Offline Routing and Spectrum Allocation Algorithms for Elastic Optical Networks with Survivability

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***Abstract*—Elastic optical networks (EONs) are a promising solution for future high-speed networks, because of their ability to efficiently manage network resources and provide better spectrum utilization. The intractable routing and spectrum allocation (RSA) problem and the eventually imposed survivability constraints play key roles in the effective design and control of EONs. In this work, we investigate priority allocation algorithms designed to solve the offline RSA problem in protection-based EONs. These algorithms are analyzed from the point of view of their main objective (minimizing the total amount of spectrum needed to serve the traffic demand), when the demand includes unicast unprotected and unicast protected requests. Unicast protected requests utilize a 1+1 dedicated path protection, with the same channel. The proposed priority allocation algorithms are based on the compact scheduling algorithm and the ordering obtained with two different metrics, both of which consider the bandwidth and required number of links of the requests presented to the network. We evaluate the performance and efficiency of the proposed algorithms across a range of demand frequency slots distributions in a mesh network. A comparative analysis of the obtained experimental results reveals that the proposed algorithms outperform existing reference algorithms in terms of spectrum utilization.**

Keywords-elastic optical networks; spectrum allocation; survivability; spectrum utilization.

I. INTRODUCTION

The increasing demand of multimedia streaming services, such as audio and video conferences, and cloud computing applications, requires increasingly higher data rates, flexible network resource management, and efficient spectral utilization. Traditional optical networks are unable to keep pace with the high data rate demands, because they are based on wavelength division multiplexing (WDM) technology, which wastes a large portion of the spectrum [1]. A different type of optical network—elastic optical network (EON)—has been recently presented in [2][3]. It can efficiently manage network resources and provide better spectrum utilization, because it is based on orthogonal frequency-division multiplexing (OFDM) technology [4]. OFDM is a multi-carrier modulation scheme that transmits a high-speed data stream by splitting it into several parallel data streams, each carrying a relatively low data rate.

Many challenges have been faced by EON researchers concerning hardware development, network control and management, and spectrum management. Routing and spectrum allocation (RSA) [5][6] is one of the key challenges to be faced, and has received much attention from researchers in recent years, because it lies at the core of the design and control of EONs. RSA includes two main functions: assigning a suitable physical path between the source and destination(s), and allocating contiguous, continuous, and non-overlapping parts of the spectrum to meet traffic demand, while minimizing the total amount of spectrum needed to serve it. RSA is an NP-hard problem, because of the continuity constraint [5]. It can be divided into offline and online RSA. The former is used when traffic demand is known in advance, and traffic variations occur over a long period of time, whereas the latter is used when traffic arrives in a random manner.

Many research has been conducted addressing the offline RSA problem. This problem was introduced by Jinno et al. [7]. Talebi et al. [8] mapped the offline RSA problem to a scheduling problem in multiprocessor systems. Genetic algorithms [9] and the tabu search algorithm [10] have also been proposed to solve the offline RSA problem and enhance spectrum utilization. We have recently proposed priority allocation algorithms [11] to handle offline RSA problem in unicast unprotected EONs. For more details about the spectrum management techniques in EONs, readers are referred to the recent excellent surveys in [1][12].

Data transmitted through the network can be of critical nature (e.g., military, medical, or financial information). Protecting the paths followed by those data is crucial, to ensure a continuous transfer of data. Survivability is an important design criterion for traditional networks in general and optical networks in particular, including EONs [13][14]; it describes the ability to continue providing services in the presence of a single failure, which could be caused by fiber cuts, active component failure inside the network equipment, or node failure [15]. Given that EONs have the capability of transmitting huge amounts of data, data transfer interruption due to node or link failures should be minimized or—if possible—completely avoided. Networks serve two types of request: protected and unprotected. Protected requests are designed to overcome a single network failure, most commonly by assigning a disjoint backup path (optical path, in the context) for each working path. The commonly used protection techniques can be divided into dedicated path protection (DPP) and shared path protection (SPP) techniques. Dedicated path protection means that each working path is assigned its own dedicated backup path, to which it can switch in case of a failure. On the other hand, shared path protection means that backup spectrum subcarriers can be shared on some links, as long as their protected segments (links, subpaths, paths) are mutually disjoint. Dedicated path protection can be either 1+1 or 1:1. In 1+1 dedicated path protection, traffic is simultaneously transmitted on both the working and backup paths. On the contrary, in 1:1 dedicated path protection, the backup path is idle and can be used to transmit low-priority traffic during normal operation. Two different channel allocation policies can be applied with the aforementioned protection schemes. The first one is a same channel (SC) policy, where the working path and the backup path share the same central frequency. The second is the different channel (DC) policy, where both the working path and the backup path can utilize any available central frequency. The different channel policy is considered to be a resource-consuming solution, in contrast with the same channel policy, which is a much more cost-effective solution [16]. In this paper, we the address offline routing and spectrum allocation problem with dedicated path protection in EONs with same channel (RSA/DPP/SC). It is worth mentioning that DPP is considered an expensive scheme, but has a quick recovery time. On the other hand, SPP saves network resources, but it needs much more time than DPP to recover from failure.

