A Spiral Approach to Solve the Routing and Spectrum Assignment Problem in Ring Topologies for Elastic Optical Networks

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Abstract: In this paper, we propose a simulation-based strategy to solve the routing and spectrum assignment problem in elastic optical networks with a static network operation for ring network topologies. First, the proposed method arrange the network users decreasingly according to their bandwidth demands. Next, we introduce the Spiral policy to allocate the frequency spectrum. This policy consists of assigning the resources to the user in a correlative manner, following a spiral, taking advantage of the ring topology. Remark that each user path is fixed, computed by any shortest path algorithm. We assess the performance and robustness of our model by comparing the proposal with two optimization models in small rings (5-8 nodes) and with the most referenced methods found in the literature for larger ring networks (5-50 nodes). The results show that consistently our method outperforms the ones proposed in the literature, in terms of network cost and fragmentation.

1 INTRODUCTION

Most of the digital data are carried by optical networks. The capacity of these networks has grown vastly over the decades through the appearance of newer technologies. So far, these networks have been able to carry out this traffic growth by introducing several technological improvements. Nevertheless, researchers have found an impending capacity crunch in optical communications. It refers to the fact that the optical fiber capacity is not limitless, and said capacity limit can be reached soon (Ellis et al., 2016; Waldman, 2018). The foregoing requires an evolution of current optical architectures to keep up the unceasing growth of the Internet. Since is the base of all our communication system, any progress means not only better communication networks but to meaningful social and economic improvements.

In this context, there are two possible solutions. First, to install more infrastructure at reaching the maximum fiber capacity. This option is simple but involves huge investments. Thus, this strategy should be avoided. Second, ro improve resources management in order to efficiently use the installed infrastructure. This second alternative is the more convenient option today, considering that current networks do not operate efficiently.

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Currently, the optical network operation is inefficient due some technological features. One of them is that the frequency spectrum assigned to each communication is fixed, according to the International Telecommunication Union (ITU) standard. This is 50[GHz] per channel (Iversen Villy, 2002). Nowadays, to satisfy said demand growth, the Internet Service Providers are rising the bit-rates using this standard transmission scheme. However, this process involves limitations, due to technical difficulties transmitting high bit-rates through long distances (Gerstel et al., 2012).

To solve the prior problem, a new paradigm has been proposed, called "Elastic Optical Network" (EON) (Layec et al., 2013; Gerstel et al., 2012; Sambo et al., 2012). The EONs allows to flexibly use the frequency spectrum to attend different traffic needs adaptively, giving only the necessary bandwidth to each user. To achieve that, the frequency spectrum is divided into frequency slots units (FSU) with a fixed bandwidth associated, and the FSU are grouped to satisfy the bandwidth required for each user. This has been an important topic of investigation for the few last years and, still needs research and development to be implemented in practice.

The design of elastic optical networks is a hot topic both at the academic and industrial levels. In particular, the design of optical networks decomposes into many different tasks. One of these tasks con-

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sists in assigning a path and a portion of the spectrum to each network user. This problem is known as the *Routing and Spectrum Allocation* (RSA) problem.

The RSA problem consists on find, for each user, a source-destination path, with available spectrum according to the user demand. This resource allocation is subject to the following constraints. First, each FSU can host one user at the same time; second, the same FSU allocated to the said user must be available in all the links on the user path; and in case that the user requires more than one FSU, the spectrum assigned must be consecutive (contiguous). The RSA problem is crucial in EON planning, however is a NP-hard (López and Velasco, 2016) problem. Therefore, in this article, we solve the RSA problem by means of simulation.

This paper focuses on solving the RSA problem for ring network topologies. For this end, we design a strategy based on heuristics and simulation. Each user path is fixed and computed prior to the network operation using a shortest path algorithm. To assign the frequency spectrum to each user, we used the well known First-Fit policy. However, we introduce the "Spiral" concept, which seeks to assign the resources using the ring topology as an advantage, sorting and allocating the FSU to each user in spiral order. By doing so, this strategy diminishes the network total cost and the spectrum fragmentation.

The remainder of this paper is as follows: In Section 2 we present the state of art on RSA strategies. Next, Section 3 presents our proposal to solve said problem be means of simulation. Section 4 contains some numerical examples. And finally, we give some conclusions and remarks in Section 5.

