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# A Topology-Based Spectrum Assignment Solution for Static Elastic Optical Networks With Ring Topologies

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**ABSTRACT** On designing elastic optical networks, one of the main tasks to be solved is to allocate enough spectrum on the users' paths to achieve communication to all network users, known as the Spectrum Assignment problem (SA). On a static network operation, the order in which the users' spectrum demands are assigned is significant. However, standard approaches do not sort them previous to the spectrum assignment process. In this work, we first sort the users to maximize the spectrum usage based on their bandwidths and path length. Then, we propose a novel topology-based spectrum allocation strategy, which takes advantage of the ring network topology. We called it Spiral Fit, consisting of assigning the frequency spectrum to the users following a spiral (or a concentric rings) order. We compare our strategy's performance and robustness with two optimization models, only in small network topologies (from 5 to 8 nodes) since optimization processes are too expensive on more significant networks. In more extensive networks, we compare the proposed method with the most referenced techniques. The results show that consistently our method obtains near-optimal results in small topologies and outperforms the heuristic solutions found in the literature in terms of network capacity (measured as a number of frequencies slot units and spectrum fragmentation).

**INDEX TERMS** Elastic optical networks, spectrum fragmentation, spectrum assignment.

## I. INTRODUCTION

Since the early times of the internet, the data transmitted over the network has been continuously growing. This amount of traffic increases typically above 30% per year [1]. For instance, Cisco expects 396 Exabytes per month by the year 2022 [2]. Most of this traffic is transmitted over optical networks. So far, this explosive growth was not an issue, thanks to the enormous capacity of optical architectures and several technological advances. However, this large capacity is not limitless. In fact, this decade, researchers predicted a potential inability of current networks to support future bandwidth demands, a situation called "Capacity Crunch" (CC) which is expected to be reached soon [3]–[5].

There are two different courses of action to solve the CC problem. The first option consists of installing more fiber and infrastructure. This investment cannot be avoided but

should be postponed as long as possible due to the significant expenses involved. The second strategy is to manage the already installed network infrastructure efficiently. Consequently, the second alternative has been an important focus of researchers [1], [6].

Nowadays, multiple signals are transmitted using different wavelengths within a pre-established frequency grid. According to the International Telecommunications Union (ITU) standard [7], the wavelengths are separated by 50 GHz. However, different users have different spectral requirements. Even so, the fixed grid operation gives everyone the same resources. Then, the two main problems appear. First, some users receive more capacity than needed. Second, when users require more than 50 GHz for its transmission, the resources are insufficient. To face the second problem, Internet Service Providers are using more complex modulations, raising the bit-rate transmitted, but using the same spectral portion. Nevertheless, these complex modulations allow only short-distance transmissions.

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A new paradigm has been proposed to solve prior problems, denoted as Elastic Optical Network (EON) [8]. This modern architecture attempts to assign resources to different users according to their bandwidth requirements. To do so, it divides the spectrum into small portions called Frequency Slot Unit (FSU). These FSUs can be grouped flexibly to provide the frequency spectrum to each user according to their needs. This flexible assignment may save significant idle bandwidth, allowing to serve more users on the fiber optics C-band than in the fixed spectrum separation case. For this reason, the EON architecture has been a remarkable topic of investigation for the few last years [1], [9]–[11].

The design of elastic optical networks can be decomposed into many different tasks. One of these tasks consists of assigning a portion of the spectrum to each user (optical connection request). This task is known as the *Spectrum Assignment* (SA) problem. The goal is to serve users with the least amount of resources possible [12], however, known to have an NP-complete computation complexity [1]. Because of its importance, it has been a hot research problem [1], [9]–[11], [13]–[22].

The SA problem is subject to the following constraints: first, each FSU hosts only one connection, and the FSUs assigned to a given connection must be maintained along the entire origin-destination route, known as the “*continuity constraint*”; second, in case the user’s bandwidth requirements must be satisfied by more than one FSU, the assigned FSUs must be consecutive in the spectrum, known as the “*contiguity constraint*”.

Nowadays, optical networks operate statically, in which the chosen paths and spectrum portion are assigned for an extended period (months or even years) to communicate users. In these networks, there is usually spectrum fragmentation over the network frequency spectrum despite the SA method used [15], [18], [23], [24]. This statement refers to the fact that there might be some free FSU in the middle spectrum frequencies which could not be assigned. The said phenomenon is significant since it can produce a meaningful waste of bandwidth if not adequately controlled. Thus, one goal is to avoid the spectrum fragmentation on the network as much as possible.

To face the spectrum fragmentation, there are some works focused on the routing strategy [17], [22], [25], [26], and some others focused on the spectrum assignment [10], [14], [18], [21], [23], [27]–[33]. Besides, some works in the literature consider that the order in which users are served on the spectrum assignment solutions is considered significant on static network operation circumstances because it can directly impact the fragmentation of the spectrum and its available use [1], [27]–[33]. Consequently, we focus our work on the spectrum assignment problem.

We focus our work on ring network topologies [34]–[36], a standard ring network found in metro and local area networks. In this paper, we take advantage of these topologies to efficiently organize the user demands on the frequency spectrum, generating a low spectrum fragmentation on the

network [10]. To this end, we propose a topology-based heuristic strategy to solve the spectrum assignment problem in ring topologies for elastic optical networks with static operation. First, we sort the users using mixed criteria, according to their bandwidth and path length. Next, we propose a “Spiral” spectrum assignment strategy. The spiral procedure takes advantage of the ring network topology to allocate the resources in a spiral (or concentric rings) form, reducing the fragmentation and network capacity required.

