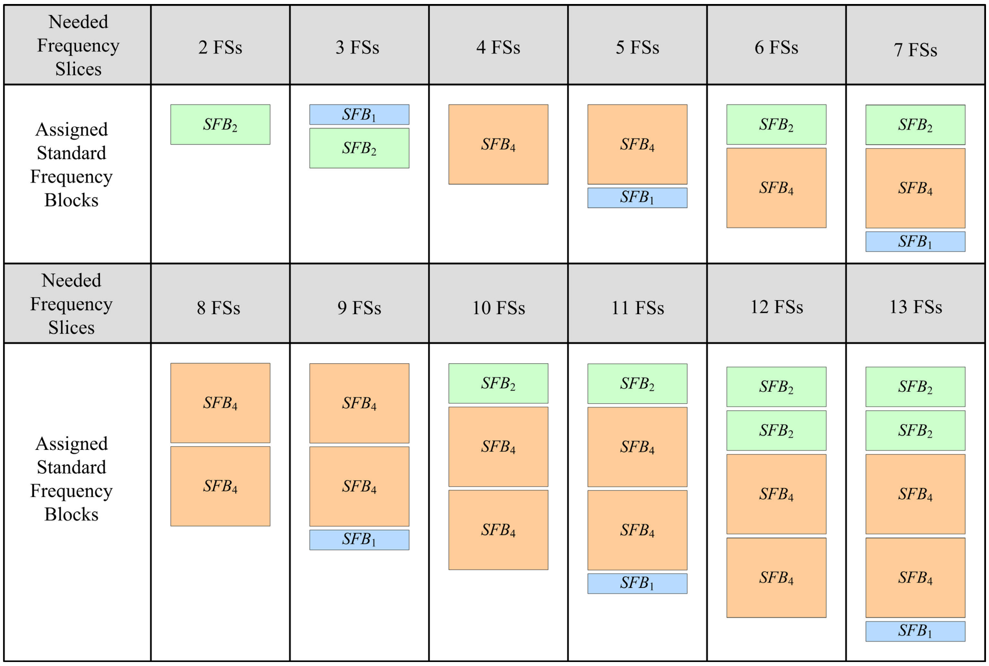


FIGURE 3. **The corresponding relation between needed frequency slices and assigned standard frequency blocks.**

frequency slices. If there are 320 frequency slices in each link, the number of periods is $320/20 = 16$.

The reason why we adopt sequence 24122441 to arrange standard frequency blocks is that, for any connection request needing any number of frequency slices, we can use several contiguous standard frequency blocks of the sequence to serve it. For example, if a connection request needs 2 or 4 frequency slices, we can use a standard frequency block 2 or a standard frequency block 4 to satisfy it; if a connection request requires 3, 5, 6 or 8 frequency slices, we can use standard frequency block combination 12, 41, 24 or 44 to meet the requirement; moreover, if a connection request asks for 7, 9 or 10 frequency slices, we can use standard frequency block combination 241, 441 or 244 to serve it. Figure 3 shows the corresponding relation between numbers of needed frequency slices N_{FS} and assigned standard frequency block combinations. We can see that, for connection request whose number of needed frequency slices is not more than 10, it can be served by not more than three contiguous standard frequency blocks in the sequence. It should be noted that, 24122441 is not the only selectable sequence, at least all of its transformations can achieve this effect, such as 41224412, 12244124, etc.

Under the RPA strategy, each connection request can be served by an SFB combination (a single standard frequency block can be regarded as a special SFB combination). An SFB combination BC can be expressed by a 2-tuple:

$$BC = (I_{first}, N_B). \tag{5}$$

where I_{first} is the index of the first standard frequency block in BC and N_B is the number of standard frequency blocks in BC.

Although we have given the corresponding relation between numbers of needed frequency slices N_{FS} and types of SFB combinations in Figure 3, the specified SFB combinations have not been listed. Additionally, if standard frequency blocks can be used across periods, more kinds of SFB combinations can be used for some values of N_{FS}. Table 1 lists the kinds of SFB combinations and set of specified SFB combinations $\mathcal{S}_{BC}$ for different numbers of needed frequency slices. We can see that, when cross-period use of standard frequency blocks is allowed, three types of SFB combinations can be used when the number of needed frequency slices equals 7. It should be noted that, although the table shows

TABLE 1. **Kinds of SFB combinations and set of specified SFB combinations for different numbers of frequency slices N_{FS}.**

N_{FS}	Kinds of SFB combinations	Set of specified SFB combinations, $\mathcal{S}_{BC}$
2	2	(1,1), (4,1), (5,1)
3	12	(3,2), (8,2)
4	4	(2,1), (6,1), (7,1)
5	41	(2,2), (7,2)
6	24	(1,2), (5,2)
7	241, 412, 124	(1,3), (2,3), (7,3), (8,3)
8	44	(6,2)
9	441	(6,3)
10	244	(5,3)
11	2441, 4412	(5,4), (6,4), (7,4)
12	2244	(4,4)
13	41224, 12244, 22441, 24412	(2,5), (3,5), (4,5), (5,5)

that four or more standard frequency blocks would be needed for some values of N_{FS}, since the value of N_{FS} is generally less than 8, the number of needed standard frequency blocks is no more than three in most cases.