2 STATE OF ART

To solve the Routing and Spectrum Allocation problem there are typically 2 scenarios: the static and dynamic case. On the static case, the resource demands are fixed and well known, hence, the routes and resources allocated are available to the user permanently. In this scenario, the goal is to maximize the spectrum usage (Talebi et al., 2014a; Meza et al., 2016). On the other hand, in the dynamic scenario the users request for resources only when they need to transmit. These demands can change over time, and the resources are release after the user ends to send data. The current optical network operate pseudo-statically. This is the resources are allocated to the user during very long periods of time (for instance, during a contract), which can be considered as permanent on the network operation. Hence, our research is focused on the static scenario.

One possible method to solve the RSA is by optimization. In literature there are several solutions. However these approaches are highly complex, due to the space state exponential growth, bringing scalability problems and inability to obtain a solution in a reasonable time for real network topologies. The complexity of these models have been widely analyzed in literature by López and Velazco (2016) (López and Velasco, 2016), Simmons (2014) (Simmons, 2014) y Talebi et al. (2014) (Talebi et al., 2014b).

Meza et al. (2016) (Meza et al., 2016) proposed two optimization models for ring topologies: a pure ILP model to solve the RSA problem simultaneously (*One Step Approach*) and another model composed by two steps *(Two Step Approach)* denoted as Shortest Path Optimal Assignment (SP-OA). The last strategy uses a shortest path heuristic to solve the routing problem and optimization to solve the spectrum assignment. Both schemes show the prior mentioned difficulties, in which both strategies obtain results until 8 and 9 nodes ring topologies, respectively.

The prior discussion reveals that it is necessary to develop heuristics solution allowing to obtain near optimal solutions with scalability to real network topologies.

The RSA problem is usually solved in two stages (Wen et al., 2011). First, the route is assigned, for instance the shortest path. Then, the amount of FSUs on each link is computed, considering that the spectrum chosen on all the links on the user path must be the same (Takagi et al., 2011). Notice that the previous restriction allows to satisfied the wavelength continuity constraint involved in optical networks.

The standard spectrum allocation (SA) techniques found in literature are Random-Fit (RF), Most-Used (MU) and First-Fit (FF) among several variations (Talebi et al., 2014a). RF assigns the frequency spectrum randomly, leading to high spectrum fragmentation (unused spectrum) (Ahumada et al., 2014). MU chooses the slots that are most-used in the network. On the other side, FF is the most common and fastest method used to date. In fact, Abkenar y Rahbar (2017) (Shirin Abkenar and Ghaffarpour Rahbar, 2017) shows that most approaches use the First-Fit scheme. In this scheme the FSUs are considered as a sequence. When searching for an available FSU, the search starts on the first FSU in the sequence. The request is accepted if the needed number of contiguous slot is available on all the links belonging to the predetermined user fixed path. Otherwise, the same request is send to the next slots on the sequence. The process continues on the same way, until there are sufficient contiguous FSU available on all the links of the path (Koganti and Sidhu, 2014; Chatterjee et al., 2013).

As consequence of the SA methods, there is spectrum fragmentation over the network frequency spectrum (Chatterjee et al., 2015; Christodoulopoulos et al., 2011). This refers to fact that there might by some free FSU in the middle area not been used despite being available on the network. Said phenomenon is important due to the fact it can produce a meaningful waste of bandwidth, if not properly controlled. Thus one of our objectives is to minimize the spectrum fragmentation on the network.

In addition, it is also important the order to allocate the resources to the user, affecting the network capacity required and the spectrum fragmentation, as pointed out by Simmons (2014) (Simmons, 2014) y Talebi et al. (2014) (Talebi et al., 2014b), which indicates that a decreasing order of user according to their bandwidth and length obtains are the more efficient approaches.

3 SIMULATION STRATEGY

This section comprises the main contribution of the article. First, we explain the model used and the associated assumptions. Then, we explain the simulation strategy to solve the RSA problem.

3.1 Model and Assumptions

We represent the network by a graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$, where $\mathcal{N}$ is the set of nodes and $\mathcal{L}$ the set of directional links, with cardinalities $|\mathcal{N}| = N$ and $|\mathcal{L}| = L$.

The set of users $\mathcal{U} \subset \mathcal{N}^2$, with cardinality $|\mathcal{U}| = U$, is composed by all the source-destination pairs. Each u element contains several values such as: $\langle s_u, d_u, i_u, bw_u \rangle$, where s_u is the source node, d_u the destination node, bw_u is the number of adjacent FSUs defined per user, considering that i_u is the index referencing the first frequency spectrum allocated.