The remaining structure of this document is as follows: Section II, reviews the main strategies used to solve the SA problem. Section III, introduces the proposal. Section IV compares the new method with the strategies founded in literature. Finally, section V illustrates the conclusions and final remarks of the work.

## II. STATE OF ART

Elastic Optical Network is an architecture with the potential to improve spectrum usage. To this end, it is necessary to resolve the SA problem efficiently. Next, we summarize the methods published in the literature. We divide these methods in two categories: *Optimization* and *Ad-hoc solutions*.

### A. OPTIMIZATION APPROACHES

In a static network operation, the paths and spectrum assignment are chosen to operate permanently, seeking to minimize the network capacity and the spectrum fragmentation. Therefore, considering that the problem to be solved is to minimize the network’s capacity, it seems natural to design a solution from the optimization perspective.

Several solutions using optimization techniques have been proposed in the literature. Using linear programming (ILP) models, or Mixed ILP combined with metaheuristics (MILP) [1], [12], [21]. However, these models have thousands or millions of variables, and consequently, prohibited execution times, even for small networks. In short, these models have scalability difficulties, and so, the inability to solve them in a reasonable time for the architectures found in practice. For instance, Meza *et al.* (2016) [12] proposed two optimization models for ring topologies: a pure ILP model to solve the Routing and SA problems simultaneously (*One Step Approach*); and another relaxed model composed of two steps (*Two-Step Approach*), denoted as Shortest Path Optimal Assignment (SP-OA). The last strategy uses pre-computed shortest paths to solve the routing problem, and then an optimization approach to solve the spectrum assignment. These schemes show scalability limits since they could only obtain results until nine nodes ring topologies [12].

### B. AD-HOC SOLUTIONS

The previous discussion reveals that it is necessary to develop heuristics strategies to obtain reasonable solutions with scalability to real network topologies.

In this context, the Routing and spectrum assignment (RSA) problem is usually solved in two stages [37]. First, the route is assigned, for instance, the shortest path.

Then, the FSUs on each link are assigned to the network users satisfying the continuity and contiguity restrictions [38].

The spectrum assignment (SA) techniques found in the literature are Most-Used (MU), Best-Fit (BF), and First-Fit (FF), among other variations [1], [39]. Abkenar y Rahbar (2017) [21] concluded that most approaches use the First-Fit scheme.

As mentioned in the previous section, some papers [1], [27]–[33] consider that sorting the network users, previous to the spectrum assignment, directly impacts the fragmentation of the spectrum and its availability. Some are focused on sorting the users according to their bandwidth demands [27], [29], [30], [32], [33]. Some others focus on sorting the users based on their path lengths [28], [31]. In general, sorting the users based on their FSU demands has been considered the best criteria. Nevertheless, the solutions do not consider mixed sorting strategies.

### III. PROPOSED METHOD

In this section, we explain in details our proposal to solve the Spectrum Assignment problem in ring topologies with static network operation.

#### A. DEFINITIONS AND SUB-PROCEDURES NEEDED

The network is represented by a graph  $\mathcal{G} = (\mathcal{N}, \mathcal{L})$ , where  $\mathcal{N}$  is the set of ring nodes, and  $\mathcal{L}$  is the set of unidirectional links, with cardinalities  $N$  and  $L$ , respectively.

The set of users  $\mathcal{U}$ , of cardinality  $U$ , contains all source-destination node pairs on the graph  $\mathcal{G}$  demanding communication between them. We specify each user  $u \in \mathcal{U}$  as  $(s_u, d_u, bw_u, i_u)$ , where  $s_u$  is the originating node,  $d_u$  the destination node,  $bw_u$  is the number of contiguous FSUs demanded, and  $i_u$  is the index of the first slot of the spectrum assigned when the SA problem is solved.

Let  $\mathcal{R} = \{r_u | u \in \mathcal{U}\}$  be the set of paths computed for all network users, in which  $r_u$  is route assigned to user  $u \in \mathcal{U}$ , and  $|r_u|$  is its length, measured as the number of hops.  $\mathcal{R}$  can also be decomposed in two subsets: one is  $\overrightarrow{\mathcal{R}} (\subseteq \mathcal{R})$  containing all the routes facing clockwise direction; and the set  $\overleftarrow{\mathcal{R}} (\subseteq \mathcal{R})$  composed by all the paths in counterclockwise direction (remember that we are considering ring network topologies).

Let  $\mathcal{C} = \{c_\ell | \ell \in \mathcal{L}\}$  be the set containing the capacity of each network link  $\ell \in \mathcal{L}$ , measured by the number of FSUs available on the link.

Let  $\mathcal{BW} = \{BW_1, \dots, BW_B\}$  be the set composed by all possible categories of bandwidth demands (measured in FSUs) required by the users in  $\mathcal{U}$ , with cardinality equal to  $|\mathcal{BW}| = B$ , also read as the number of different bandwidth demands in the network. This set is sorted from the smallest demand of FSU to the biggest one.

Finally, let  $\mathcal{U}_b \subset \mathcal{U}$  be the subset of users with bandwidth requirements  $BW_b \in \mathcal{BW}$ , and  $\mathcal{U}_h \subset \mathcal{U}$  be the subset composed by the users whose path has  $h$  hops (Note that, in general,  $\mathcal{U}_b \cap \mathcal{U}_h \neq \emptyset$ ).

The method also uses the following function to work.

**Fit()**: assign the required FSUs to a user. The inputs for this function are: the bandwidth demands  $bw_u$  of user  $u$ , the user path  $r_u$ . Let us symbolically write  $s := \text{Fit}(bw_u, r_u)$  to represent the execution of this sub-procedure.

