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A Single–Multi-Path Combinatorial RMSA Algorithm with Least Resource Consumption in Semi-Filterless Optical Networks

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Abstract: Filterless optical networks (FONs) have become a cost-effective solution for optical network deployment due to their low-cost characteristics. However, eliminating active switching elements causes signals to propagate over unintended links, wasting spectral resources. Therefore, semi-filterless optical networks (Semi-FONs) have become a more cost-effective solution. This paper mainly studies the routing, modulation, and spectrum assignment (RMSA) problem in semi-filterless optical networks. It proposes a single–multi-path combination (LR-SMPC) RMSA algorithm with the least resource consumption. The algorithm first obtains the K shortest paths that satisfy the conditions according to the K short path (KSP) algorithm and re-orders the paths according to the resource consumption path re-ordering strategy, selecting the three paths that consume the least resources as the set of candidate paths. Then, based on the single–multi-path combination scheme of the set of candidate paths, the resource consumption of each scheme and the maximum number of available spectrum blocks for each path is calculated, from which the single path or multi-path with the least resource consumption is selected to serve the request. We perform simulation experiments on two network topologies using Poisson traffic models and compare them with existing single-path algorithms (S-P), fixed spectrum assignment granularity algorithms ($g = 1$), and adaptation spectrum assignment algorithms (g adaptation) to evaluate the performance of the proposed algorithm. The simulation results show that the proposed algorithm exhibits better performance in terms of both blocking rate and spectrum utilization.

Keywords: semi-filterless; optical networks; single–multi-path; routing and spectrum assignment



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1. Introduction

Network operators face a severe challenge with the increasing broadband access networks and the rapid growth in global business volumes. They must cope with the growing network traffic by maintaining a moderately stable income [1]. Compared with traditional wavelength division multiplexing (WDM) networks, networks based on optical orthogonal frequency division multiplexing (O-OFDM) technology have significant differences. In a WDM network, the channel can only use a fixed wavelength, while O-OFDM technology can achieve a more flexible spectrum assignment by using the technology to split the network into multiple spectrum segments, where each connection request can use a number of the split spectrum segments [2,3]. Therefore, O-OFDM technology enables the network to adapt to growing demands and better cope with the increasing surge in network traffic.

Elastic optical networks (EONs) are an emerging network architecture whose flexibility makes it ideal for meeting the growing traffic demands. EONs can provide higher bandwidth efficiency and flexibility by flexibly assigning spectrum resources through O-OFDM technology [4]. Compared with elastic optical networks, filterless optical networks (FONs) have become a more cost-effective solution in optical networks due to their low

cost and low energy consumption [5]. In FON, passive splitters and combiners are used instead of expensive wavelength selective switches (WSSs), thus reducing the cost of the network [6,7]. In addition, the FON also has to divide the network into a set of optical fiber trees, and the division of these optical fiber trees must not contain closed loops to prevent the problem of laser loops due to the broadcasting and amplification of the signals [8].

Eliminating WSS causes the signal to be broadcast on all output ports, causing the optical signal to travel over unexpected links, which wastes more resources than an active network [9]. Therefore, saving FON equipment costs will lead to severe disadvantages, such as higher wavelength and spectrum utilization, while removing active equipment will also reduce signal quality [10]. In order to alleviate these problems, semi-filterless optical networks (Semi-FONs) are proposed as an improved solution for FONs. In semi-filterless optical networks, the broadcast characteristics of FONs are limited by equipping filters at selected nodes, thus reducing the waste of spectral resources. In addition, the placement of filters also allows different fiber trees to communicate through the filter nodes. Therefore, as an improvement to FONs, semi-filterless optical networks have significant advantages [11,12].

As traffic demand in the network continues to grow, semi-filterless optical networks may find it difficult to satisfy changing service requests through single-path routing, which may result in increased network congestion and blocking [13]. To ensure that the network can efficiently handle a large number of service requests, we need to adopt more flexible routing strategies. Therefore, a spectral approach, i.e., multi-path approach, has emerged, in which a service can be split into multiple sub-flows and transmitted over a discontinuous spectrum [14]. To achieve split flow, additional optics and signal processing modules need to be introduced to support the splitting and reorganization of traffic [15]. This increases equipment cost and deployment complexity and requires more sophisticated control and management algorithms. In addition, the splitting technique requires more guard bands. As service traffic is split into multiple sub-streams and assigned to different paths for transmission, each sub-flow needs to occupy a certain amount of guard band. Therefore, split flow techniques face the challenge of increased hardware and software complexity and the need for more guard bands. Nevertheless, we can still utilize parallel transmission of multiple paths to improve the transmission efficiency of the network and reduce the blocking rate. Therefore, in this paper, by using the O-OFDM technique's elasticity characteristics, the service traffic is split into multiple sub-flows, and they are assigned to different transmission paths to improve the overall network performance.

This paper proposes a single–multi-path combination (LR-SMPC) RMSA algorithm with the least resource consumption. The algorithm first obtains the K shortest paths that satisfy the conditions based on the K short path (KSP) algorithm [16] and re-orders the paths according to the resource-consuming path re-ordering strategy, selecting the three paths with the least resource consumption as the candidate path set. Then, it fully considers the resource consumption of all single–multi-path combination strategies, selects the path with the least resource consumption, and performs spectrum allocation. The simulation results show that the LR-SMPC algorithm exhibits better performance in terms of blocking rate and spectrum utilization compared with the use of the traditional single-path algorithm (S-P), the fixed spectrum assignment granularity algorithm ($g = 1$), and the adaptation spectrum assignment algorithm (g adaptation).

The remainder of this paper is organized as follows: The Section 2 summarizes the studies on filterless optical networks, semi-filterless optical networks, and multi-path spectrum assignment algorithms. In the Section 3, the proposed LR-SMPC algorithm is introduced. In the Section 4, the network model of this paper is first given, and then, the performance of the proposed algorithm is verified using simulation experiments. In the Section 5, a brief discussion is provided. In the Section 6, a short conclusion is provided.