A significant amount of research has been carried out to study the issue of survivability of EONs. Some of these research efforts have been directed to the online (i.e., dynamic) RSA problem [17][18], whereas others considered the offline (i.e., static) RSA problem in survivable EONs, considering the different protection techniques mentioned above. (This later problem is the focus of this work.) In particular, the use of DPP in EONs has been addressed in [16][19]-[21]. Recently, Ruan et al. [15] studied the offline survivable multi-path RSA problem with DPP in EONs. They formulated the problem as an integer linear programming (ILP) problem. In the same context, Klinkowski [9] addressed RSA problem in EONs with DPP with static traffic demand, and he used genetic algorithms to develop an efficient algorithm, which performs better than other reference algorithms. Concurrently, the use of SPP in EONs has also been studied by many researchers [22]-[24]. Walkowiak et al. [23] addressed the offline RSA problem in EONs with SPP, formulating it also as an ILP problem. More details about the use of protection techniques in EONs can be found in [25], a recent survey of the topic.

In a recent paper [11], we addressed the offline RSA problem in EONs by introducing priority allocation algorithms for unicast unprotected networks. These algorithms are based on both the compact scheduling algorithm [8] and a combination of the request bandwidth and the number of links used by that request. Simulation results show that our proposed priority allocation algorithms, when applied to different network topologies (e.g., a chain network and the National Science Foundation network (NSFNET)) with diverse bandwidth distributions outperform the existing algorithms, and produce close to optimal solutions in a unicast unprotected network. In this paper, we extend our priority allocation algorithms to handle survivability in EONs with the goal of minimizing the amount of spectrum needed to serve the traffic demand. In particular, we study the behavior of the proposed algorithms when the traffic demand includes unicast unprotected, and unicast protected requests. We consider spectrum usage as a performance metric, to show the effectiveness of the proposed algorithms.

The rest of the paper is structured as follows. Section II formulates the problem. Section III reviews priority allocation algorithms, with working examples. Section IV discusses the experimental results. We present our conclusion in the last section.

II. PROBLEM FORMULATION

In this section, we present and explain the offline RSA problem in protection-based EONs, with an example that will be used in the priority allocation algorithms section.

A. Problem Statement

The problem to be addressed can be formulated as follows: Given: a) A directed graph $G(V, E)$, where G denotes the physical topology of an EON, V denotes the set of nodes, and E denotes the set of bidirectional optical links. b) A set of frequency slices (i.e., subcarriers) in each optical link, of cardinality sc. c) A set of requests between source-destination pairs $(s, d)_i$ of request size sz (i.e., the number of frequency slices needed to serve a request), where $i \in I$ represents the request type. Our aim is to minimize the amount of spectrum needed to serve the traffic demand—which includes different types of request to the mesh network—under the following constraints:

1) Spectrum contiguity constraint: Each request should be assigned to a contiguous portion of the spectrum.

2) Spectrum continuity constraint: Each request should be assigned to a similar portion of spectrum for all the corresponding links.

3) Non-overlapping spectrum constraint: Requests that need to use similar links should be assigned to non-overlapping portions of the spectrum.

4) Same channel (applies only to RSA/DPP/SC): For each unicast protected request, the working and backup paths should be assigned to similar portions of the spectrum.

In this paper, we consider two types of request, $I = \{1, 2\}$. A request can be unicast unprotected ($i = 1$), or unicast protected ($i = 2$). When the demand includes a unicast unprotected request $(s, d)_1$ from source s to destination d, the request will be served by contiguous subcarriers on all optical links belonging to the predetermined fixed working path from s to d. However, when the demand includes a unicast protected request $(s, d)_2$, the request will be served by contiguous subcarriers on all optical links belonging to both the predetermined fixed working path and the predetermined fixed backup path from s to d.