This function consists of finding an amount of  $bw_u$  available consecutive FSUs to the user  $u$ . The search starts on the first FSU ( $s = 1$ ) seeking if the FSUs are available from the  $s$  FSU to the  $s + bw_u - 1$  one, on all the links belonging to the route  $r_u$ . The procedure assigns those FSU and returns the first slot allocated ( $s$  value in the algorithm) if they are available. On the other hand, the  $s$  value is increased by one, and the procedure is repeated.

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#### Algorithm 1 Fit

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1: procedure Fit( $bw_u, r_u$ )
2:    $s := 0$ ;
3:   while not assigned do
4:     Search if FSUs from  $s$  to  $s + bw_u - 1$  are free in
        $r_u$ ;
5:     if FSUs are available then
6:       Assign the slots to user  $u$ ;
7:       Break;
8:     else
9:        $s := s + 1$ ;
10:  return  $s$ 

```

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#### B. SPECTRUM ASSIGNMENT STRATEGY

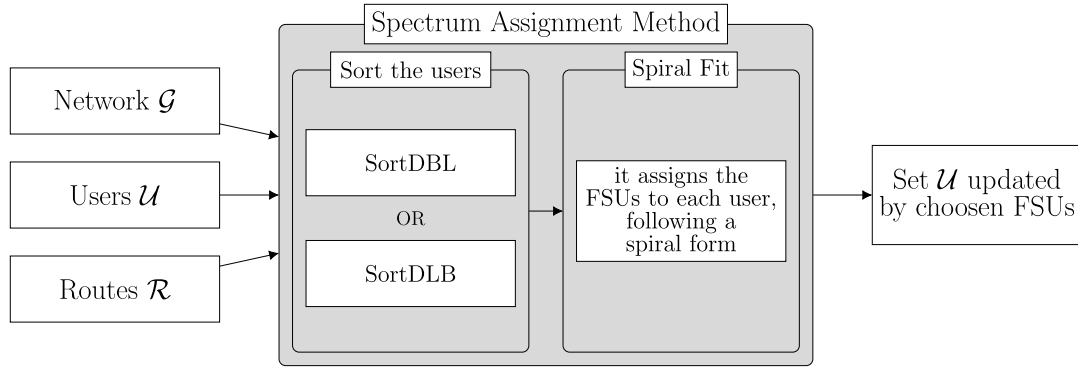
Figure 1 contains a diagram with the inputs required, the two steps composing our proposal, and the outputs obtained by the method execution.

The inputs are: the network topology  $\mathcal{G} = (\mathcal{N}, \mathcal{L})$ , which can be any network topology; the set of users  $u \in \mathcal{U}$ ; and the set of paths  $\mathcal{R}$ .

Among the inputs required, the set of routes  $\mathcal{R}$  is critical, which can be obtained by any means available in the literature. In this work, we compute the users' paths using the shortest path criterion using Dijkstra's algorithm [40]. However, for ring topologies with a pair number of nodes, some users have two shortest paths. In these cases, we choose the path to maintain the same number of users in clockwise and counterclockwise directions achieving symmetry in the direction of those paths. We call this strategy as *Shortest Path Balanced Users* (SP-BU).

The output of the method is composed of the FSUs assigned to each network user. Remark that each user  $u$  has associated its source and destination nodes, the demand of FSU  $bw_u$ , and  $i_u$  the first FSU allocated to user  $u$ . Therefore, the method output is the set of users  $\mathcal{U}$  with its  $i_u$  values updated.

In Figure 1, we illustrate that to solve the spectrum assignment problem in static network operations. We split the strategy into two steps. First, to sort the users (for this purpose, we evaluate two different alternatives), and later assign the spectrum to each user following a spiral strategy. Next, we explain those stages.



**FIGURE 1.** Diagram showing the inputs required to run our proposal, the two steps to perform the method, and the outputs delivered.

### Algorithm 2 Spiral-Fit (SF)