2. Existing Studies

FONs reduce network costs by eliminating or reducing active switching elements and replacing them with passive components [17]. The semi-filterless optical network not only has significant advantages in the cost of the network but also improves the performance and reliability of the network. In order to reduce the blocking rate of the semi-filterless optical network, an elastic routing method using O-OFDM is adopted so that the service traffic can be split over multiple, thus improving the performance of the network. Therefore, the study of multi-path routing has attracted academic attention. By developing new routing algorithms and optimization strategies, it can further efficiently utilize the spectrum resources and reduce the blocking rate of the network.

FON has become the preferred solution to reduce the cost of networks, and researchers have conducted extensive studies on various aspects of FON. In 2007, C. Tremblay et al. first proposed the concept of FON [18]. In 2012, FON was deployed for the first time in Europe [19], which marked a new stage of commercialization of FON. With the widespread promotion and application of FON, people's demand for its performance and benefits is becoming increasingly urgent, further promoting the innovation and development of FON technology. In 2015, the RSA problem in elastic filterless networks was formally introduced [20], which was an introduction that once again demonstrated the significant bandwidth-saving advantages of elastic filterless networks over fixed-grid filterless solutions. In 2016, some scholars began to generate extensive research interest in FON, and an important early research study outlining FON's development marked the field's beginning [1]. In 2020, O. Ayoub et al. compared the cost issues of FON and wavelength-switched optical networks (WSONs) based on active equipment and showed that the FON is less expensive than WSON [8].

Despite extensive research on FONs, it suffers from wavelength reuse constraints and broadcast limitations, which makes semi-filterless optical networks seem more promising. In 2011, S. Khanmohamadi et al. proposed the concept of semi-filterless optical networks. They showed the advantages of semi-filterless optical networks in terms of cost and wavelength utilization through network topology [11]. In 2018, O. Ayoub et al. evaluated the network cost and spectrum utilization of filterless and semi-filterless optical networks. The simulation results showed that the semi-filterless optical network reduces the waste of broadcast spectrum by being equipped with filters [12].

In 2013, W. Lu et al. proposed a dynamic multi-path algorithm for elastic optical networks based on O-OFDM, which splits the traffic over multiple different paths, and the simulation results showed that the fixed bandwidth assignment granularity has a lower blocking rate compared to the single-path algorithm [13]. In the same year, Z. Zhu et al. proposed an online service algorithm that combines dynamic routing and hybrid single/multi-path routing (HSMR) schemes [21]. The algorithm is mainly based on two schemes: one is to calculate HSMR using online paths, and the other is to calculate HSMR using a fixed set of paths. The experimental results showed that by combining dynamic RMSA and HSMR schemes, the network can better adapt to real-time service requirements and provide more reliable and efficient online services.

In 2015, L. Altarawneh et al. conducted a study to investigate the impact of spectral fragmentation on the efficiency of elastic optical networks in single/multiple routing transmissions. They proposed the concept of "minimum bandwidth assignment granularity adaptation", which is intended to replace the traditional fixed minimum bandwidth assignment granularity approach. The algorithm reduces the effect of spectrum fragmentation by dynamically updating the minimum bandwidth assignment granularity. The results showed that the algorithm with dynamically updated minimum bandwidth granularity has significant advantages in reducing the blocking rate compared to the algorithm using fixed minimum bandwidth assignment granularity [22].

In 2018, Z. Zhang et al. conducted an in-depth study on the buffering cost and proposed a dynamic buffering cost-saving multi-path routing algorithm based on differential delay constraints. This algorithm aims to effectively reduce buffering costs by optimizing

routing in the network. By introducing a multi-path routing algorithm that dynamically saves buffering costs, the network can use available paths more efficiently and reduce buffering costs and delays [23].

In 2020, A. Alyatama et al. proposed an adaptive multi-path routing and spectrum assignment algorithm based on the relative cost in elastic optical networks. This algorithm aims to select the single path or multi-path with the smallest relative cost to serve requests [24]. The calculation method of relative cost includes single-link relative cost and path relative cost. The relative cost of a single link and the relative cost of a path represents the additional cost of occupying a certain amount of continuous spectrum on a link or a path, respectively. The relative cost calculation method involves link failure income, call reward, discount rate, and other factors. The experimental results show that the proposed algorithm significantly improves the network gain loss compared to the original multi-path algorithm, which shows that the proposed algorithm has achieved remarkable results in optimizing path selection and spectrum assignment.

As global service volumes continue to increase, FONs may have difficulty coping with high traffic loads due to their broadcast characteristics [25]. Thus, semi-filterless optical networks may become an effective solution. In addition, it is difficult for a single path to satisfy dynamic service requests under high service volumes, which leads to a high blocking rate. Therefore, in this paper, we propose an LR-SMPC algorithm. The algorithm is divided into two parts: the consideration of resource-consuming path re-ordering strategies and the consideration of resource-consuming single–multi-path combination scheme selection. When considering the resource consumption path re-ordering strategy, we fully consider the resource consumption of the K shortest paths, while the resource usage of each scheme in the combined single–multi-path and the maximum number of available spectrum blocks on each path are fully considered in the path scheme selection. In addition, we will use the single-path algorithm (S-P), the fixed spectrum assignment granularity algorithm ($g = 1$), and the adaptive spectrum assignment algorithm (g adaptation) as comparison algorithms to evaluate the performance of the proposed algorithms.

3. The Proposed LR-SMPC Algorithm

This section details the proposed LR-SMPC algorithm, which aims to optimize the routing algorithm by considering the spectrum resource consumption and the maximum available spectrum blocks. This section is organized as follows: first, we introduce the path re-ordering strategy considering resource consumption; then, we introduce the LR-SMPC algorithm and illustrate the performance of the algorithm with examples; finally, we present the flow of the algorithm and the time complexity of the algorithm.