B. RSA/DPP/SC Example

To exemplify the problem, consider the mesh network illustrated in Figure 1, with four nodes and five bidirectional links, and the corresponding spectrum demand matrix $\boldsymbol{D}$ shown below. The demand matrix includes the requests from each source to each destination in the mesh network; the total number of requests in this example is therefore equals to 12.

In the case of a unicast unprotected request, the routing algorithm chooses an arbitrary fixed path (the working path) selected from the set of shortest paths computed with Dijkstra's algorithm. Unicast protected requests with DPP utilize both a working path and a backup path. The working path is fixed and arbitrarily selected from the set of shortest paths computed with Dijkstra's algorithm; likewise, the backup path is fixed and arbitrarily selected from the set of shortest paths computed by Dijkstra's algorithm, after removing all edges belonging to the working path.

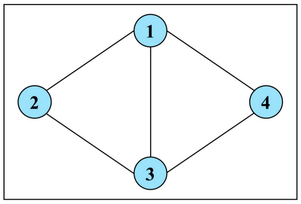


Figure 1. Mesh network with four nodes.

$$\mathbf{D} = \begin{bmatrix} 0 & 1 & 10 & 100 \\ 100 & 0 & 100 & 1 \\ 1 & 10 & 0 & 4 \\ 10 & 100 & 10 & 0 \end{bmatrix}$$

TABLE I. REQUESTS MADE TO THE MESH NETWORK

Requests (s, d)$_i$	**Type of request**	**Size (sz)**	**Working path**	**Backup path**
τ_1 (1, 3)$_2$	Unicast protected	10	1-3	1-4-3
τ_2 (4, 3)$_2$	Unicast protected	10	4-3	4-1-3
τ_3 (2, 4)$_2$	Unicast protected	1	2-1-4	2-3-4
τ_4 (2, 1)$_1$	Unicast unprotected	100	2-1	____
τ_5 (2, 3)$_2$	Unicast protected	100	2-3	2-1-3
τ_6 (1, 2)$_1$	Unicast unprotected	1	1-2	____
τ_7 (3, 1)$_2$	Unicast protected	1	3-1	3-2-1
τ_8 (3, 2)$_1$	Unicast unprotected	10	3-2	____
τ_9 (3, 4)$_2$	Unicast protected	4	3-4	3-1-4
τ_{10} (4, 1)$_1$	Unicast unprotected	10	4-1	____
τ_{11} (1, 4)$_1$	Unicast unprotected	100	1-4	____
τ_{12} (4, 2)$_1$	Unicast unprotected	100	4-1-2	____

Table I shows the requests made to the mesh network, type (unicast unprotected or protected), size (1, 4, 10, 40, or 100), and the nodes traversed by the working and backup paths. Those requests will be sorted based on the selected sorting mechanism, and the sorted list of requests will be used as an input to the compact scheduling algorithm [8].

III. PRIORITY ALLOCATION ALGORITHMS

In this section, we evaluate the extended version of the proposed algorithms [11] as a solution to the offline RSA problem in survivable OFDM optical networks; the objective is to minimize the amount of spectrum needed to serve traffic demand when it includes unicast unprotected, and unicast protected requests. The RSA problem has two different dimensions: the spectrum (or bandwidth) and the links. The combination of these two dimensions plays a key role in improving the process of spectrum allocation. Therefore, the proposed solution is based on combining them in multiple ways. First, we introduce the compact scheduling algorithm [8], which has been used to show the effectiveness of the proposed algorithms. We then review our priority allocation algorithms; specifically, the sorting mechanisms. Finally, we show a working example, to demonstrate the performance of the algorithms when compared with the existing algorithms.

A. Compact Scheduling Algorithm

The priority allocation algorithms proposed in [11] are based on an existing algorithm, the compact scheduling algorithm, proposed by Talebi et al. [8]. The compact scheduling algorithm is a typical list scheduling algorithm, where the quality of the solution is very sensitive to the order of requests in the list. It has a complexity of $O(n^2)$, where n is the number of requests in the list. The input to the compact scheduling algorithm is a sorted list of requests to the mesh network. The algorithm is constituted by the following steps:

1) Select the first request in the list and assign it to a set of consecutive links.
2) Delete the executed request from the list, and update the status (idle or busy) of the corresponding links.
3) Scan the list at the same scheduling instant to select requests that can be executed simultaneously with the currently executed requests.
4) Continue scanning the list until there are no other requests that can be executed at that scheduling instant or no available links.
5) Advance the scheduling time based on the earliest finishing request, and add the available links to the set of free links.
6) Repeat the aforementioned steps until all the requests have been satisfied.