```

1: procedure Spiral-Fit( $\mathcal{U}, \mathcal{G}$ )
2:    $\mathcal{R} := \text{Routing}(\mathcal{U}, \mathcal{G})$ ;
3:    $\{\mathcal{U}_a, \forall a \in \mathcal{A}\} := \text{Sort}(\mathcal{U}, \mathcal{R})$ ;
4:   for each subset  $\mathcal{U}_a$ , with  $a \in \mathcal{A}$  (in order) do
5:      $dnode := 1$ ;
6:     while  $\mathcal{U}_a \neq \phi$  do
7:       for each  $u \in \mathcal{U}_a$  (in order) do
8:         if  $s_u = dnode$  then
9:            $i_u := \text{Fit}(bw_u, r_u)$ ;
10:           $dnode := d_u$ ;
11:           $\mathcal{U}_a = \mathcal{U}_a \setminus u$ ;
12:          break;
13:        if not users with  $s_u = dnode$  in  $\mathcal{U}_a$  then
14:           $dnode := dnode + 1$ ;
15:   return  $\mathcal{U}, \mathcal{R}$ 

```

#### 1) SORTING THE USERS

In [10], [35], the authors pointed out the importance of sorting the users since it influences the network performance in terms of network capacity and the spectrum fragmentation (idle frequency slots present on the network).

One way to order the users is to sort them, in decreasing order, by their path length, i.e., from longer to shorter. We denote this strategy as *DL*. Another way to sort them is by the amount of FSUs demanded to transmit, in decreasing order, which we call as *DB*.

Simmons et.al. [35] (among others) shows that in general the second option (DB) obtains better results. However, here we propose a hybrid approach admitting two variants. On the first variant, the users set  $\mathcal{U}$  is divided into  $B$  subsets, where users in subsets  $\mathcal{U}_b$ , with  $1 \leq b \leq B$ , have the bandwidth demands equal to  $BW_b$ . These subsets are ordered in decreasing order, according to their value of  $BW_b$ . Then, each subset of users is sorted according to their route length, in a decreasing manner. We called this variant as *Decreasing Bandwidth-Length (DBL)*.

The second variant first partitions the set of users  $\mathcal{U}$  into subsets of users with the same path length  $\mathcal{U}_h$ , and arranges

them in decreasing order, according to their length. Then, each subset of users is sorted by their bandwidth requirement, in decreasing order. We denote this variant as *Decreasing Length-Bandwidth (DLB)*.

To represent the execution of this sub-procedure, despite the criteria used, let us symbolically write  $\{\mathcal{U}_a, \forall a \in \mathcal{A}\} := \text{Sort}(\mathcal{U}, \mathcal{R})$ , where the list of subsets  $\{\mathcal{U}_a, \forall a \in \mathcal{A}\}$  contains all the users sorted according to the chosen criteria. For instance, for the DBL variant, each subset  $\mathcal{U}_a$  is equivalent to the subsets  $\mathcal{U}_b$ , with  $b = 1, \dots, B$ . Otherwise, for the DLB criterion, the  $\mathcal{U}_a$  list is the list of subsets  $\mathcal{U}_h$ , with  $h = 1, \dots, H$ .

#### 2) SPIRAL STRATEGY

Now, we explain the Spiral-Fit (SF) strategy. The proposal is illustrated in an algorithmic form on the pseudo-code displayed in Algorithm 2.

In the algorithm, we are given the network topology  $\mathcal{G}$  and the set of users of the network  $\mathcal{U}$ . Remark that set  $\mathcal{U}$  is composed of the source and destination node ( $s_u$  and  $d_u$ ) together with the FSU demands ( $b_u$ ). Then, we first start computing the set of user paths by executing the sub-procedure  $\text{Routing}(\mathcal{U}, \mathcal{G})$  in **line 2**. Later, in **line 3**, we sort the users by any criteria proposed in the previous sub-section. Remark that  $\{\mathcal{U}_a, \forall a \in \mathcal{A}\}$  is the sorted list of the subset of users created according to the chosen sorting criteria (DBL or DLB).

Next, the spectrum assignment procedure is executed. We iterate from **line 4 to 14** for each of the users' sets  $\mathcal{U}_a$  obtained in **line 3**, on the specific order given.

The main goal is to assign all the users of set  $\mathcal{U}_a$ , one by one, harnessing the ring network topology. Therefore, we initialize the variable  $dnode$  equal to 1. The purpose of this auxiliary variable will be explained next. Then, we iterate from **line 6 to 14**, assigning the users in  $\mathcal{U}_a$  following the *next rule*. This rule states that the next user's path to be served must begin at the previously allocated user's destination. To this end, the destination node of the previously attended user is stored in  $dnode$ . This criterion implies that the assignment can be done sequentially, assigning all the network users one by one, following the ring form. This rule enhances the