3.1. Considering Resource Consumption Path Re-Ordering Strategy

Semi-filterless optical networks are a compromise between filterless and active optical networks. Equipping filters on selected nodes limits the network's broadcast characteristics and reduces the network's cost and the occupation of spectrum resources. In addition, the placement of the filters also enables nodes that belong to different fiber trees and cannot communicate with each other to communicate with each other through the filter nodes. However, due to the limited number of placed filters in semi-filterless optical networks, signals are transmitted over unintended links, thus wasting spectral resources. To reduce this waste, we can control the number of links and try to transmit signals on fewer links. At the same time, we hope that the signal will be transmitted over a shorter path and that a higher modulation level will be selected to reduce the number of spectrum slots required and to reserve more resources for new incoming services. Therefore, path-based resource consumption is mainly affected by the number of links, L (including broadcast links), and the number of spectrum slots, S , required by the path.

Based on two indicators, L and S , we propose a path re-ordering strategy that considers resource consumption. When the services arrive, first use the KSP algorithm to obtain K shortest paths, $Path_1, Path_2, \dots, Path_K$. For each path, $Path_i$, calculate the number of links,

L_i (including broadcast paths), and the number of consecutive spectrum slots, S_i , to be assigned. We define the product of the two metrics as the resource consumption, R_i , of the paths, as shown in Equation (3). For L_i , we need to determine the number of links required for each path based on the selected path. For S_i , firstly, calculate the path distance, d_i , and derive the modulation level, M_i , from d_i using Equation (1) (the per symbol bits under each modulation format are 1, 2, 3, 4, 5, and 6, corresponding to maximum transmission distances of 8000 km, 4000 km, 2000 km, 1000 km, 500 km, and 250 km, respectively, [26]), and from M_i , calculate S_i according to Equation (2). Therefore, for each path, $Path_i$, the resource consumption, R_i , is calculated from the metrics L_i and S_i using Equation (3).

$$M_i = mlul(d_i), \quad i = 1, 2, \dots, K \tag{1}$$

$$S_i = \lceil \frac{C}{B_{slice} \cdot M_i} \rceil + S_g, \quad i = 1, 2, \dots, K \tag{2}$$

$$R_i = L_i \cdot S_i, \quad i = 1, 2, \dots, K \tag{3}$$

In the above equations, i denotes the i -th path, a total of K paths; $mlul()$ denotes the highest modulation level supported by each path; $\lceil \cdot \rceil$ denotes rounding up; C denotes the requested capacity; B_{slice} denotes the bandwidth capacity of a spectrum slot; and S_g denotes the guard band.

Based on each path’s resource consumption, R_i , re-sort the K shortest paths, $Path_1, Path_2, \dots, Path_K$, according to the resource consumption from smallest to largest. We choose the top three paths for the sorted paths as the set of candidate paths for spectrum assignment.

For example, Figure 1 shows a network topology with eight nodes containing three fiber trees, where the blue represents $Tree_1$, the green represents $Tree_2$, and the red links 3–8 represent $Tree_3$; the red nodes are filter nodes, and the numbers on the lines represent the distances of the links. Consider an $LR(3, 8, 185Gb)$ that first finds K shortest paths according to the KSP algorithm, which is $Path_1: 3 \rightarrow 8$, $Path_2: 3 \rightarrow 2 \rightarrow 1 \rightarrow 8$, and $Path_3: 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7 \rightarrow 8$. Calculate resource consumption, R_i , for each path, $Path_i$: determine the number of links for each path: $L_1 = 1, L_2 = 3, L_3 = 5$. Each path needs to assign the number of continuous spectrum slots: $S_1 = 3 + 1 = 4, S_2 = 3 + 1 = 4$, and $S_3 = 4 + 1 = 5$ (with one of the guard bands); then, the resource consumption, R_i , is $R_1 = 1 \times 4 = 4, R_2 = 3 \times 4 = 12$, and $R_3 = 5 \times 5 = 25$. The K shortest paths are sorted as $Path_1 < Path_2 < Path_3$. For the sorted K paths, take out the top three as the set of candidate paths.

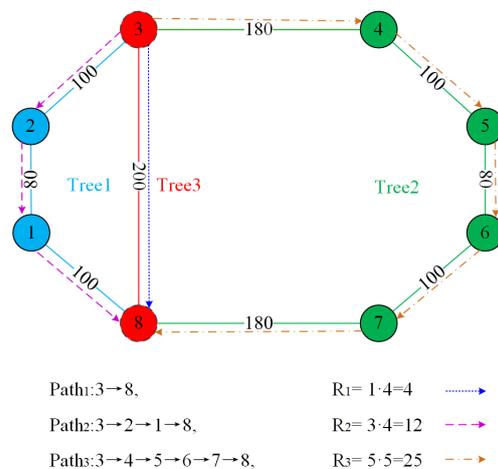


Figure 1. Example of path re-ordering for resource consumption.

Since the number of links that different paths may occupy and the number of spectrum slots required by the paths are different, the resource consumption of each path is different, so it is necessary to determine the final set of candidate paths. First, we can calculate

the K shortest paths. Then, the K shortest paths are re-ordered according to the resource consumption of each path. This can ensure we choose paths with short path distances and the least resource consumption.