B. Sorting Mechanisms

In [11], we proposed two priority allocation algorithms that consider both dimensions of the problem: the links and the spectrum (or bandwidth). It is worth mentioning that in the present paper the link dimension is represented by the number of links used by the working path in the case of unicast unprotected requests, and by the number of links used by both the working and backup paths in the case of unicast protected requests. On the other hand, in our previous work [11], the link dimension was represented by the number of links used by only the working path, because only unicast unprotected requests were being considered there. The sorting mechanisms, the longest then widest compact algorithm (LWC) and the area compact algorithm (AC), are described below.

1) Longest then Widest Compact Algorithm (LWC): In the first proposed algorithm, we consider both dimensions of the problem, the links and spectrum (or bandwidth), using two levels (a primary and a secondary sorting mechanisms) to sort the requests in the demand. In the primary sorting mechanism, requests are sorted based on the amount of needed spectrum or bandwidth (BW_i), from higher to lower. Then, in the secondary sorting mechanism, requests with equal bandwidth are sorted based on the required number of links (LK_i)—obtained in the terms described before—from higher to lower.

2) Area Compact Algorithm (AC): In the second proposed algorithm, we also consider both dimensions of the problem, but in a different way. The amount of spectrum needed for a request and the required number of links (in the working path, or the working and backup paths, depending on the type of request) are multiplied ($LK_i \times BW_i$), thus providing a shape area. This area captures both dimensions of the problem and constitutes a better ordering metric. In this mechanism, the areas are used to sort the requests in the list, from higher to lower.

C. *Working Example*

In this subsection, we discuss the behavior of the above-mentioned algorithms, and show how different sorting mechanisms can affect the amount of spectrum needed to satisfy the demand, when it includes both unicast unprotected and unicast protected requests. The requests lists presented below are based on the spectrum demand described in the problem formulation section.

1) Existing Algorithms:

The longest first compact algorithm (LFC), which was proposed in [8], sorts the requests based on the required amount of spectrum, from higher to lower. The sorted list of requests that will be used as input to the compact scheduling algorithm after applying the LFC algorithm is shown below:

$$\{\tau_4, \tau_5, \tau_{11}, \tau_{12}, \tau_8, \tau_{10}, \tau_1, \tau_2, \tau_9, \tau_6, \tau_7, \tau_3\}$$

Running the compact scheduling algorithm with LFC shows that 224 subcarriers are needed to serve the considered demand (which includes both unicast unprotected and unicast protected requests).

The widest first compact algorithm (WFC), also proposed in [8], sorts the requests based on the required number of links used by the working and/or backup paths, from higher to lower. The sorted list of requests that will be used as input to the compact scheduling algorithm after applying the WFC algorithm is shown below:

$$\{\tau_3, \tau_2, \tau_5, \tau_7, \tau_9, \tau_1, \tau_{12}, \tau_4, \tau_6, \tau_8, \tau_{10}, \tau_{11}\}$$

Running the compact scheduling algorithm with WFC shows that 215 subcarriers are needed to serve the considered demand.

2) LWC:

The sorted list of requests that will be used as input to the compact scheduling algorithm after applying the LWC algorithm is shown below:

$$\{\tau_5, \tau_{12}, \tau_{11}, \tau_4, \tau_1, \tau_2, \tau_8, \tau_{10}, \tau_9, \tau_3, \tau_7, \tau_6\}$$

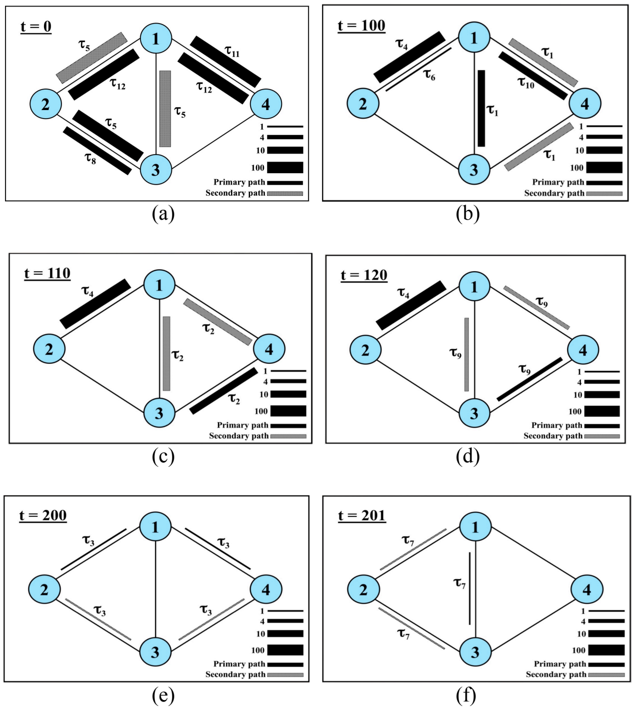
Running the compact scheduling algorithm with LWC shows that only 202 subcarriers are needed to serve the same demand. The number of subcarriers needed with LWC is therefore lower than if either LFC or WFC are used (224 and 215, respectively).