B. THE ENHANCED-MOST-USED (EMU) POLICY

The Most-Used policy is designed for RWA problem in WDM networks [9], which compares available wavelengths to assign the busiest/worst one to the current connection request and leaves better resources to later coming connection requests. In this article, we propose an Enhanced-Most-Used policy for RMSA problem in EONs, which improves the Most-Used policy in three aspects:

1) Comparison object is changed from wavelength to SFB combination.
2) Comparison range is extended from just one path to several paths.
3) Comparison index is increased from one to two sequential ones.

The first improvement is obvious. Since the needed resources of each connection request are an SFB combination composed by several standard frequency blocks, we must compare the SFB combination as a whole. Next we explain the second and the third improvements.

In the EMU policy, K candidate paths are divided into M (M is the maximum value of adoptable maximal modulation levels in all candidate paths) path groups and denoted as $PG_M, PG_{M-1}, \cdots, PG_2, PG_1$. In all the paths of a path group, the adoptable maximal modulation levels are the same, so the numbers of needed frequency slices are the same too. Therefore, the kinds of SFB combinations and specified SFB combinations in all paths of each path group are identical. The EMU policy would compare SFB combinations in terms of path group rather than path. Concretely, we would find all available SFB combinations in all paths of a path group and choose the one with the maximum comparison index among them.

In the EMU policy, two indexes of each SFB combination BC are considered, namely the sum of total used links STU and the sum of used neighbors links SNU. They can be calculated by the following formulas:

$$STU = \sum_{SFB \in BC} TU_{SFB} \tag{6}$$

$$SNU = \sum_{SFB \in BC} NU_{SFB} \tag{7}$$

In which, TU_{SFB} is the number of links of the network in which SFBs are occupied and NU_{SFB} is the number of neighbor links of the current candidate path in which SFBs are occupied. The EMU policy choose specified SFB combination according to the following three sequential rules:

- if there are several available SFB combinations for a connection request, the one with the maximum STU would be chosen;
- if several available SFB combinations have the maximum STU at the same time, the one with the maximum SNU would be selected;
- if there are still ties, the first available SFB combination in the ties would be finally chosen.

C. PROCEDURE OF THE RPA-BASED RMSA ALGORITHM

The proposed algorithm has two goals, i.e., using the least spectrum resources to service each connection request and at the same time making both the idle frequency slices more aligned. The first goal can be reached by checking the path groups in the order of modulation level from high to low, and the second goal can be achieved by using the EMU policy within each path group.

Procedure of the RPA-based RMSA algorithm is shown in Algorithm 1. Input of the algorithm is a connection request $r = (s, d, C)$ with source s, destination d and capacity C. Output of the algorithm is an available SFB combination in one of the K candidate paths.

Algorithm 1 RPA-Based RMSA Algorithm

Input: A connection request $r = (s, d, C)$ with source s, destination d and capacity C.
Output: An available SFB combination in a candidate path.

Set $BC^* = Null$ and $P^* = Null$
Set $STU^* = 0$ and $SNU^* = 0$.
for $m = M$ *to* 1 **do**
    Load path group PG_m between s and d.
    Calculate the number of needed frequency slices N_{FS} and load the set of SFB combinations $\mathcal{S}_{BC}$.
    for *each path* P_k *in* PG_m **do**
        for *each SFB combination* BC *in* $\mathcal{S}_{BC}$ **do**
            Calculate the states of SFBs in BC.
            if *all SFBs in BC are idle* **then**
                Calculate STU and SNU of BC.
                if $(STU > STU^*)$ *or* $(STU == STU^*$ *and* $SNU > SNU^*)$ **then**
                    $STU^* = STU$ and $SNU^* = SNU$.
                    $BC^* = BC$ and $P^* = P_k$.
                end
            end
        end
    end
    if $BC^* \neq Null$ **then**
        return BC^* *and* P^*
    end
end
return *Null*

In the algorithm, we use BC^* and P^* to express the temporarily selected SFB combination and its path during the running process of the algorithm. Initially, their values are set as *Null*, i.e., they do not point to any SFB combination and path. Furthermore, we use STU^* and SNU^* to record the numbers of total used links and used neighbor links of the temporarily selected SFB combination. Their initial values are both set as zero.

In the algorithm, the candidate paths would be checked to find an available SFB combination for the connection request. The K candidate paths have been divided into M path groups according to their adoptable maximal modulation levels. The M-th path group would be checked first, because the least frequency slices are needed in these paths. In all paths of a path group, the adoptable SFB combinations are the same. Hence, we would find all available SFB combinations in all the paths within a path group and compare their *STU* and *SNU* (if needed), rather than compare them in one path at a time. If available SFB combinations are found in a path group, the available SFB combination with the maximum *STU* would be returned and the algorithm would be finished, without further checking the remainder path groups. If no available SFB combination is found in the current path group, the next path group would be further checked. If the algorithm has not returned after all path groups have been checked, *Null* would be returned, which means that none available SFB combination is found in all paths; in this case the connection request would be blocked.