3.2. Consider Least Resource Consumption Algorithm

After re-ordering the K shortest paths, we obtain a candidate path set with three paths. For this candidate path set, we need to determine the final path according to the network status and the resource usage and provide services for the request. We consider a request, $LR(s,d,C)$ (where C denotes the capacity of the request). For single-path service requests, the capacity on each single path is C . We can use Equation (2) to calculate the number of continuous spectrum slots, S_i , assigned to each path. For multi-path service requests, the capacity split on each path is C_i ; the load that should be satisfied on each routing path is calculated according to the network status distribution, as shown in Equation (4); and the split capacity on each path should be equal to the total capacity requested. According to the split flow of each path, the number, S_i , of continuous spectrum slots assigned to each path is obtained, as shown in Equation (5).

$$C = \sum C_i \quad (4)$$

$$S_i = \lceil \frac{C_i}{B_{slice} \cdot M_i} \rceil + S_g \quad (5)$$

In the above equations, i denotes the i -th path; C_i denotes the bandwidth capacity required for the requested i -th path; $\lceil \cdot \rceil$ denotes rounding up; M_i denotes the modulation level selected for the i -th path; B_{slice} denotes the bandwidth capacity of a spectrum slot; and S_g denotes the guard band. In addition, guard bands are required for each split traffic when traffic splitting is performed. This study assumes that the guard band is inserted at the highest indexed position in the spectrum assignment for each connection.

Based on our proposed LR-SMPC algorithm, instead of only using a single path or multi-path to serve the request, or instead of just prioritizing a single path or multi-path, we fully consider a combination of single path and combinations of single path (multi-path) comprehensively, and each method does not have a time sequence. In addition, our algorithm does not use a fixed spectrum assignment granularity. However, it selects the maximum available spectrum granularity on the appropriate path (the minimum number of spectrum slots needed to be judged on the last path) and finally determines the paths and ways of spectrum assignment based on resource consumption. For example, when the set of candidate paths contains three paths, we first consider the dynamic combinations of each case (including a single path) and then calculate the resource consumption based on each combination using Equation (3). Regarding the calculation of the resource consumption, we distinguish between single-path and multi-path cases:

- Single-path resource consumption: Firstly, judge whether the path can provide service for the request and discard the path that cannot serve the request; secondly, for the path that can provide the request, calculate the number of links occupied by the path and the number of spectrum slots required; finally, combine Equation (3) and calculate the resource consumption of the path.
- Multi-path resource consumption: The combined resource consumption should be calculated from the first path for a candidate set with three paths. For the combination of the first path, it is first to judge whether a single path can satisfy the demand. If the requirements are met, we will not calculate any combination of the first and subsequent paths. Otherwise, judge the number of links, L , and the maximum number of available consecutive spectrum slots, S , on the first path; calculate the resource consumption, R_1 , of the first path by combining with Equation (3); and remove this spectrum slot from the first path available bandwidth (BW) to update the capacity, C . Then, judge whether the maximum available consecutive spectrum slots of the second path is greater than the number of spectrum slots to be assigned (whether capacity,

C, has been assigned or not), and if the condition is satisfied, judge the number of minimum required spectrum slots on the second path, and combine with Equation (3) to calculate the resource consumption R_2 for the second path, and update the combining strategy $R_{12} = R_1 + R_2$; if it is not satisfied, the judgment continues with combining the second and third paths and the first, second, and third paths. For any combination of the second and third paths, use the same traversal method as the first.

Based on the above two situations, the criterion for whether the request is completed is whether capacity C can be fully assigned. When C can be fully assigned, the scheme is feasible. If there is no feasible solution, the service is blocked. When multiple feasible schemes exist, we choose the scheme with the least resource consumption to assigned spectrum resources.

Figure 2 shows an example of the dynamic single–multi-path combination of resource consumption. The “Length” number on the line represents the distance of the link, and “Bandwidth” represents the number of continuous spectrum slots available for that path. Blue indicates $Tree_1$, green indicates $Tree_2$, red links 3–8 indicate $Tree_3$, and red nodes are filter nodes. Consider a request $LR(3,8,185\text{ Gb})$. From the first example, we obtain a candidate path set with three paths: $Path_1: 3 \rightarrow 8$, $Path_2: 3 \rightarrow 2 \rightarrow 1 \rightarrow 8$, and $Path_3: 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7 \rightarrow 8$. Firstly, calculate the resource consumption of the available single path. Since the maximum number of spectrum slots available for $Path_1$ and $Path_2$ is less than the number of spectrum slots required, they are not used; for $Path_3$, calculate the resource consumption, $R_3 = 5 \times (4 + 1) = 25$ (1 guard band). Secondly, calculate the multi-path resource consumption. For the combination scheme of the first path, $Path_1$, first judge $Path_1$ and $Path_2$. For $Path_1$, the maximum available continuous spectrum slot is $S_1 = 3$ (1 guard band), the spectrum slot is then removed from BW, and then $C = C - C_i = C - 12.5(S_1 - 1)M_1 = 185 - 12.526 = 35\text{ Gb}$; for $Path_2$, the number of continuous spectrum slots required by the remaining traffic, C, in $Path_2$ is $S_2 = 2$ (1 guard band), and its resource consumption $R_{12} = 1 \times (2 + 1) + 3 \times (1 + 1) = 9$. $Path_1$ and $Path_2$ are feasible schemes, so there is no need to calculate other combination schemes of $Path_1$. Similarly, for the combination scheme of the second path, $Path_2$, only the combination schemes of $Path_2$ and $Path_3$ need to be calculated, and its resource consumption $R_{23} = 3 \times (1 + 1) + 5 \times (3 + 1) = 26$. For the three feasible schemes, we finally choose the combination of $Path_1$ and $Path_2$ with the least resource consumption to serve the request, as shown in Figure 2b.