3) AC:

The sorted list of requests that will be used as input to the compact scheduling algorithm after applying the AC algorithm is shown below:

$$\{\tau_5, \tau_{12}, \tau_4, \tau_{11}, \tau_1, \tau_2, \tau_9, \tau_{10}, \tau_8, \tau_3, \tau_7, \tau_6\}$$

In Figure 2 (a), request 5 is assigned at t = 0, and it occupies 100 subcarriers from the following links: 2-3, 2-1, and 1-3. Then, request 12 is assigned, and it occupies 100 subcarriers from the following links: 4-1, and 1-2. After that, request 11 is assigned, and it occupies 100 subcarriers from link 1-4. Last request that will be assigned at t = 0 is request 8, and it occupies 10 subcarriers from link 3-2. Figure 2 shows the spectrum utilization as time proceeds, using the AC algorithm. Running the compact scheduling algorithm with AC shows that 202 subcarriers are required for the considered demand. The number of subcarriers needed for AC is equal to the number of subcarriers needed for LWC, and lower than the numbers needed for both LFC and WFC (224 and 215, respectively).



(a) (b) (c) (d) (e) (f)

Figure 2. Area compact algorithm progression. (a) Step 1. (b) Step 2. (c) Step 3. (d) Step 4. (e) Step 5. (f) Step 6.

Although in the example both LWC and AC require the same number of subcarriers (i.e., 202 subcarriers) to serve the demand, their behaviors are quite different. They have different request ordering mechanisms and different request allocation orders. The performance difference between them will be discussed in the experimental results and analysis section.

IV. EPERIMENTAL RESULTS AND ANALYSIS

In this section, we present a comparative evaluation between our algorithms and the heuristics recently proposed in [8] (i.e., LFC and WFC). We start by presenting the comparison metric used for performance evaluation, along with the simulation environment. We use three traffic frequency slot distributions (discrete uniform, discrete high, and discrete low) to measure and compare the performances of our algorithms. Finally, we present the performance and analysis results. It is worth mentioning that both LFC and WFC were developed in the context of an RSA problem without additional survivability constraints in the mesh network. Therefore, we modified the aforementioned existing algorithms to address the new constraints resulting from the use of protection.

A. Comparison Metric

We consider spectrum usage as the goal metric to evaluate the performance of our proposed algorithms. Spectrum usage is defined here as the number of subcarriers needed to serve a traffic demand including the three different types of request (i.e., unicast unprotected and unicast protected requests).

B. Simulation Setup

To test the proposed algorithms in terms of survivability EONs, we use the NSFNET like topology as in [11]. The mesh network is composed of 14 nodes and 20 bidirectional links, as shown in Figure 3. In the case of unicast unprotected requests, the routing algorithm assumes an arbitrary fixed path, selected from the set of shortest paths computed with Dijkstra's algorithm. Unicast protected requests with dedicated path protection utilize both a working path and a backup path. As with the unicast unprotected requests, the working path is fixed and arbitrarily selected from the set of shortest paths computed with Dijkstra's algorithm; likewise, the backup path is fixed and arbitrarily selected from the set of shortest paths computed with Dijkstra's algorithm, after removing all edges belonging to the working path.

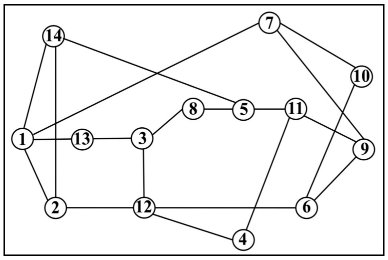


Figure 3. NSFNET-like topology.

We use a distance-adaptive spectrum allocation strategy to allocate the spectrum for each traffic demand based on its needed frequency slots and the length of its path as reported in [7][8][26]. We assume an elastic optical network with five different types of request sizes. Each demand requests 1, 4, 10, 40, and 100 frequency units. The size of the traffic demand is generated using three different types of frequency slot distributions (discrete uniform, discrete high, and discrete low). In the discrete uniform distribution case, all frequency slots have the same probability, whereas in the discrete high distribution higher frequency slots have higher probabilities, and in the discrete low distribution higher frequency slots have lower probabilities. The details of these three distributions and their frequency slot selection probabilities are listed in Table II.