User u transmission follows a particular route or path between its source and its terminal, expressed by r_u, and we denote by $\mathcal{R} = \{r_u \mid c \in \mathcal{U}\}$ the set of routes used. These routes are fixed and can be computed by any algorithm available in the literature (Dijkstra, 1959; Jara et al., 2017; Koganti and Sidhu, 2014) prior to network operation. Due to the fact that the network topologies considered are ring topologies, we can divide the set $\mathcal{R}$ in two subsets. The subset $\overrightarrow{\mathcal{R}} \subseteq \mathcal{R}$ contains the path in clockwise direction, and the subset $\overleftarrow{\mathcal{R}} \subseteq \mathcal{R}$ composed by the counterclockwise routes.

In EON, the frequency spectrum is divided in small frequency segments, denoted as Frequency Slot Units (FSU). Then, let $\mathcal{BW} = \{bw_u | u \in \mathcal{U}\}$ be the set of bandwidth requirements measured as a number of FSU per user $u \in \mathcal{U}$.

Let $\mathcal{C} = \{c_\ell | \ell \in \mathcal{L}\}$ be the set containing the capacity of each network link $\ell \in \mathcal{L}$, in which the capacity c_ℓ is the number of FSU allocated to the link ℓ, and let $\mathcal{F} = \{f_{i\ell} | i \leq c_\ell, \ell \in \mathcal{L}\}$ be the set of FSU allocated on each network link, where i is the FSU index and ℓ the corresponding network link.

3.2 Routing Strategy

The routing problem consists in finding, for each connection, a route to be followed by the data to be transmitted, while taking into account some spectrum assignment scheme, and with the smallest cost possible. In this paper, the users path are computed fixed, only one per user, prior the network operation.

In this paper, we consider a ring network topology with N nodes, in which every user has two possible routes: clockwise or counterclockwise. The path then is chosen as the shortest path measured by the number of hops from source to destination. However, in the case the ring has a pair number of nodes (par value of N), the users communicating through the network diameter, these are the users with a distance equals to $N/2$ between the source and destination node, both clock and counter-clock paths are equal in length. In these cases, the criteria to assign the routes is to balance the network links, thus half (or close to half) of the user will have a clockwise route, and the remaining user will have a counterclockwise path.

In algorithmic form, the procedure can be written as shown in Figure 1. Symbolically, its execution will be written $\mathcal{R} := Routing(\mathcal{U}, \mathcal{R})$, since its output is the set of all the users path.

3.3 Spectrum Allocation Strategy

The spectrum assignment (*SA*) problem consists in finding, for each user $u \in \mathcal{U}$, the same FSUs available on all the links in its route. This means, it searches a number of adjacent slots on each link, using the same FSU in the whole route. Here we use the First-Fit spectrum assignment approach since it is simple and performs adequately in terms of network cost with a small computational overhead. In a nutshell, the method orders the different FSU available, and sequentially searches until there is one available on the whole path; if not, the method allocates the user at the end, after the last FSU allocated on the links in the user path.

Algorithm 1: Routing.

procedure ROUTING($\mathcal{U}$, $\mathcal{R}$)
  $balance \leftarrow 0$
  for all $u \in \mathcal{U}$ **do**
    Calculate routes of minimum length
    if there is just one result **then**
      if r_u is clockwise **then**
        $\overrightarrow{\mathcal{R}} = \overrightarrow{\mathcal{R}} \cup r_u$
      else
        $\overleftarrow{\mathcal{R}} = \overleftarrow{\mathcal{R}} \cup r_u$
    else
      if $balance > N/2$ and $N\%2 = 0$ **then**
        $\overleftarrow{\mathcal{R}} = \overleftarrow{\mathcal{R}} \cup r_u$
      else
        $\overrightarrow{\mathcal{R}} = \overrightarrow{\mathcal{R}} \cup r_u$
        $balance \leftarrow balance + 1$

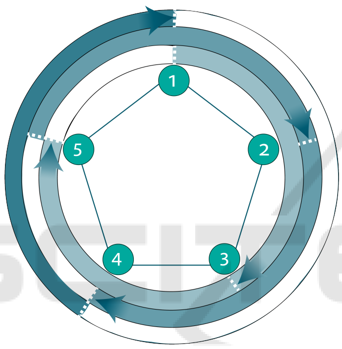

Figure 1: Spiral routing allocation example.

To assign each user we use the First-Fit scheme to solve the spectrum allocation. However, we use a predefined order to follow the FF allocation. The main idea of our proposal is to create subsets of users according to some given criteria. Then, we follow said subsets to execute the FF algorithm, taking into advantage the form of the topology, this means to try to form rings or a spiral when allocating each user. In this way giving some order when assigning the frequency spectrum. To illustrate this way of spectrum allocation in figure 1 we present a spiral spectrum allocation. In figure 1 the circumference surrounding the ring represents a FSU, and the bigger the circle radio, the bigger is the FSU index. The arrows on the figure indicate both the path and the resource allocation direction. The order of the user is chosen in a spiral order, hence the user allocation order is: 1-3, 3-5, 5-2, 2-4, 4-1. Remark that the spiral resource allocation is obtain since the next user to be allocated has a source node equal to the destination node of the prior user in the list.