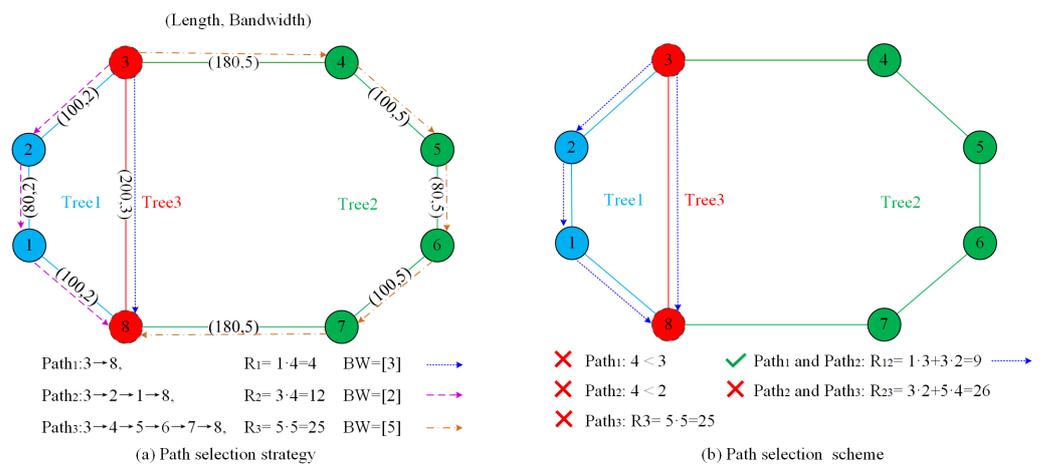


Figure 2. Example of 8-node dynamic single–multi-path combination.

3.3. LR-SMPC Algorithm

The LR-SMPC algorithm is shown in Algorithm 1. The LR-SMPC algorithm mainly considers the resource consumption of different path combinations and the maximum number of available spectrum blocks. The input parameters of the LR-SMPC algorithm

include network topology, $G(V, E, F, T)$, and request, $LR(s, d, C)$, where V represents the node set, E represents the fiber link set, F represents the number of frequency slots in each link, T represents the fiber tree set, s represents the source node, d represents the destination node, and C represents the requested capacity.

Algorithm 1: LR-SMPC algorithm

```

Input: Network topology,  $G(V, E, F, T)$ ; request,  $LR(s, d, C)$ .
Output: Request the generated spectrum assignment scheme (SAC).
1  Reset the collection (SAC), and update the spectrum for all link  $E$  in collection  $V$ .
2  while the network is operational do
3    For the source–destination pair ( $s, d$ ), use the  $K$  shortest paths algorithm to find  $K$  shortest paths,
       $Path_1, Path_2, \dots, Path_K$ .
4    for  $k = 1$  to  $K$  do
5      | Calculate the resource consumption,  $R_i$ , for  $Path_i$  using Equation (3).
6    end
7    Sort paths according to ascending order of resource consumption,  $R_i$ .
8    Select the first three as a candidate path set.
9    for  $i = 1$  to 3 do
10   | if  $S_i > S$  then
11   | | Calculate the resource consumption,  $R_i$ , for  $Path_i$  using Equation (3).
12   | | Add the scheme to the set  $RS$ .
13   | else
14   | | Abandon the single-path scheme.
15   | end
16   end
17   while the existence of actionable pathways do
18   | Determine  $Path_1$  the maximum number of spectrum blocks available,  $S_1$ .
19   |  $C = C - C_1$ .
20   | Remove available consecutive slots from the  $BW$ .
21   | if  $C > 0$  then
22   | | Determine  $Path_2$  the maximum number of spectrum blocks available,  $S_2$ .
23   | |  $C = C - C_2$ .
24   | | Remove available consecutive slots from the  $BW$ .
25   | end
26   | if  $C < 0$  then
27   | | Add the scheme to the set  $RS$  to restore the removed spectrum slots.
28   | | break.
29   | else
30   | | Continue to judge the combination of  $Path_1$  and other paths.
31   | end
32   end
33   while the existence of actionable pathways do
34   | Determine  $Path_2$  the maximum number of spectrum blocks available,  $S_2$ .
35   |  $C = C - C_2$ .
36   | Remove available consecutive slots from the  $BW$ .
37   | if  $C > 0$  then
38   | | Determine  $Path_3$  the maximum number of spectrum blocks available,  $S_3$ .
39   | |  $C = C - C_3$ .
40   | | Remove available consecutive slots from the  $BW$ .
41   | end
42   | if  $C < 0$  then
43   | | Add the scheme to the set  $RS$  to restore the removed spectrum slots.
44   | | break.
45   | end
46   end
47   if  $RS == None$  then
48   | Blocking business requests.
49   else
50   | Select the scheme with the least resource consumption and add it to the SAC for spectrum
      resource assignment.
51   end
52 end
53 return SAC
  
```

A detailed process of the algorithm is shown in the LR-SMPC algorithm. Line 1 resets the spectrum assignment scheme set (SAC), which is used to save the requested spectrum assignment scheme as the final output of the algorithm. At the same time, the spectrum of all links in the link set, E , of the network topology, G , usage is updated in real time. Lines 2–53 generate a spectrum assignment scheme for the request, LR . Line 2 enters the while loop until the network is inoperable. Lines 3–52 generate all executable policies for each request and determine the final path and spectrum assignment scheme. Line 3 uses the KSP algorithm to find K shortest paths ($Path_1, Path_2, \dots, Path_K$) that meet the requirements. Lines 4–6 calculate the resource consumption, R_i , of each path according to Equation (3). Line 7 sorts the K paths according to the resource consumption, R_i , and in line 8, we obtain a candidate path set with three paths, $Path_1, Path_2$, and $Path_3$, according to the resource consumption. Lines 9–16 judge whether the single-path scheme is feasible. If the maximum number of consecutive spectrum slots, S_i , available for the path, $Path_i$, is greater than the number of spectrum slots, S , required for the request, it is considered a feasible scheme. Add feasible schemes to the scheme set (RS); otherwise, discard the scheme. Lines 17–46 determine the feasibility of a multi-path combination scheme. Lines 17–32 judge whether the combination scheme of $Path_1$ is feasible, lines 33–46 judge whether the combination scheme of $Path_2$ is feasible, and add the feasible scheme to the set RS. Lines 47–51 are to judge whether a feasible scheme exists. If not, then block the service request; otherwise, select the scheme with the least resource consumption for spectrum assignment and add the spectrum assignment scheme to the SAC. Finally, the SAC is returned as the output of the algorithm.