TABLE II. DETAILS OF THE USED TRAFFIC FREQUENCY SLOTS DISTRIBUTION

Frequency slot	Discrete uniform	Discrete high	Discrete low
1	0.2	0.1	0.3
4	0.2	0.15	0.25
10	0.2	0.2	0.2
40	0.2	0.25	0.15
100	0.2	0.3	0.1

To evaluate our algorithms, we consider a scenario where the traffic demand includes both unicast unprotected and unicast protected requests; the ratio of unicast protected to unicast unprotected requests varies from 0 % to 50 %, in increments of 10 %, with different traffic demand generation patterns. Note that in the first data point in the graphs, all the requests are unicast unprotected, while in the last data point, half of the requests are unicast unprotected, and half are unicast protected. Table III presents the number of unicast unprotected and unicast protected requests in the scenario.

TABLE III. NUMBER OF REQUESTS IN THE SCENARIO

Percentage (%)	Number of requests	
	Unicast unprotected	*Unicast protected*
0	182	0
10	164	18
20	146	36
30	128	54
40	110	72
50	91	91

Our proposed algorithms are implemented in C++ using Xcode (version 6.3.1) on a MacBook Pro with OS X El Capitan (version 10.11.4), a 2.2-GHz Intel Core i7 processor, and 16 GB of memory.

C. Performance Analysis and Results

In this subsection, we determine the average percentual improvement in the number of needed subcarriers to evaluate the performances of our proposed algorithms (LWC and AC) when compared with the two existing algorithms proposed in [8] (LFC and WFC). For each data point in our experiment, a large number of random problem instances (up to 8000) were executed, and only the resulting average values are being reported. The averaged results were obtained with 99 % confidence, with a confidence interval smaller than 1 % of the average value.

Figures 4, 5 and 6 show the average number of needed subcarriers versus the percentage of unicast protected requests, for both proposed algorithms and existing algorithms. Table IV presents the performance improvements of our proposed algorithms when compared to LFC and WFC, for different frequency slot distributions.

TABLE IV. AVERAGE PERCENTUAL IMPROVEMENTS

Distribution	LWC		AC	
	LFC	***WFC***	***LFC***	***WFC***
Uniform	8.5 %	6.9 %	8.5 %	6.9 %
Discrete high	9.5 %	7.1 %	9.6 %	7.2 %
Discrete low	6.3 %	6.1 %	6.3 %	6.1 %

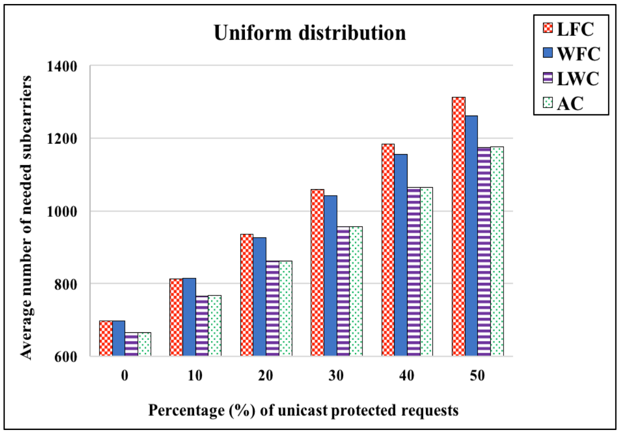


Figure 4. Average number of subcarriers as a function of the percentage of unicast protected requests; uniform frequency slot distribution.

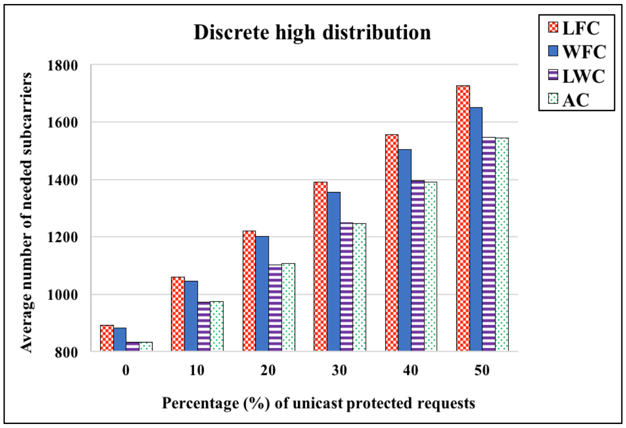


Figure 5. Average number of subcarriers as a function of the percentage of unicast protected requests; discrete high frequency slot distribution.