D. COMPLEXITY ANALYSIS

Denoting the number of nodes in the network is N, the number of frequency slices in links is F, the number of periods of SFBs is P and the number of candidate paths between each source-destination pair is K. The calculation of candidate paths and partition of path groups can be done before the beginning of the algorithm; the operations just need be done for one time, so they should not be counted into the complexity of the algorithm.

The algorithm includes three loops. The first two loops would realize the checking of all candidate paths, so their total running time is $O(K)$. The third loop would check the corresponding set of SFB combinations in a candidate path, its running time is $O(P)$, which is less than $O(F)$. To judge whether an SFB combination in a candidate path is available, all links in the path should be checked and the number of links within each candidate path is not more than N, so the running time of this operation is less than $O(N)$. To calculate *STU* and *SNU* of an SFB combination, all links of the network should be checked and the number of links of the network is less than $\frac{N(N-1)}{2}$, so the running time of this operation is $O(N^2)$. Totally, the running time of the algorithm is $O(K \cdot F \cdot (N + N^2)) = O(KFN^2)$.

IV. PERFORMANCE SIMULATIONS

In this section, we investigate performance of the proposed RPA-based RMSA algorithm by simulations. We first introduce simulation parameters, then compare blocking probability of the proposed algorithm under different numbers of candidate paths, and finally compare blocking probability of the proposed algorithm with three existing algorithms.

A. SIMULATION SETTINGS

We choose two networks to do simulations, namely the National Science Foundation Network (NSF-Net) and the USA Backbone Network (UBN). Topologies of the networks are shown in Figures 4 and 5, in which numbers on the links are their lengths in kilometers.

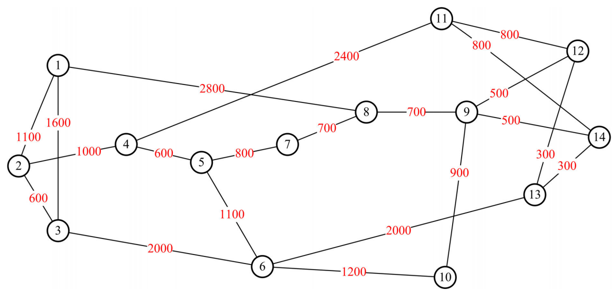


FIGURE 4. Topology of the Natural Science Foundation network (NSF-Net).

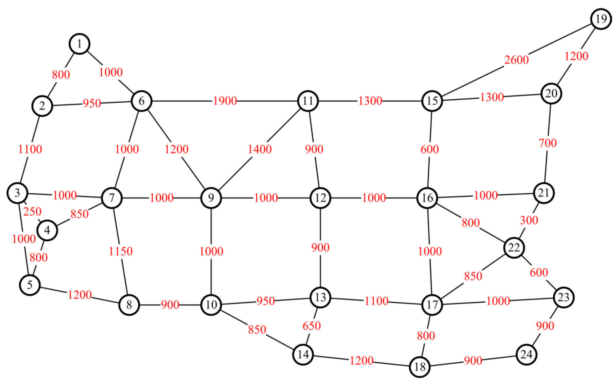


FIGURE 5. Topology of the USA Backbone Network (UBN).

In the simulations, spectrum resources in each link are divided into 320 frequency slices and the spectrum bandwidth of each frequency slice is 12.5 GHz. The frequency slices are further divided into periodically arranged standard frequency blocks according to the method given in Section III. For each source-destination pair, K candidate paths are calculated by Yen's algorithm. In different candidate paths, the selectable modulation formats are BPSK, QPSK, 8QAM and 16QAM, their bits per symbol are 1, 2, 3, and 4, and their reachable distance are 10000 km, 5000 km, 2500 km and 1250 km, respectively [53].

In the simulations, connection requests arrive at nodes along the Poisson distribution and the holding time of each connection follows the exponential distribution. Concretely, the mean of exponential distribution is set as 100 seconds and the mean of Poisson distribution equals the quotient of traffic density divided by mean of exponential distribution. For each simulation, 10^6 connection requests are generated. The capacity of each connection request is randomly and evenly chosen from [10, 20, 40, 80, 160] Gbit/s [6], [54]. All the simulation parameters are summarized in Table 2.

TABLE 2. Simulation parameters.