Let $\mathcal{U}_b \subset \mathcal{U}$ be the set of user with the same bandwidth requirements $b = bw$, with $bw \in \mathcal{BW}$. Thus,

Algorithm 2: DB-SFF.

procedure DB-SFF
  $\mathcal{R} = \emptyset$
  for all $\ell \in \mathcal{L}$ **do**
    $c_\ell = 0$
  Routing($\mathcal{U}$, $\mathcal{R}$);
  $\{\mathcal{U}_1, ..., \mathcal{U}_b\}$ = Classify(BW, $\mathcal{U}$);
  for each $\mathcal{U}_b \in \mathcal{U}$ **do**
    $totalAssigned \leftarrow 0$
    sort($\mathcal{U}_b$) ▷ sort by length, decreasing order
    Assign($\mathcal{U}_b[1]$)
    $nextSource \leftarrow \mathcal{U}_b[1].d_u$
    while $totalAssigned \neq |\mathcal{U}_b|$ **do**
      for $j \leftarrow 0$ **to** $|\mathcal{U}_b|$ **do**
        if $\mathcal{U}_b[j].s_u = nextSource$ **then**
          Assign($\mathcal{U}_b[j]$)
          $nextSource \leftarrow \mathcal{U}_b[j].d_u$
        else if $j = |\mathcal{U}_b|$ **then**
          $nextSource \leftarrow nextSource + 1$
  return $\mathcal{U}, \mathcal{R}, \mathcal{C}$

the set of user $\mathcal{U}$ is decomposed in subsets U_b, each subset is sorted according to the route length in decreasing order. Then, we start to allocate the user using the subset U_b with bigger bandwidth requirements, this is the subset U_b with b with a higher value. The spectrum assignment is made following the First-Fit strategy, but following a Spiral order, as previously explained. If there is not an user on U_b to fulfill the Spiral rule, then the next user to be allocated will be the next in subset. If all user in U_b have been allocated, then we continue with the next U_b subset, until all the network user their spectrum assigned.

The pseudo-code of the procedure can be written as shown in Figure 2. The inputs of the simulations are the network topology ($\mathcal{G}(\mathcal{N}, \mathcal{L})$), and the set of users ($\mathcal{U}$) with its respective bandwidth demands ($\mathcal{BW}$). On the other hand, the outputs are the set of routes ($\mathcal{R}$) connecting all the user in $\mathcal{U}$, the set of all the links capacity ($\mathcal{C}$) measured as number of FSUs, and the set of FSUs allocated on each network link ($\mathcal{F}$).

4 NUMERICAL EXAMPLES

To compare our proposal with other methodologies, it is necessary to evaluate their performances. The most important metrics for the RSA problem are: the cost of the network and the spectrum fragmentation obtained.

As commonly used (Ramaswami et al., 2009; Simmons, 2014; Talebi et al., 2014b), in this work

Table 1: Table comparing the proposed method (DB-SFF) with both optimization methods proposed in (Meza et al., 2016) for ring network topologies with bandwidth requirements proportional to the user path length.

Nodes	C_{net}			SFR [%]			Time [s]		
	Optimal	SP-OA	DB-SFF	Optimal	SP-OA	DB-SFF	Optimal	SP-OA	DB-SFF
5	54	54	54	3,70	3,70	7,40	0.375	0,031	0,00057
6	114	118	114	0,00	3,39	0,00	49,23	4,219	0,00074
7	198	198	212	1,01	1,01	7,54	997,5	58,01	0,00092
8	353	372	352	0,28	3,49	0,00	429916	21600	0,00121
9	-	-	572	-	-	5,59	-	-	0,00140
10	-	-	657	-	-	5,78	-	-	0,00177
25	-	-	13563	-	-	4,96	-	-	0,02469
50	-	-	100822	-	-	2,87	-	-	0,21571

the total network cost C_{net} is defined as the sum of all FSU of all network links, that is,

$$C_{net} = \sum_{\ell}^{\mathcal{L}} c_\ell \tag{1}$$

, where c_ℓ is the spectrum capacity assigned to link ℓ. This definition is justified because the cost of most components in an optical network is mainly affected by this parameter. In fact, it determines how many infrastructure resources are needed to achieve the network operation (Banerjee and Mukherjee, 2000).