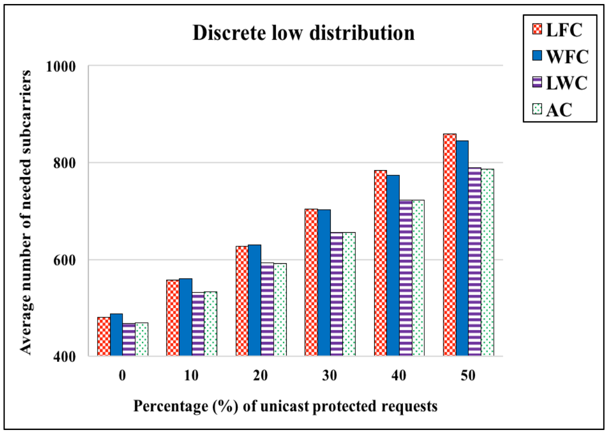


Figure 6. Average number of subcarriers as a function of the percentage of unicast protected requests; discrete low frequency slot distribution.

As shown in the figures, the proposed algorithms performed better than both the LFC and WFC algorithms. In other words, the number of needed subcarriers with our algorithms was less than the number of needed subcarriers with either LFC or WFC. In particular, in the case of a discrete high distribution of the requested frequency slots, LWC and AC improved the results obtained with LFC by 9.5 %, and 9.6 %, respectively; when compared with WFC, improvements of 7.1 % and 7.2 % were respectively obtained. As mentioned previously, considering both dimensions; the amount of spectrum and the number of links; while sorting the requests, affects the number of subcarriers needed to serve the traffic demand. Therefore, our sorting mechanisms outperform the existing mechanisms, and require less number of subcarriers.

V. CONCLUSION

In this paper, we addressed the intractable offline RSA problem in protection-based EONs. We investigated the efficiency of priority allocation algorithms based on the compact scheduling algorithm and the ordering obtained with two different metrics, both of which consider the bandwidth and required number of links of the requests presented to the network, albeit in slightly different ways. Our objective was to minimize the total amount of spectrum needed to serve traffic demand when this demand includes unicast unprotected and unicast protected requests. We evaluated the performance and efficiency of our algorithms across a range of frequency slot distributions. The obtained experimental results have shown that the proposed priority allocation algorithms outperformed other reference algorithms in term of spectrum utilization. The proposed priority allocation algorithms are robust, and can be used in EONs with different setups.

This work can be extended in several interesting directions. For instance, it would be enlightening to investigate the online RSA problem in EONs, in which concerns the reduction of blocking and/or fragmentation obtainable by combining multiple bin packing algorithms (e.g., first fit, best fit, and random fit). Moreover, it would also be very interesting to focus on the problem of how to efficiently handle the multicast protection problem in EONs, by finding the backup tree for a working (multicast) tree with the minimum amount of spectral resources.

REFERENCES

[1] S. Talebi, et al., "Spectrum management techniques for elastic optical networks: a survey," *Opt. Switch. Netw.*, vol. 13, pp. 34-48, July 2014.

[2] M. Jinno, et al., "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.

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

[4] G. Zhang, M. De Leenheer, A. Morea, and B. Mukherjee, "A survey on OFDM-based elastic core optical networking," *IEEE Commun. Surv. Tuts.*, vol. 15, no. 1, pp. 65-87, Feb. 2012.

[5] Y. Wang, X. Cao, and Y. Pan, "A study of the routing and spectrum allocation in spectrum-sliced elastic optical path networks," *Proc. 2011 IEEE INFOCOM*, Shanghai, 2011, pp. 1503-1511.

[6] M. Klinkowski and K. Walkowiak, "Routing and spectrum assignment in spectrum sliced elastic optical path network," *IEEE Commun. Lett.*, vol. 15, no. 8, pp. 884-886, Aug. 2011.

[7] M. Jinno, et al., "Distance-adaptive spectrum resource allocation in spectrum-sliced elastic optical path network," *IEEE Commun. Mag.*, vol. 48, no. 8, pp. 138-145, Aug. 2010.

[8] S. Talebi, E. Bampis, G. Lucarelli, I. Katib, and G. Rouskas, "Spectrum assignment in optical networks: a multiprocessor scheduling perspective," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 6, no. 8, pp. 754-763, Aug. 2014.