Parameters	Values
Network topologies	NSF-Net, UBN24
F, number of frequency slices	320
C_{slice}, bandwidth of frequency slice	12.5 GHz
N_g, number of guard frequency slices	1
Selectable modulation formats	BPSK, QPSK, 8QAM, 16QAM
Modulation levels of modulation formats (in bit/symbol)	1, 2, 3, 4
Reachable distance of modulation formats (in km)	10000, 5000, 2500, 1250
Capacity of connection requests (in Gbit/s)	10, 20, 40, 80, 160
Ratio of different connection requests	1 : 1 : 1 : 1 : 1
Arrival rate of connection requests	Poisson distribution
Holding time of connection requests	Exponential distribution

In the simulations, we investigate blocking probability of connection requests. For a connection request r, denoting its capacity and holding time as C_r and D_r, respectively, then traffic of the connection request is C_rD_r. Denoting the sets of arrived connection requests and blocked requests as $\mathcal{R}$ and $\mathcal{R}_B$ respectively, blocking probability of connection requests can be calculated by the following formula:

$$P_B = \frac{\sum_{r\in\mathcal{R}_B} C_rD_r}{\sum_{r\in\mathcal{R}} C_rD_r}. \quad (8)$$

B. COMPARISON FOR DIFFERENT NUMBERS OF CANDIDATE PATHS

The number of candidate paths would impact the blocking probability of connection requests. We do simulations to show the performance of the proposed algorithm under different numbers of candidate paths first. Simulation results in the NSF-Net and the UBN are shown in Figures 6 and 7, respectively.

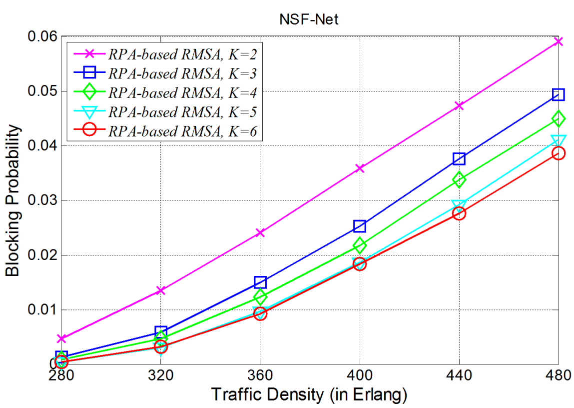


FIGURE 6. Comparison of the RPA-based RMSA algorithm under different numbers of candidate paths in the NSF-Net.

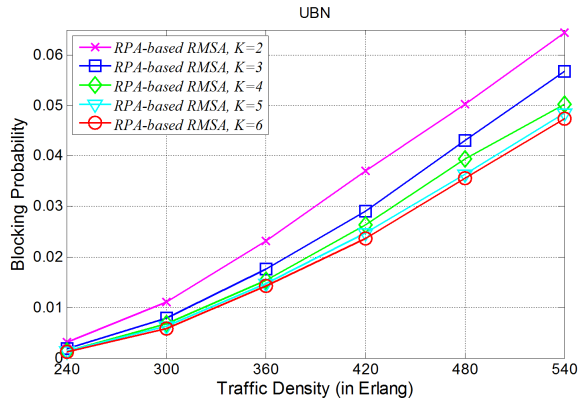


FIGURE 7. Comparison of the RPA-based RMSA algorithm under different numbers of candidate paths in the UBN.

The figures show that, blocking probability of the proposed algorithm decreases with the increase of K, yet decreasing speed of blocking probability decreases with the increase of K, whether in the NSF-Net or the UBN. For example, the decreasing of blocking probability is significant when K changes from 2 to 3, while it is slight when K changes from 5 to 6. The reasons are as follows. When candidate paths increase, connection requests get more chances to get available standard frequency block combinations, so their blocking probability would decrease. However, the total spectrum resources in the network are fixed and the links for different candidate paths are intersectional with each other, so the effect of reducing blocking probability by adding candidate paths is discounted with the increase of K.

C. COMPARISON WITH EXISTING ALGORITHMS

We compare our algorithm with three existing algorithm, the First-Last-Fit algorithm, the Block-Assignment algorithm and the Tradeoff-RnI algorithm. All the comparison algorithms are alignment-based. In the simulations, the number of candidate paths is set as 6, since a bigger K can only slightly decrease blocking probability. Simulation results in NSF-Net and the UBN are shown in Figures 8 and 9, respectively.

From the figures we can see that, the First-Last-Fit algorithm and the Block-Assignment algorithm have the similar blocking probability, the Tradeoff-RnI algorithm has a lower blocking probability than the First-Last-Fit and Block-Assignment algorithms, and the proposed RPA-based RMSA algorithm always has the lowest blocking probability, whether in the NSF-Net or the UBN. The reasons are as follows.

The First-Last-Fit algorithm divides frequency slices into several partitions and tries to concentre the occupied frequency slices to the boundaries of two adjacent partitions. However, it only considers one candidate path at a time, which leads to the result that, although there are available resources nearer to the boundary in other candidate path, centering frequency slices are still chosen. Since different candidate paths generally have common links, the use of centering

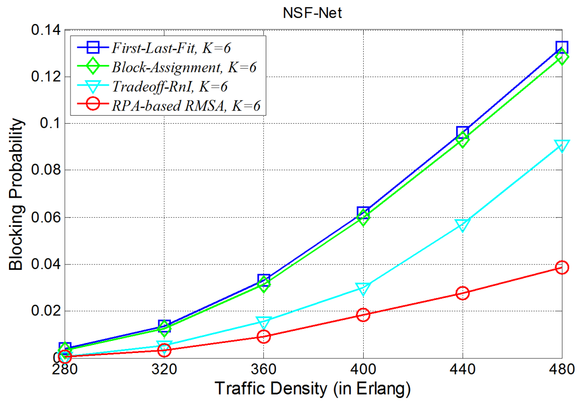


FIGURE 8. Comparison of the RPA-based RMSA algorithm with three existing algorithms in the NSF-Net.