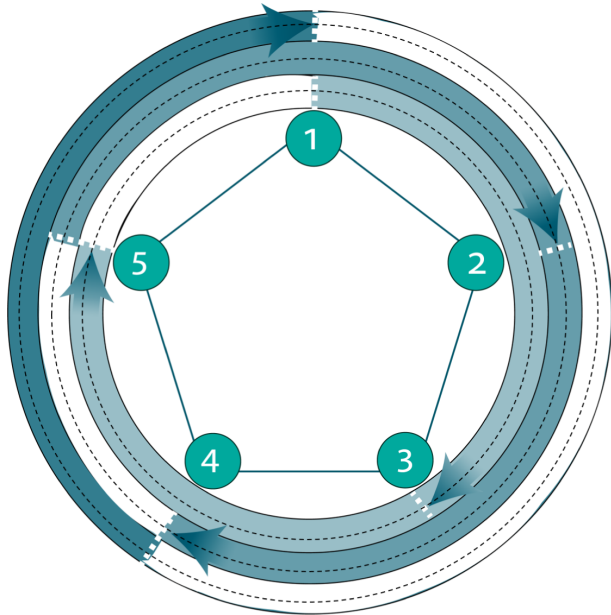


FIGURE 2. Spiral assignment example with users demanding two FSUs.

benefits obtained by sorting the users, since we serve together all the users with the same FSU demands (or path lengths), decreasing, in general, the network fragmentation and in the meantime, decreasing the total network capacity. In line 9, the sub-procedure *Fit* seeks several consecutive FSUs for user  $u$  on its selected path. Then, we update  $dnode$  variable storing the just served user  $u$  destination node (line 10), and in line 11, we subtract the user from the subset  $\mathcal{U}_a$ .

Otherwise, if there is no user with a source node equal to  $dnode$  in  $\mathcal{U}_a$ , the search continues with the node after the one stored in  $dnode$ , as seen in line 13 to 14.

Figure 2 exemplify the spiral approach with users demanding two FSU. Each circumferences surrounding the ring topology represents an FSU, and the higher the radius of this circumference, the higher the index of the FSU. The arrows in Figure 2 indicate both orientations of the route and the spectrum assignment. For example, the users' order of assignment is 1-3, 3-5, 5-2, 2-4, 4-1. Note that the sequential spectrum assignment is observed when the first user's destination node is the source node of the second user assigned. In general, the source node of the user  $n$  assigned is the destination of the user  $n - 1$ . As we can see, there are some unused FSUs (see first two FSUs of link 5-1), which can be filled with user 5-1, despite it demanding one or two FSUs; this is the reason why the sets are ordered in decreasing order.

To finish Algorithm 2, when all users in subset  $\mathcal{U}_a$  are served, we repeat previous steps for each subset of users  $\mathcal{U}_a \in \mathcal{U}$  (lines 4 to 14) until all users in  $\mathcal{U}$  are attended. Finally, the algorithm returns all the users' allocation of information stored in  $\mathcal{U}$  and their corresponding routes  $\mathcal{R}$ .

### C. COMPUTATIONAL COMPLEXITY

The total time complexity of the Spiral-Fit algorithm is computed in two parts: The Fit function (Algorithm 1), and then the Spiral-Fit procedure in Algorithm 2.

TABLE 1. Simulation Parameters.

Parameter	Values
Topology	5 to 50 node rings
Routing strategy	Shortest Path Balanced Users (SP-BU)
Sorting strategies	DB, DL, DBL, DLB
SA Algorithms	SF, FF, Optimization
BW demands distribution	Random, Proportional, Inverse

The Fit function time complexity is proportional to the maximum link capacity ( $C$ ) and the longest user path. The longest route in a ring network topology when choosing the shortest path is equal to  $N/2$ . Therefore, the complexity is  $O(C \cdot N)$ .

The Spiral-Fit algorithm first computes all users' paths ( $O(X)$  using the node's ids); second, it sorts the network users ( $O(X^2)$ ), and finally, it searches the available spectrum for all the users following the Spiral procedure. The Spiral-Fit executes the Fit function for all the users; then its associated cost is  $O(X \cdot C \cdot N)$ . Consequently, the total computational complexity is  $O(X^2 + X \cdot C \cdot N)$ .

### IV. NUMERICAL EXAMPLES

In this section, we illustrate the Spiral-Fit proposal's performance for the elastic optical networks with static operation by comparing its output with the commonly used techniques found in the literature.

Our spectrum assignment solution was evaluated using an event-discrete simulator based on C++. We performed the simulations for different network topologies, users' sorting strategies, and bandwidth demands distribution. Table 1 summarizes the values of the relevant parameters used to perform the different simulation scenarios. We chose different bandwidth demand distribution to evaluate the influence of these criteria. Specifically, the **Random** distribution assigns the user bandwidth demands randomly but using the same seed in order to replicate the results. The **Proportional** distribution assigns the FSU demands proportional to the user's path length (number of links of the route). Last, the **Inverse** distribution define the slot requirements for all users inversely proportional to the user's path length. In our experiments, we consider that there are not guard spectrum frequencies in between the users. However, they can be easily included in the spectrum assignment procedure.