[9] M. Klinkowski, "A genetic algorithm for solving RSA problem in elastic optical networks with dedicated path protection," *Adv. Intell. Syst. Comput*, vol. 189, pp. 167-176, 2013.

[10] R. Goscien, K. Walkowiak, and M. Klinkowski, "Tabu search algorithm for routing, modulation, and spectrum allocation in elastic optical network with anycast and unicast traffic," *Comput. Netw.*, vol. 79, pp. 148-165, March 2015.

[11] R.W. Alaskar, I. Ahmad, and A. Alyatama, "Offline routing and spectrum allocation algorithms for elastic optical networks," *Opt. Switch. Netw.*, vol. 21, pp. 76-92, July 2016.

[12] B. Chatterjee, N. Sarma, and E. Oki, "Routing and spectrum allocation in elastic optical networks: a tutorial," *Commun. Surv. Tuts.*, vol. 17, no. 3, pp. 1776-1800, May 2015.

[13] S. Ramamurthy and B. Mukherjee, "Survivable WDM mesh networks, Part I – Protection," *18th Annu. Joint Conf. IEEE Computer and Communications Societies*, New York, 1999, pp. 744-751.

[14] C. Politi, et al., "Dynamic operation of flexi-grid OFDM-based networks," *Optical Fiber Communication Conf. and Expo. and the Nat. Fiber Optic Engineers Conf.*, Los Angeles, CA, 2012, pp. 1-3.

[15] L. Ruan and Y. Zheng, "Dynamic survivable multipath routing and spectrum allocation in OFDM-based flexible optical networks," *J. Opt. Commun. Netw.*, vol. 6, no. 1, pp. 77-85, Jan. 2014.

[16] M. Klinkowski and K. Walkowiak, "Offline RSA algorithms for elastic optical networks with dedicated path protection consideration," *4th Int. Congress on Ultra-Modern Telecommunications and Control Systems and Workshops*, St. Petersburg, 2012, pp. 670-676.

[17] A. Alyatama, "Dynamic spectrum allocation for orthogonal frequency-division multiplexing optical networks with survivability and multicasting," *J. High Speed Netw.*, vol. 22, no. 1, pp. 1-13, Feb. 2016.

[18] A. Tarhan and C. Cavdar, "Shared path protection for distance adaptive elastic optical networks under dynamic traffic," *5th Int. Congr. on Ultra-Modern Telecommunications and Control Systems and Workshops*, Almaty, 2013, pp. 62-67.

[19] M. Klinkowski, "An evolutionary algorithm approach for dedicated path protection problem in elastic optical networks," *Cybern. Syst.*, vol. 44, no. 6-7, pp. 589-605, Aug. 2013.

[20] J. López, Y. Ye, V. López, and F. Jimenez, "Traffic and power-aware protection scheme in elastic optical networks," *XVth Int. Telecommunications Network Strategy and Planning Symposium*, Rome, 2012, pp. 1-6.

[21] K. Walkowiaka, M. Klinkowskib, B. Rabiegaa, and R. Gościeńa, "Routing and spectrum allocation algorithms for elastic optical networks with dedicated path protection," *Opt. Switch. Netw.*, vol. 13, pp. 63-75, July 2014.

[22] M. Liu, M. Tornatore, and B. Tornatore, "Survivable Traffic Grooming in Elastic Optical Networks—Shared Protection," *J. Lightw. Technol.*, vol. 31, no. 6, pp. 903-909, March 2013.

[23] K. Walkowiak and M. Klinkowski, "Shared Backup Path Protection in Elastic Optical Networks: Modeling and Optimization," *9th Int. Conf. Design of Reliable Communication Networks*, Budapest, 2013, pp. 187-194.

[24] C. Yang, N. Hua, and X. Zheng, "Shared Path Protection based on Spectrum Reserved Matrix Model in Bandwidth-Variable Optical Networks," *7th Int. ICST Conf. Communications and Networking in China*, Kun Ming, 2012, pp. 256-261.

[25] G. Shen, G. Guo, and S.K. Bose, "Survivable elastic optical networks: survey and perspective," *Photonic Netw. Commun.*, vol. 31, no. 1, pp. 71-87, Feb. 2016.

[26] M. Fayez, I. Katib, G.N. Rouskas, and H.M. Faheem, "Spectrum assignment in mesh elastic optical networks," *Proc. 24th Int. Conf. Computer Communications and Networks*, Las Vegas, NV, 2011, pp. 1-6.