3.4. Complexity Analysis

The time complexity of the LR-SMPC algorithm is analyzed below. Suppose the network topology is expressed as $G(V, E, F, T)$, where the number of nodes in the network is $|V|$, the number of links is $|E|$, the number of spectrum slots each link is $|F|$, and the number of fiber trees is $|T|$. In the LR-SMPC algorithm, line 1 is used to update the spectrum utilization of the link with a time complexity of $O(|E| \cdot |F|)$. The first level loop is the while loop from lines 2–52, which is executed $|D|$ times, representing the $|D|$ service requests that may arrive, and line 3 is the KSP algorithm, which has a time complexity of $O(K \cdot |D| \cdot (|E| + |V|) \cdot \log|V|)$. In the first level loop, the while loop contains four sub-loops: the first sub-loop is the for loop in lines 4–6, the second sub-loop is the for loop in lines 9–16, the third sub-loop is the while loop in lines 17–32, and the fourth sub-loop is the while loop in lines 33–46, which are executed $|D|$ times. The first for loop time complexity is $O(|D| \cdot K)$, the second for loop time complexity is $O(3 \cdot |D| \cdot |T| \cdot |E| \cdot |F|)$, the third while loop time complexity is $O(7 \cdot |D| \cdot |T| \cdot |E| \cdot |F|)$, and the fourth while loop time complexity is $O(2 \cdot |D| \cdot |T| \cdot |E| \cdot |F|)$. Therefore, the time complexity of the algorithm is not greater than $O(|D|(K(|E| + |V|) \cdot \log|V| + |T| \cdot |E| \cdot |F|))$.

4. Performance Simulations

In this section, we evaluate the performance of the proposed algorithm through simulation experiments and introduce the performance of the algorithm in terms of blocking rate, single–multi-path occupancy ratio, and spectrum utilization. This section is organized as follows: First, we briefly introduce the network topology and traffic model. Then, we show the simulation results and present the experimental results through the simulation results graphically and analyze the algorithm’s performance in different scenarios. Finally, we summarize the main results of the simulations.

4.1. Simulation Settings

To evaluate the performance of the algorithm, we perform simulations on German–Net and Henan–Net, as shown in Figure 3, where (a) shows the topology of the German network and (b) shows the topology of the Henan network. In these two network topologies, the red nodes represent the filter nodes and the same colors in the rest of the differently

colored nodes represent each fiber tree. At the same time, the numbers labeled on the lines in the figure indicate the corresponding link lengths (in kilometers). All the links are bi-directional, and the spectral resources are split into 320 frequency slices in each direction, with a granularity of 12.5 GHz. In all simulations, it is assumed that the selectable modulation formats include BPSK, QPSK, 8QAM, 16QAM, 32QAM, and 64QAM, with bits per symbol (M) of 1, 2, 3, 4, 5, and 6 for each modulation format, and maximum reachable distances of 8000 km, 4000 km, 2000 km, 1000 km, 500 km, and 250 km for the modulation formats, respectively, [26].

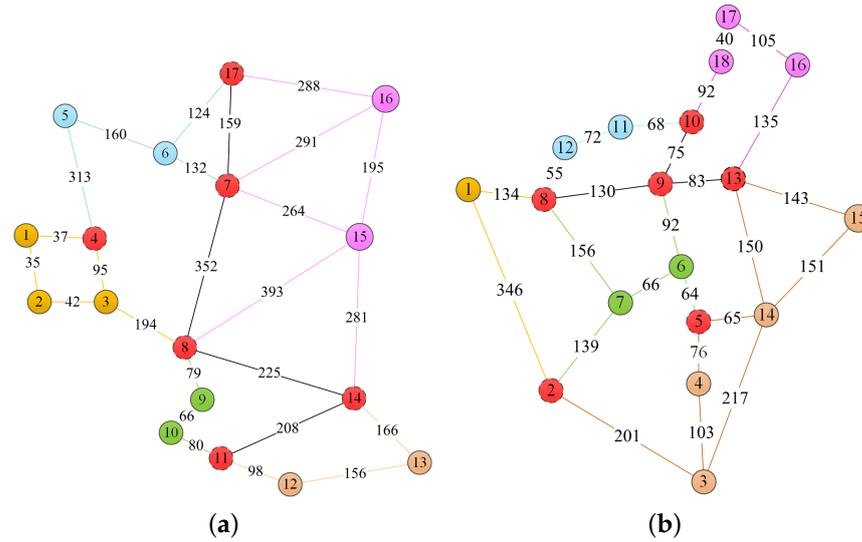


Figure 3. Network topologies. (a) German-Net. (b) Henan-Net.

In the simulation experiments, we adopt a dynamic traffic model in which the optical path requests arrive sequentially, the intervals between request arrivals obey a Poisson distribution with parameter $1/\lambda$, the request durations obey an exponential distribution with parameter u , and the traffic is randomly and uniformly distributed among all nodes. The network’s traffic load is defined as $u \cdot \lambda \cdot 5$ (in Erlang), and we fix the parameter, u , to be 100, and by changing the value of λ , we change the traffic load in the network. The required traffic for each destination node of the request ranges from 25 to 200 Gb. Suppose the required traffic for the request is simplified to the number of frequency slices required and given in BPSK modulation format. In this case, the frequency slices are all randomly generated from 2 to 16, with an average value of 10. For each source–destination node pair, pre-calculate K paths through the KSP algorithm, where K is not some certain value determined, but all the paths that satisfy the requirement are traversed according to the distance of the paths from small to large.