#### A. RELEVANT METRICS

First, we define relevant metrics to evaluate the performance of the different methods evaluated in this work. The most important ones for the RSA problem are the network capacity and the spectrum fragmentation metrics.

The total network capacity ( $C_{net}$ ) is the amount of FSUs used on all the network links. This is:

$$C_{net} = \sum_{\forall \ell \in \mathcal{L}} c_{\ell}, \quad (1)$$

where  $c_{\ell}$  is the spectrum capacity computed for link  $\ell$ . This metric has been commonly used to evaluate RSA algorithms [35], [39].

**TABLE 2.** Results obtained for OPT, SP-OA, DBL-SF and DLB-SF, for ring network topologies with Proportional BW demands distribution.

Nodes	$C_{net}$				$\mathcal{F}$ [%]				Time [s]			
	OPT	SP-OA	DBL-SF	DLB-SF	OPT	SP-OA	DBL-SF	DLB-SF	OPT	SP-OA	DB-SF	DL-SF
5	54	54	54	54	3,70	3,70	3,70	3,70	0,375	0,031	0,00057	0,00088
6	114	118	114	114	0,00	3,39	0,00	0,00	49,23	4,219	0,00074	0,00101
7	198	198	212	214	1,01	1,01	7,54	8,41	997,5	58,01	0,00092	0,00125
8	353	372	353	359	0,28	3,49	0,28	1,95	429.916	21.600	0,00121	0,00141
9	-	-	572	578	-	-	5,59	6,57	-	-	0,00140	0,00166
10	-	-	657	672	-	-	5,78	8,04	-	-	0,00177	0,00209
15	-	-	2.457	2.556	-	-	4,76	8,45	-	-	0,00405	0,00418
25	-	-	13.563	13.888	-	-	4,96	7,27	-	-	0,02469	0,02528
50	-	-	100.822	102.307	-	-	2,87	4,43	-	-	0,21571	0,21210

**TABLE 3.** Results obtained for OPT, SP-OA, DBL-SF and DLB-SF, for ring network topologies with Inverse BW demands distribution.

Nodes	$C_{net}$				$\mathcal{F}$ [%]				Time [s]			
	OPT	SP-OA	DBL-SF	DLB-SF	OPT	SP-OA	DBL-SF	DLB-SF	OPT	SP-OA	DB-SF	DL-SF
5	42	42	44	44	4,76	4,76	9,09	9,09	0,265	0,031	0,00059	0,00579
6	102	104	102	102	0,00	1,92	0,00	0,00	5,843	5,969	0,00068	0,00078
7	140	142	159	153	0,00	1,40	11,95	8,59	18,063	0,344	0,00088	0,00082
8	288	292	316	320	0,00	1,37	8,86	10,00	19,907	202,5	0,00106	0,00129
9	-	362	412	399	-	0,55	12,62	9,77	-	752,9	0,00129	0,00141
10	-	646	718	708	-	5,88	12,25	11,01	-	21600	0,00215	0,00200
15	-	-	1.994	2.124	-	-	6,72	12,42	-	-	0,00411	0,00392
25	-	-	7.311	7.456	-	-	9,72	11,58	-	-	0,01972	0,01528
50	-	-	63.238	64.038	-	-	7,89	9,25	-	-	0,17934	0,16638

As previously mentioned, the most used technique to solve the SA problem is First-Fit. Then, we also add the savings ( $\mathcal{S}$ ) achieved using the Spiral-Fit (SF) solution compared to the First-Fit approach's results in terms of total network capacity. Then,  $\mathcal{S}$  is evaluated as:

$$\mathcal{S} = 100 \cdot \left( \frac{C_{net}(SF) - C_{net}(FF)}{C_{net}(FF)} \right). \quad (2)$$

The presence of non-used FSUs on the network links should be avoided because it constitutes a waste of network resources. Consequently, we define the spectral fragmentation  $\mathcal{F}$  as the proportion of unused frequency slots over the total network capacity. The  $\mathcal{F}$  is evaluated as follows (Eq (3)):

$$\mathcal{F} = 100 \cdot \left( \frac{\text{Non-used FSUs}}{C_{net}} \right). \quad (3)$$

If  $\mathcal{F}$  value is equal to 0, then there is no spectrum fragmentation on the network, obtaining an optimal spectrum assignment.

We split the numerical experiments first, comparing our proposal against optimization solutions, and later against the best and most common heuristic approaches found in the literature.

## B. OPTIMIZATION

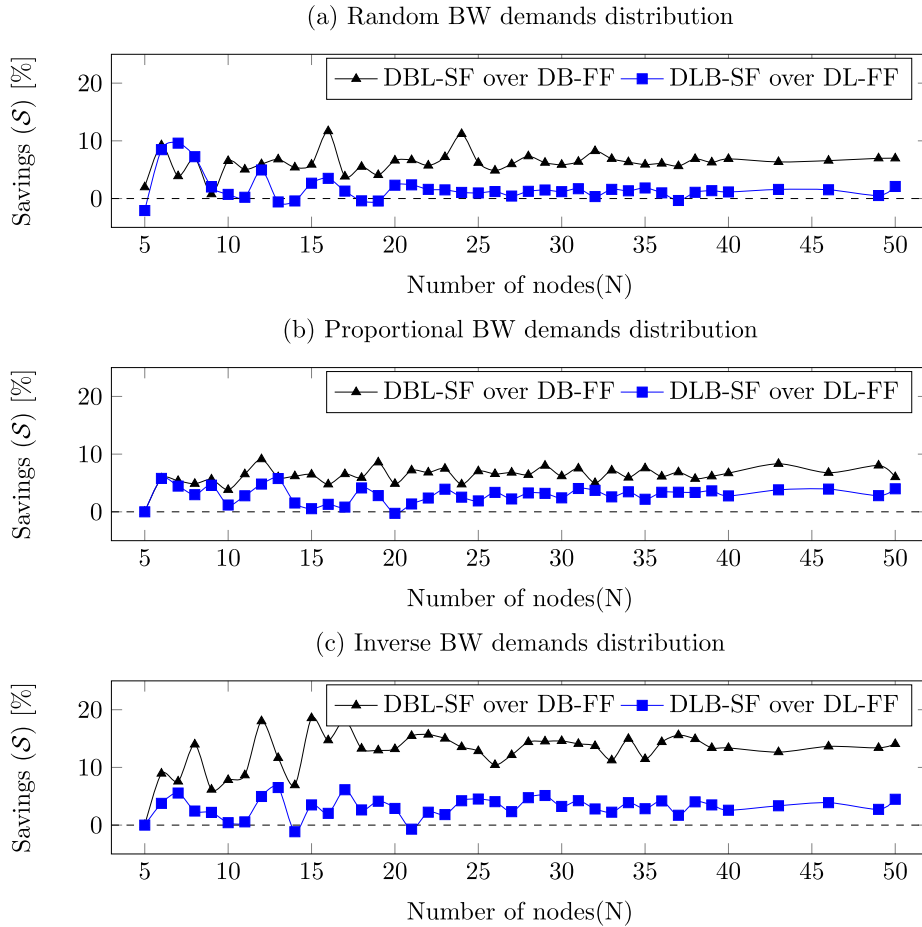
First, we compared the results obtained by the Spiral-Fit (SF) with the optimization methods found in Meza et al. [12]. These are the one-step approach (OPT) calculating both routes and spectrum assignment using optimization techniques; and the two steps approach, denoted as *Shortest Path Optimal Assignment* (SP-OA), relaxing the users' paths (pre-computing the shortest path) and solving the spectrum assignment optimally. The results obtained by the optimization