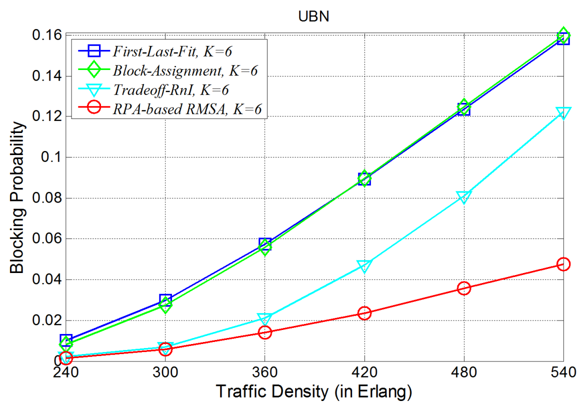


FIGURE 9. Comparison of the RPA-based RMSA algorithm with three existing algorithms in the UBN.

resources in a candidate path may impact the alignments of resources in other candidate paths, even the candidate paths for other source-destination pairs. Hence, the effect of the First-Last-Fit strategy is limited.

The Tradeoff-RnI algorithm extends the First-Last-Fit strategy from only one candidate path to all candidate paths. In the algorithm, all available frequency blocks in all candidate paths are found first. Frequency blocks in different candidate paths may have different sizes. The algorithm would make a tradeoff between consumed resources and interval between boundary. In other words, in order to choose a frequency block nearer to the boundary, the algorithm is willing to expend more resources to arrange a connection request. Hence, the blocking probability of the Tradeoff-RnI algorithm is significantly lower than that of the Block-Assignment algorithm.

The Block-Assignment algorithm divides frequency slices into multilevel-nested standard frequency blocks with size 1, 2, 4, 8, etc. The measure can make occupied frequency slices more aligned. However, the standard frequency blocks with different sizes are nested with each other. The use of a standard frequency block would affect higher level blocks who cover it. Hence, the effect of the measure is affected.

The proposed RPA-based RMSA algorithm also divides frequency slices into standard frequency blocks. The difference is that, the standard frequency blocks are independent with each other. In means that, the use of a standard frequency block would not affect the states of other standard frequency blocks. Additionally, the enhanced-most-used policy is used to find available standard frequency blocks for connection requests, which can make the occupied and idle standard frequency blocks more aligned. Hence, the proposed algorithm can get a lower blocking probability than the comparison algorithms.

V. CONCLUSION

In this article, we proposed a resource-periodic-arrangement (RPA) strategy for RMSA problem in elastic optical networks and further designed an RPA-based RMSA algorithm. The RPA strategy divides frequency slices into standard frequency blocks with size 1, 2 and 4, and periodically arranges them as a pattern 24122441. For a connection request needing any number of frequency slices, we can find an adaptive standard frequency block combination from the pattern. Additionally, in the proposed RPA-based RMSA algorithm, when several standard frequency blocks are available for a connection request, an enhanced-most-used (EMU) policy is used to choose the one whose corresponding counterparts in other links of the network are most used. Both the RPA strategy and the EMU policy can make the occupied and idle resources more aligned. Simulation results show that the proposed algorithm has a lower blocking probability than three existing algorithms.

REFERENCES

[1] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, "Spectrum-efficient and scalable elastic optical path network: Architecture, benefits, and enabling technologies," *IEEE Commun. Mag.*, vol. 47, no. 11, pp. 66–73, Nov. 2009.

[2] O. Gerstel, M. Jinno, A. Lord, and S. J. Yoo, "Elastic optical networking: A new dawn for the optical layer?" *IEEE Commun. Mag.*, vol. 50, no. 2, pp. s12–s20, Feb. 2012.

[3] S. Talebi, F. Alam, I. Katib, M. Khamis, R. Salama, and G. N. Rouskas, "Spectrum management techniques for elastic optical networks: A survey," *Opt. Switching Netw.*, vol. 13, pp. 34–48, Jul. 2014.

[4] M. Jinno, B. Kozicki, H. Takara, A. Watanabe, Y. Sone, T. Tanaka, and A. Hirano, "Distance-adaptive spectrum resource allocation in spectrum-sliced elastic optical path network [topics in optical communications]," *IEEE Commun. Mag.*, vol. 48, no. 8, pp. 138–145, Aug. 2010.

[5] B. Kozicki, H. Takara, Y. Sone, A. Watanabe, and M. Jinno, "Distance-adaptive spectrum allocation in elastic optical path network (SLICE) with bit per symbol adjustment," in *Proc. Opt. Fiber Commun. Conf. (OFC/NFOEC), Collocated Nat. Fiber Opt. Eng.*, San Diego, CA, USA, 2010, pp. 1–3.