When conducting simulation experiments, we calculate the blocking rate of the network. The blocking rate is an important index to evaluate the performance of the proposed algorithm under different loads and network conditions [27]. The calculation of the blocking rate BP is shown in Equation (6):

$$BP = \frac{\sum T_{BR} \cdot C_{BR}}{\sum T_{LR} \cdot C_{LR}} \tag{6}$$

In the above equations, LR denotes a set of arriving connection requests; T_{LR} denotes the duration of the request, LR ; C_{LR} denotes the capacity of the request, LR ; BR denotes a blocking connection request; T_{BR} denotes the duration of the blocking request; and C_{BR} denotes a requested capacity of the blocking request.

4.2. Simulation Results

Each algorithm uses the same pseudo-random sequence to randomly generate ten sets of 100,000 unicast requests (generated by using 10 random seeds corresponding to a total of 1 million requests) for testing the performance of these algorithms. By simulating German-Net and Henan-Net, we obtained the simulation result graphs of blocking rate as a function of traffic load (Erlangs), as shown in Figure 4. Each plotted point in Figure 4 represents the average of 10 different runs, and the error bars indicate the 95% confidence intervals. The comparison algorithms use a single-path algorithm (S-P), a fixed spectrum assignment granularity algorithm ($g = 1$), and an adaptation spectrum assignment algorithm (g adaptation). The fixed spectrum assignment granularity algorithm ($g = 1$) is used when serving requests on multiple routing paths with a minimum spectrum slot size of g assigned on each path [21], while for the adaptive spectrum assignment algorithm (g adaptive), instead of using a fixed assignment granularity for all candidate multi-paths, each path has an updated spectrum assignment granularity based on fragmentation status and achieves granularity adaptive performance by adaptively changing the value of the spectrum assignment granularity [22].

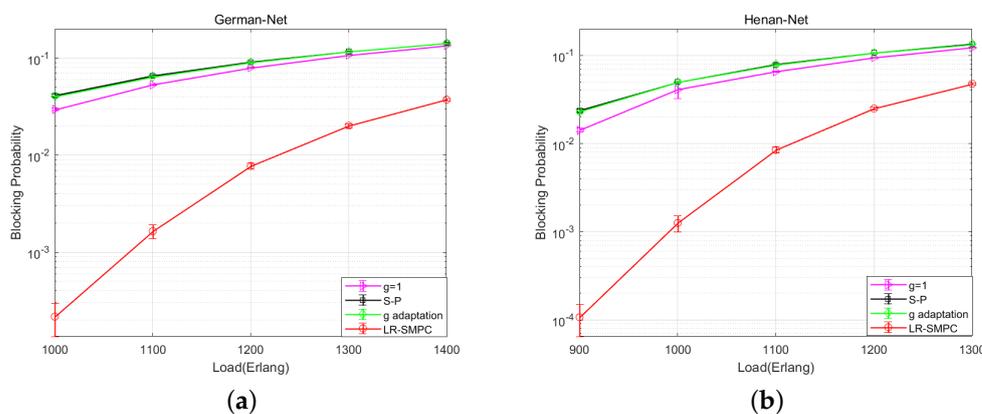


Figure 4. Blocking probability. (a) Blocking probability of German-Net. (b) Blocking probability of Henan-Net.

By observing the numerical results in Figure 4, it is clearly seen that our proposed algorithm has a lower blocking rate. Under low traffic load, spectrum resources are relatively abundant, and there may be a large number of unused spectrum resources. The supply of spectrum resources far exceeds the demand for connection requests, most of the services can be satisfied, and the blockage rate is low. With the traffic load gradually increasing, the state of spectrum resources becomes tense, and the blocking rate starts to rise. Therefore, the blocking rate shows a slow and then quickly increasing trend with the increase in traffic load. In particular, the blocking rate increases significantly when the German-Net and Henan-Net traffic loads reach 1300 Erlangs and 1200 Erlangs. This result can be attributed to decisions on path selection and spectrum assignment granularity. Regarding path selection, proper path selection can reduce unnecessary waste of spectrum resources. Furthermore, regarding the spectrum assignment granularity, smaller spectrum granularity may waste more spectrum resources as guard bands. In comparison, larger spectral granularity limits the range of choices for many spectral resources because they cannot meet the required spectral granularity requirements. However, the algorithm proposed in this paper selects the best available paths and spectrum assignment granularity by calculating the resource consumption of each scheme and the maximum number of available spectrum blocks for each path to ensure that more spectrum resources are assigned to the appropriate paths without wasting network resources. Therefore, the algorithm proposed in this paper can effectively utilize the network resources and reduce the blocking rate.

Figure 5 shows the distribution of the proposed algorithm’s paths. When the traffic load is lower than 1000 Erlangs, we observe that the single path accounted for 100% of the total. This is because, with lower traffic loads, the network links are less congested, the resource consumption of a single path is usually lower than that of multiple paths, and most connection requests can be satisfied by a single path. Therefore, the single path percentage is relatively high. However, as the traffic load increases, the links start to become congested, and the spectrum assignment algorithm has difficulty in finding a single path that satisfies the request, or the resource consumption of a single path is higher than that of a multi-path, which leads to an increase in the percentage of multi-path. Multi-path becomes an effective solution under high traffic load conditions because it reduces the load on a single path by dividing the traffic evenly across multi-path, thus improving the overall network connection success rate. Therefore, a single–multi-path combination becomes an effective solution to satisfy more connection requests and improve network performance. By using the single–multi-path combination scheme, traffic can be evenly distributed over multi-path, reducing the load on individual paths and improving the overall network connection success rate.