approaches, OPT and SP-OA, together with two versions of our proposals, are illustrated in Tables 2 and 3. The first one sorts the user demands according to the DBL criterion (bandwidth demands first, decreasing order, and the ties arranged by their path length), and later use the Spiral-Fit to solve the spectrum assignment. We denote this version as **DBL-SF**. The second version uses the DLB sorting variant to order the users before using the spiral approach to solve the spectrum assignment problem. We called this second version as **DLB-SF**. Both Tables 2 and 3 show the total network capacity  $C_{net}$ , the spectrum fragmentation  $\mathcal{F}$ , and the time needed to execute all the mentioned methods. The execution of the SP-OA approach was stopped after six hours [12].

In both Tables, we can appreciate that our solutions have a near-optimal performance in network capacity and spectrum fragmentation. However, our proposal execution time is orders of magnitude faster than optimization approaches. For instance, OPT and SP-OA require, on average, 8 and 6 orders of magnitude more time than DBL-SF, for the Proportional BW demands distribution, respectively. For the Inverse bandwidth scenario, both optimization approaches take four orders of magnitude extra time than the DBL-SF solution. Remark that, due to the RSA problem's complexity, optimization models can only achieve results for small networks. Therefore, optimization strategies were able to obtain solutions up to 8 nodes in Table 2, and ten nodes on Table 3 (Proportional and Inverse bandwidth demand distribution, respectively).

## C. HEURISTIC MODELS

In this subsection, we compare the same metrics ( $C_{net}$  and  $\mathcal{F}$ ) against scalable ad-hoc solutions found in the literature.



**FIGURE 3.** Savings ( $\mathcal{S}$ ) achieved by the Spiral-Fit proposals (DLB-SF and DBL-SF) over their First-Fit counterparts approaches (DL-FF and DB-SF) in terms of network capacity, for 5 to 50 nodes ring topologies using a Random (a), Proportional (b) and Inverse (c) bandwidth demands distribution.

**TABLE 4.** Average Savings  $\mathcal{S}$  obtained by the DBL-SF over DB-FF method, and DLB-SF solution over DL-FF strategy, for all bandwidth demands distribution scenarios.

Methods	Proportional	Random	Inverse
DBL-SF over DB-FF	6.44%	6.34%	13.06%
DLB-SF over DL-FF	4.28%	1.80%	5.38%

As stated in Section I, the standard approach is First-Fit (FF) due to its simplicity and good performance. Then, we compare the spiral approach (SF) to First-Fit (FF). Besides, in static operation networks, we can sort the network users improving the subsequent spectrum assignment strategy’s performance. Therefore, we consider both single sorting demands strategies (DB and DL) and compared them with our mixed criteria proposals (DBL and DLB), as displayed in Table 1. Consequently, we join the sorting demands approaches and the spectrum assignment methods found in the literature( **DB-FF** and **DL-FF**) and compare them with the techniques proposed in this work (**DBL-SF** and **DLB-SF**).

Heuristic solutions allow us to solve real-size network topologies. Then, we evaluate them for ring network topologies from 5 to 50 nodes.

Figure 3 contains the Savings  $\mathcal{S}$  achieved by the DBL-SF over DB-FF, and DLB-SF over DL-FF for the Random (Fig.IV-B), Proportional (Fig.IV-B) and Inverse (Fig.IV-B) bandwidth demands distribution. With few exceptions, the Spiral-Fit with mixed criteria for sorting the demands decreases the network capacity needed to serve the same users’ demands. The biggest capacity savings are obtained by DBL-SF over DB-FF, despite the scenario illustrated.

To obtain a general perspective of the savings metric, we present in Table 4 the average network capacity savings  $\mathcal{S}$  achieved by our proposal over the ones in the literature for Random, Proportional, and Inverse bandwidth demands distribution scenarios. We can observe that the most significant savings are obtained on the Inverse bandwidth demands distribution, in which the FSU requirements are inversely proportional to the users’ path.

Next, we focus on the spectrum fragmentation obtained by the methods compared here. Figure IV-C contains the number of non-used FSUs achieved by our proposals (DLB-SF and