[6] J. Yuan, R. Zhu, Y. Zhao, Q. Zhang, X. Li, D. Zhang, and A. Samuel, "A spectrum assignment algorithm in elastic optical network with minimum sum of weighted resource reductions in all associated paths," *J. Lightw. Technol.*, vol. 37, no. 21, pp. 5583–5592, Nov. 1, 2019.

[7] J. Yuan, D. Zhang, Q. Zhang, X. Li, and Z. Ren, "A routing and spectrum assignment algorithm in elastic optical network based on minimizing contiguity reduction," *Photonic Netw. Commun.*, vol. 38, no. 1, pp. 51–61, Aug. 2019.

[8] F. S. Abkenar and A. G. Rahbar, "Study and analysis of routing and spectrum allocation (RSA) and routing, modulation and spectrum allocation (RMSA) algorithms in elastic optical networks (EONs)," *Opt. Switching Netw.*, vol. 23, pp. 5–39, Jan. 2017.

[9] A. Rosa, C. Cavdar, S. Carvalho, J. Costa, and L. Wosinska, "Spectrum allocation policy modeling for elastic optical networks," in *Proc. High Capacity Opt. Netw. Emerg./Enabling Technol.*, Dec. 2012, pp. 242–246.

[10] R. Wang and B. Mukherjee, "Spectrum management in heterogeneous bandwidth optical networks," *Opt. Switching Netw.*, vol. 11, pp. 83–91, Jan. 2014.

[11] B. C. Chatterjee, S. Ba, and E. Oki, "Fragmentation problems and management approaches in elastic optical networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 183–210, 1st Quart., 2018.

[12] W. Fadini and E. Oki, "A subcarrier-slot partition scheme for wavelength assignment in elastic optical networks," in *Proc. IEEE 15th Int. Conf. High Perform. Switching Routing (HPSR)*, Jul. 2014, pp. 7–12.

[13] B. C. Chatterjee, N. Sarma, and E. Oki, "Routing and spectrum allocation in elastic optical networks: A tutorial," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 3, pp. 1776–1800, 3rd Quart., 2015.

[14] T. Fukuda, L. Liu, K.-I. Baba, S. Shimojo, and S. J. B. Yoo, "Fragmentation-aware spectrum assignment for elastic optical networks with fully-distributed GMPLS," in *Proc. Opt. Fiber Commun. Conf.*, Los Angeles, CA, USA, Mar. 2015, pp. 1–3.

[15] J. Yuan, Z. Ren, R. Zhu, Q. Zhang, X. Li, and Y. Fu, "A RMSA algorithm for elastic optical network with a tradeoff between consumed resources and distance to boundary," *Opt. Fiber Technol.*, vol. 46, pp. 238–247, Dec. 2018.

[16] Z. Zhu, W. Lu, L. Zhang, and N. Ansari, "Dynamic service provisioning in elastic optical networks with hybrid single-/multi-path routing," *J. Lightw. Technol.*, vol. 31, no. 1, pp. 15–22, Jan. 1, 2013.

[17] H. Yang, J. Zhang, Y. Zhao, S. Wang, W. Gu, J. Han, Y. Lin, and Y. Lee, "Multi-flow virtual concatenation triggered by path cascading degree in flexi-grid optical networks," *Opt. Fiber Technol.*, vol. 19, no. 6, pp. 604–613, Dec. 2013.

[18] R. Muñoz, R. Vilalta, M. S. Moreolo, J. M. Fábrega, R. Casellas, F. J. Vílchez, R. Martínez, S. Frigerio, and A. Lometti, "Dynamic differential delay aware RMSA for elastic multi-path provisioning in GMPLS flexi-grid DWDM networks," in *Proc. Opt. Fiber Commun. Conf.*, San Francisco, CA, USA, 2014, pp. 1–3.

[19] L. Altarawneh and S. Taebi, "Bandwidth granularity adaptation for multipath provisioning in elastic optical OFDM-based networks," in *Proc. IEEE Int. Conf. Electro/Inf. Technol. (EIT)*, Dekalb, IL, USA, May 2015, pp. 236–240.

[20] X. Wang, G. Shen, Z. Zhu, and X. Fu, "Benefits of sub-band virtual concatenation for enhancing availability of elastic optical networks," *J. Lightw. Technol.*, vol. 34, no. 4, pp. 1098–1110, Feb. 15, 2016.

[21] R. Zhu, Y. Zhao, H. Yang, X. Yu, J. Zhang, A. Yousefpour, N. Wang, and J. P. Jue, "Dynamic time and spectrum fragmentation-aware service provisioning in elastic optical networks with multi-path routing," *Opt. Fiber Technol.*, vol. 32, pp. 13–22, Dec. 2016.

[22] Z. Zhang, S. Yin, S. Guo, Z. Lin, Y. Chen, and S. Huang, "Dynamic buffering cost-saving multi-path routing under differential delay constraint in EONs," in *Proc. Asia Commun. Photon. Conf. (ACP)*, Hangzhou, China, Oct. 2018, pp. 1–3.