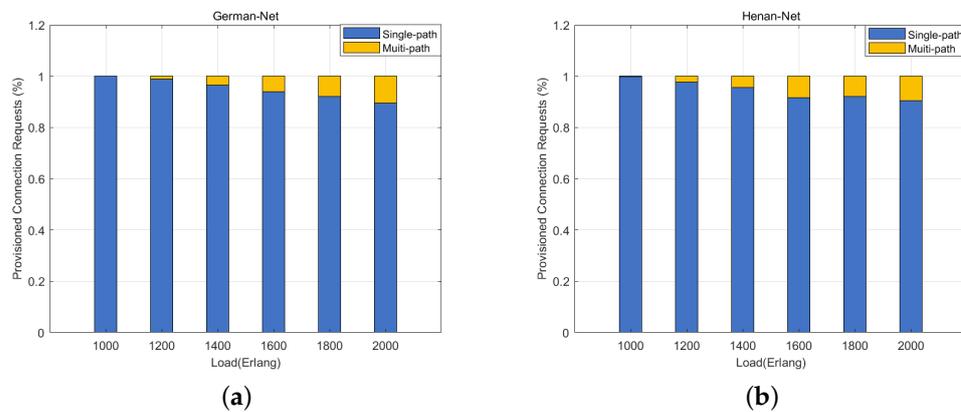


Figure 5. Path distribution for single and multi-path services. (a) Path distribution of German-Net single-path and multi-path services. (b) Path distribution of Henan-Net single-path and multi-path services.

Figure 6 shows the numerical results of the proposed algorithm and the comparison algorithm in terms of spectrum utilization. We can observe that in both networks, the spectrum utilization increases as the traffic load increases. This is caused by an increase in connection requests per unit of time. In addition, the proposed LR-SMPC algorithm exhibits lower spectrum utilization compared to the comparison algorithms under the same traffic load. This is because the LR-SMPC algorithm fully considers the resource consumption in determining the set of candidate paths and the selection of the path scheme, and gives priority to the path with the least resource consumption for the assignment of spectrum resources. The comparison algorithm only considers the shortest path problem and ignores the resource consumption. Such a path selection strategy can effectively save spectrum resources, thus obtaining a lower service blocking rate with lower spectrum utilization under the same traffic load. Therefore, our simulation results further demonstrate the effectiveness of the proposed algorithm, which can significantly reduce the waste of spectrum resources.

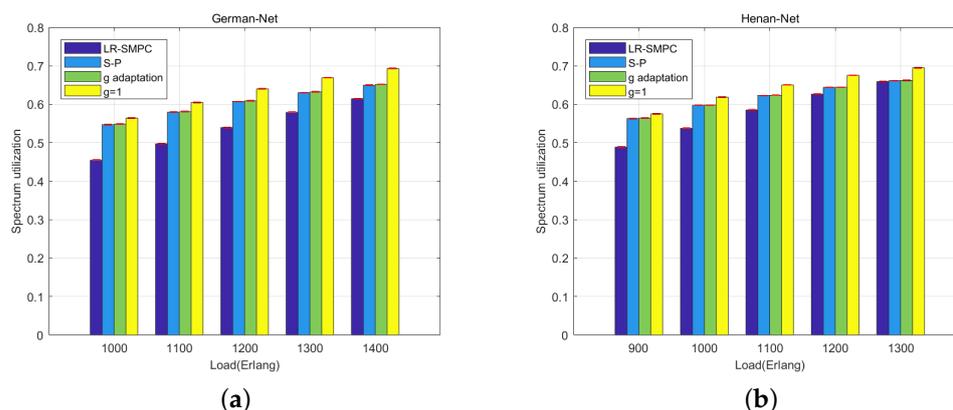


Figure 6. Spectrum utilization. (a) Spectrum utilization of German-Net. (b) Spectrum utilization of Henan-Net.

5. Discussion

We design a single-multi-path combinatorial RMSA algorithm with the least resource consumption: the LR-SMPC. Firstly, obtain K shortest paths for the arriving services by using the KSP algorithm, then calculate the resource consumption of the K shortest paths, re-order the paths based on the resource-consuming path re-ordering strategy, and select the three paths with the least amount of resource consumption as a candidate path set. When calculating the resource consumption of each path, we consider two main factors: the number of links, L (including broadcast links), that the path contains and the number of spectrum slots, S , that the path requires. We define the product of L and S as the resource consumption, R . Then, by calculating the resource consumption of the single-multi-path combination scheme of the set of candidate paths and the maximum number of available spectrum blocks for each path, the single path or multi-path that consumes the least resources is selected from them to serve the request. The study simulated two network topologies using the Poisson traffic model. It evaluated the performance of the proposed algorithm by comparing it with existing single-path algorithms, fixed spectrum assignment granularity algorithms, and adaptive spectrum assignment algorithms.

According to our results, the LR-SMPC algorithm performs better and can reduce the blocking rate. Due to the broadcasting characteristics of semi-filterless optical networks, calculating the number of resources becomes particularly important, which can effectively minimize the waste of resources and reserve more resources for upcoming services. However, our method still needs some improvement, such as determining the granularity of spectrum assignment. Optimizing the granularity of spectrum assignment makes fuller use of spectrum resources, which means that our algorithm still has room for improvement, and we will further consider this issue in future research. We will explore new methods and strategies to improve the efficiency and flexibility of spectrum assignment and reduce the network's blocking rate.

6. Conclusions

This paper studies the RMSA problem in semi-filterless optical networks and proposes an LR-SMPC algorithm. The algorithm first finds out the K shortest paths based on the KSP algorithm, then selects a candidate path set with three paths through the resource-consuming path re-ordering strategy, and, finally, determines the final spectrum assignment paths and schemes based on evaluating the resource consumption of different combinations of the three paths. The simulation results show that the algorithm proposed in this paper exhibits better performance in terms of both blocking rate and spectrum utilization compared to the comparison algorithms. In addition, as traffic increases, the proportion of multi-path also increases. Therefore, the algorithm proposed in this paper is an important step in

reducing the blocking rate of semi-filterless optical networks, which provides promising prospects for future network optimization and performance improvement.

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