DBL-SF) compared to the First-Fit strategies (DLB-FF and DBL-FF) on ring network topologies with 5 to 50 nodes for the Random bandwidth demands distribution. Broadly speaking, we can see that the Spiral-Fit diminishes the number of fragmented slots despite the variant.

Figure 4 shows how the Spiral-Fit strategies outperform the First-Fit variants. However, it is hard to see the differences in all the ring topologies due to the graph scale (the same situation happens in all the bandwidth demands distribution scenarios). Therefore, we add Figure 5 showing the percentage of spectrum fragmentation  $\mathcal{F}$  obtained by both the Spiral-Fit variants (DBL-SF and DLB-SF) and both First-Fit variants (DBL-FF and DLB-FF) for 5 to 50 nodes ring network topologies for the Random (Fig.IV-C), Proportional (Fig.IV-C), and Inverse (Fig.IV-C) FSU requirements

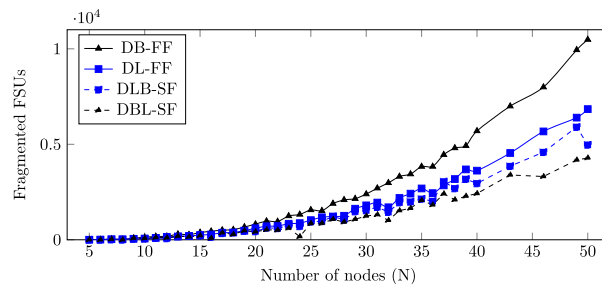


FIGURE 4. Number of fragmented FSUs obtained by DLB-SF, DBL-SF, DL-FF and DB-FF methods on a Random bandwidth demands distribution.

distribution scenarios. Figure 5 illustrates that the spectrum fragmentation of the Spiral-Fit methods is lower than the

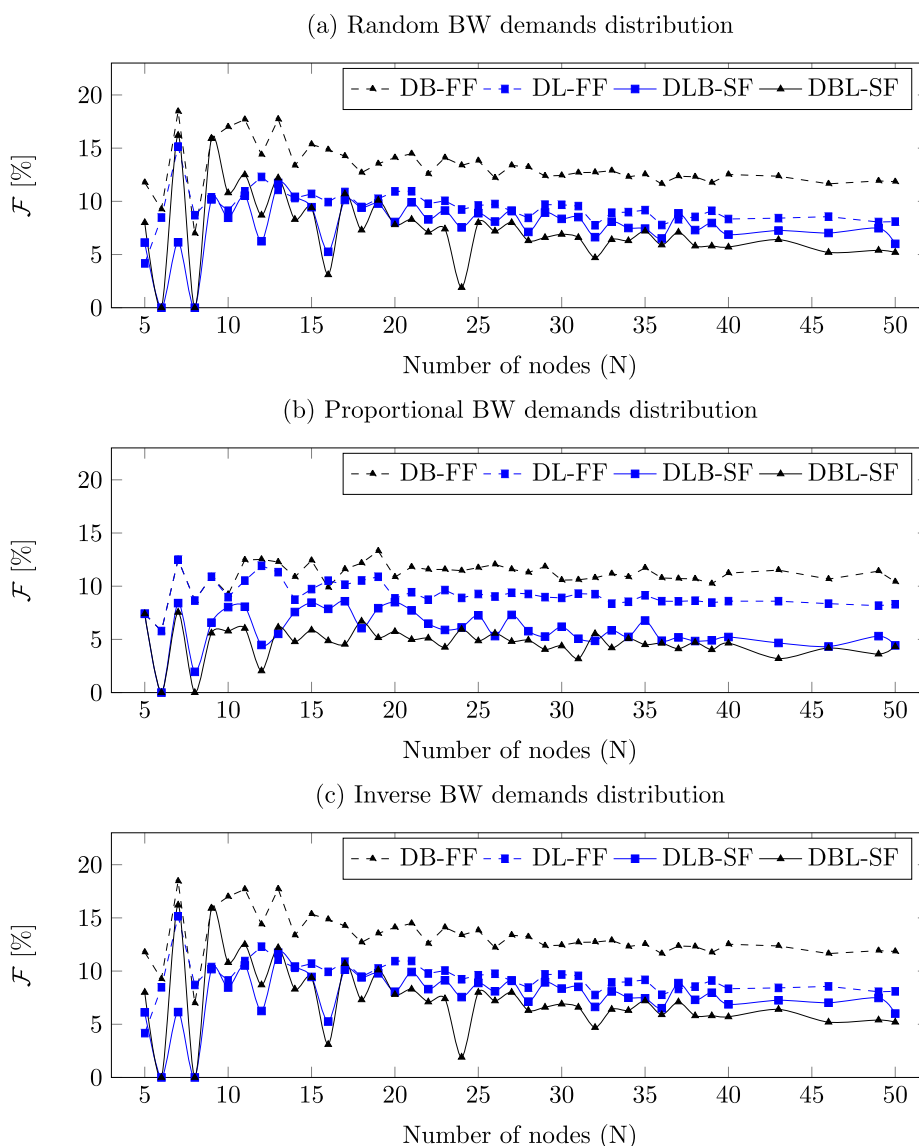


FIGURE 5. Spectrum Fragmentation  $\mathcal{F}$  obtained for the DLB-SF, DBL-SF, DB-FF, and DL-FF methods for 5 to 50 node ring topologies with Random (a), Proportional (b) and Inverse (c) bandwidth demands distribution scenarios.



**TABLE 5.** Average Spectrum Fragmentation  $\mathcal{F}$  obtained by all the Spiral-Fit and First-Fit variants for all bandwidth demands scenarios.

Method	Proportional	Random	Inverse
DBL-SF	3.96%	7.57%	8.4%
DLB-SF	6.01%	7.77%	10.75%
DB-FF	9.24%	9.47%	13.99%
DL-FF	11.03%	13.27%	20.57%

First-Fit approaches for all the ring network topologies and bandwidth demands scenarios.

Finally, we illustrate in Table 5 the average spectrum fragmentation  $\mathcal{F}$  achieved by the Spiral-Fit and First-Fit approaches for the Random, Proportional, and Inverse bandwidth requirements scenarios. The Spiral-Fit diminishes the overall network spectrum fragmentation compared to the FF approaches. For the DBL sorting variant, SF decreases the spectrum fragmentation compared to the DB-FF approach is 57%, 20%, and 40% on the proportional, random, and inverse scenarios, respectively. Meanwhile, on the DLB sorting variant, SF reduces the spectral fragmentation against the DL-FF strategy in 45%, 41%, and 48%, for the proportional, random, and inverse cases, respectively.

## V. CONCLUSION

This work presents a new method to solve the spectrum assignment (SA) problem on ring network topologies for elastic optical networks. First, we sort the users previous to the network assignment, using their paths and bandwidth demands in different variants. Later, we harvest the network topology to decrease the required network capacity to serve all the users and diminish the spectrum fragmentation in all the network links. The new method, called Spiral-Fit, searches for available FSUs in a correlative manner, serving the users following the ring topology in a spiral form (or concentric rings).

Clearly, the proposed Spiral-Fit solution outperforms the First-Fit strategy. This performance can be explained since we harvest the ring topology to define a better order policy. The search for available FSUs is done in a specific order, consecutively serving the users, following the ring topology. Therefore, the users are forcibly allocated in a more tidy way, and, in the end, improving both the overall network capacity required to attend them all and consequently decreasing the network spectrum fragmentation. For instance, we contrast our proposal against the optimal solution, obtaining a near-optimal performance with a more simple, fast, and scalable approach. Later, comparing our proposal against the commonly found ad-hoc solution in the literature. Our results were better in terms of network capacity and spectrum fragmentation. In fact, on a total of 117 cases evaluated in this work, nearly 100% of the results were better than the heuristics strategies found in the literature.

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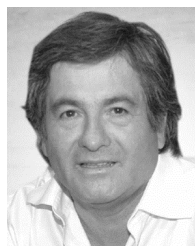
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