[23] J. Yuan, Z. Xu, R. Zhu, Q. Zhang, X. Li, and J. Zhang, "A pre-split multi-flow RMSA algorithm in elastic optical networks," *Opt. Fiber Technol.*, vol. 52, Nov. 2019, Art. no. 101993.

[24] L. R. Costa, G. N. Ramos, and A. C. Drummond, "Leveraging adaptive modulation with multi-hop routing in elastic optical networks," *Comput. Netw.*, vol. 105, pp. 124–137, Aug. 2016.

[25] L. R. Costa and A. C. Drummond, "New distance-adaptive modulation scheme for elastic optical networks," *IEEE Commun. Lett.*, vol. 21, no. 2, pp. 282–285, Feb. 2017.

[26] C. Garrido, A. Leiva, and A. Beghelli, "A RMLSA algorithm with modulation format conversion at intermediate nodes," in *Proc. 19th Int. Conf. Transparent Opt. Netw. (ICTON)*, Jul. 2017, pp. 1–4.

[27] M. Feng, R. Jiang, and J. Shen, "A segmentation modulation based spectral allocation scheme for elastic optical networks," in *Proc. 16th Int. Conf. Opt. Commun. Netw. (ICOCN)*, Aug. 2017, pp. 1–3.

[28] B. H. Ramaprasad, T. Schondienst, and V. M. Vokkarane, "Dynamic continuous and non-continuous advance reservation in SLICE networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Sydney, NSW, Australia, Jun. 2014, pp. 3319–3324.

[29] W. Lu, S. Ma, C. Chen, X. Chen, and Z. Zhu, "Implementation and demonstration of revenue-driven provisioning for advance reservation requests in OpenFlow-controlled SD-EONs," *IEEE Commun. Lett.*, vol. 18, no. 10, pp. 1727–1730, Oct. 2014.

[30] H. Chen, Y. Zhao, J. Zhang, R. He, W. Wang, J. Wu, Y. Wang, Y. Ji, H. Zheng, Y. Lin, and B. Hou, "Time-spectrum consecutiveness based scheduling with advance reservation in elastic optical networks," *IEEE Commun. Lett.*, vol. 19, no. 1, pp. 70–73, Jan. 2015.

[31] N. Wang, J. P. Jue, X. Wang, Q. Zhang, H. C. Cankaya, and M. Sekiya, "Holding-time-aware scheduling for immediate and advance reservation in elastic optical networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, London, U.K., Jun. 2015, pp. 5180–5185.

[32] W. Lu, Z. Zhu, and B. Mukherjee, "On hybrid IR and AR service provisioning in elastic optical networks," *J. Lightw. Technol.*, vol. 33, no. 22, pp. 4659–4670, Nov. 15, 2015.

[33] 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. Int. Conf. Photon. Switching (PS)*, Florence, Italy, Sep. 2015, pp. 178–180.

[34] P. Afsharlar, A. Deylamsalehi, J. M. Plante, J. Zhao, and V. M. Vokkarane, "Routing and spectrum assignment with delayed allocation in elastic optical networks," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 9, no. 3, pp. B101–B111, Mar. 2017.

[35] W. Wang, Y. Zhao, H. Chen, J. Zhang, H. Zheng, Y. Lin, and Y. Lee, "Re-provisioning of advance reservation applications in elastic optical networks," *IEEE Access*, vol. 5, pp. 10959–10967, 2017.

[36] X. Li, J. Yuan, Q. Zhang, Z. Ren, and L. Yang, "Farsighted spectrum resource assignment method for advance reservation requests in elastic optical networks," *IEEE Access*, vol. 7, pp. 167836–167846, 2019.

[37] R. Zhu, S. Li, P. Wang, and J. Yuan, "Time and spectrum fragmentation-aware virtual optical network embedding in elastic optical networks," *Opt. Fiber Technol.*, vol. 54, Jan. 2020, Art. no. 102117.

[38] P. M. Moura, N. L. S. da Fonseca, and R. A. Scaraficci, "Traffic grooming of batches of deadline-driven requests in elastic optical networks," in *Proc. IEEE Global Commun. Conf.*, Austin, TX, USA, Dec. 2014, pp. 1284–1289.

[39] W. Lu, Z. Zhu, and B. Mukherjee, "Optimizing deadline-driven bulk-data transfer to revitalize spectrum fragments in EONs [invited]," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 7, no. 12, pp. B173–B183, Dec. 2015.

[40] W. Kmiecik and K. Walkowiak, "Dynamic overlay multicasting for deadline-driven requests provisioning in elastic optical networks," in *Proc. 20th Conf. Innov. Clouds, Internet Netw. (ICIN)*, Paris, France, Mar. 2017, pp. 31–35.

[41] W. Lu and Z. Zhu, "IR/AR/MR service provisioning in elastic optical networks," in *Proc. 15th Int. Conf. Opt. Commun. Netw. (ICOCN)*, Sep. 2016, pp. 1–3.

[42] W. Lu, L. Liang, and Z. Zhu, "On vNF-SC deployment and task scheduling for bulk-data transfers in inter-DC EONs," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, Qingdao, China, Oct. 2017, pp. 1–4.

[43] H. Chen, Y. Zhao, J. Zhang, W. Wang, and R. Zhu, "Static routing and spectrum assignment for deadline-driven bulk-data transfer in elastic optical networks," *IEEE Access*, vol. 5, pp. 13645–13653, 2017.

[44] R. Zhu, S. Li, P. Wang, Y. Tan, and J. Yuan, "Gradual migration of co-existing fixed/flexible optical networks for cloud-fog computing," *IEEE Access*, vol. 8, pp. 50637–50647, 2020.

[45] X. Li, J. Yuan, Z. Ren, Q. Zhang, and L. Yang, "RMSA algorithm for malleable-reservation requests in elastic optical networks," *Opt. Fiber Technol.*, vol. 57, Jul. 2020, Art. no. 102236.

[46] B. Li, W. Lu, S. Liu, and Z. Zhu, "Deep-learning-assisted network orchestration for on-demand and cost-effective VNF service chaining in inter-DC elastic optical networks," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 10, no. 10, pp. D29–D41, Oct. 2018.

[47] X. Chen, J. Guo, Z. Zhu, R. Proietti, A. Castro, and S. J. B. Yoo, "Deep-RMSA: A Deep-Reinforcement-Learning routing, modulation and spectrum assignment agent for elastic optical networks," in *Proc. Opt. Fiber Commun. Conf.*, San Diego, CA, USA, 2018, pp. 1–3.

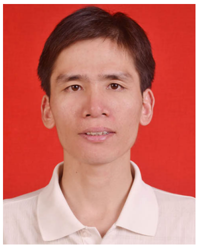
[48] Q. Yao, H. Yang, A. Yu, and J. Zhang, "Transductive transfer learning-based spectrum optimization for resource reservation in seven-core elastic optical networks," *J. Lightw. Technol.*, vol. 37, no. 16, pp. 4164–4172, Aug. 15, 2019.

[49] J. Yu, B. Cheng, C. Hang, Y. Hu, S. Liu, Y. Wang, and J. Shen, "A deep learning based RSA strategy for elastic optical networks," in *Proc. 18th Int. Conf. Opt. Commun. Netw. (ICOCN)*, Huangshan, China. Aug. 2019, pp. 1–3.

[50] X. Chen, B. Li, R. Proietti, H. Lu, Z. Zhu, and S. J. B. Yoo, "DeepRMSA: A deep reinforcement learning framework for routing, modulation and spectrum assignment in elastic optical networks," *J. Lightw. Technol.*, vol. 37, no. 16, pp. 4155–4163, Aug. 15, 2019.
[51] M. Salani, C. Rottondi, and M. Tornatore, "Routing and spectrum assignment integrating Machine-Learning-Based QoT estimation in elastic optical networks," in *Proc. IEEE INFOCOM-IEEE Conf. Comput. Commun.*, Paris, France, Apr. 2019, pp. 1738–1746.
[52] R. Zhu, S. Li, P. Wang, L. Li, A. Samuel, and Y. Zhao, "Deep reinforced energy efficient traffic grooming in fog-cloud elastic optical networks," in *Proc. Opt. Fiber Commun. Conf. (OFC)*, San Diego, CA, USA, 2020, pp. 1–3.
[53] X. Zhou, W. Lu, L. Gong, and Z. Zhu, "Dynamic RMSA in elastic optical networks with an adaptive genetic algorithm," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Anaheim, CA, USA, Dec. 2012, pp. 2912–2917.
[54] Y. Yin, M. Zhang, Z. Zhu, and S. J. B. Yoo, "Fragmentation-aware routing, modulation and spectrum assignment algorithms in elastic optical networks," in *Proc. Opt. Fiber Commun. Conf./Nat. Fiber Optic Eng. Conf.*, Anaheim, CA, USA, 2013, pp. 1–3.

SHURU LIU received the M.S. degree from Hangzhou Dianzi University, Hangzhou, China, in 2005. He is currently a Lecturer with the School of Computer and Telecommunication Engineering, Zhengzhou University of Light Industry, Zhengzhou, China. His research interests include routing and spectrum assignment technologies in elastic optical networks.

QIANG GUO received the Master of Military Science degree from the Air Defense Forces Command Academy of PLA, Zhengzhou, China, in 2010. His research interests include mathematical modeling and reliability data analysis.



JUNLING YUAN received the M.S. degree from Zhengzhou University, Zhengzhou, China, in 2008, and the Ph.D. degree from the University of Science and Technology Beijing, Beijing, China, in 2013. He is currently an Associate Professor with the School of Computer and Telecommunication Engineering, Zhengzhou University of Light Industry, Zhengzhou. His research interests include routing and switching technologies of all-optical networks.

QIKUN ZHANG received the Bachelor of Engineering degree from Xidian University, in 2004, the Master of Engineering degree from the Lanzhou University of Technology, in 2008, and the Doctor of Engineering degree from the Beijing Institute of Technology, in 2013. His research interests include information security and cryptography.