As mentioned in the state of art, the non-used FSU on the network link should be avoided. Thus the spectrum fragmentation SFR (percentage) is the sum of all the fragmented FSU in relation to the network total cost C_{net}. This is

$$SFR = 100 \cdot \frac{\text{Number of Non-used FSU}}{C_{net}}. \tag{2}$$

In case the SFR value obtained is 0, the resource allocation is optimal, thus there are not unused spectrum portions.

As prior mentioned, First-Fit is the most referenced scheme to solve the spectrum assignment problem since it is a fast and simple strategy with good performance. In the text, we called it `FF`. In consequence, we adopt this approach in all the numerical examples. However, recall that the Spiral rule to allocate the user on the network alters the FF strategy by defining an specific order to assign the user on the network following a spiral o concentric rings order. In the experiments, we denoted it as `SFF`.

To judge the methods under several scenarios, we evaluate them by means of simulation on diverse ring topologies, having different sizes. For a fair comparison, the procedures considered here use a fixed routing shortest path (estimated by Dijkstra's algorithm).

4.1 Comparison with Optimization Models

First, we compared the results obtained by our proposal (DB-DFF) and the optimization methods proposed by Meza et.al. (Meza et al., 2016), these are the full optimization method (Optimal) and the Two Steps Approach denoted as *Shortest Path Optimal Assignment* (SP-OA).

Meza et al. (Meza et al., 2016) defined two forms to define the users bandwidth requirements, these are: proportional to the users path length, and inversely proportional to the users route length. In Tables 1 and 2 we present the results obtained the Optimal, SP-OA and our DB-SFF, showing the network total cost C_{net}, spectrum fragmentation SFR and the time needed to execute the method.

As previously discussed on the state of art section, due to the RSA problem complexity, both optimization methods can be executed on small networks. Despite our strategy can be executed in topologies with 50 (and more) nodes, on the Table 1 with proportional bandwidth requirements we can compare our proposal to optimization only from 5 to 8 node ring networks, and in the Table 2 with inversely proportional bandwidth requirements we can contrast the strategies from 5 to 10 node rings.

We can see in Tables 1 and 2 that in some cases the DB-SFF is able to achieve the optimum solution, however, in most cases it does not reach said objective. We can conclude that our proposal achieves results close to the optimal solution on the studied scenarios.

4.2 Comparison with Heuristic Models

In this section we compare the same metrics analyzed on the previous section (C_{net} and SFR) for ring net-

Table 2: Table comparing the proposed method (DB-SFF) with both optimization methods proposed in (Meza et al., 2016) for ring network topologies with bandwidth requirements inversely proportional to the user path length.

Nodes	C_{net}			**SFR** [%]			**Time [s]**		
	Optimal	SP-OA	DB-SFF	Optimal	SP-OA	DB-SFF	Optimal	SP-OA	DB-SFF
5	42	42	44	4,76	4,76	9,09	0.265	0,031	0,00059
6	102	104	102	0,00	1,92	0,00	5.843	5,969	0,00068
7	140	142	159	0,00	1,40	11,95	18,063	0,344	0,00088
8	288	292	316	0,00	1,37	8,86	19,907	202,5	0,00106
9	-	362	412	-	0,55	12,62	-	752,9	0,00129
10	-	646*	718	-	5,88	12,25	-	21600	0,00215
25	-	-	7311	-	-	9,72	-	-	0,01972
50	-	-	63238	-	-	7,89	-	-	0,17934

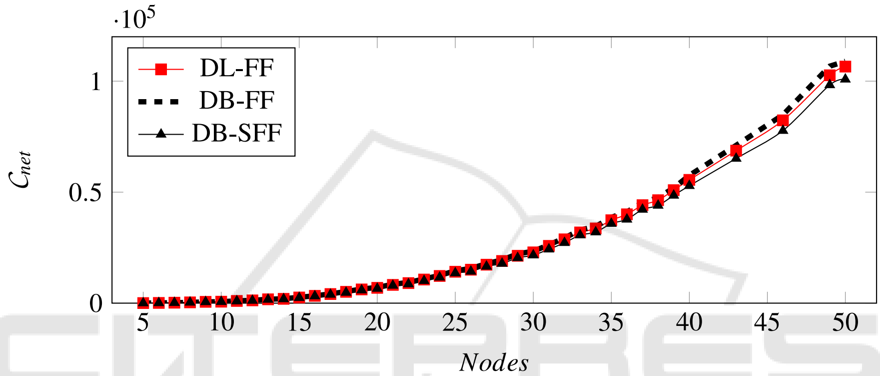

Figure 2: C_{net} obtained by DB-SFF, DB-FF and DL-SFF on ring topologies between 5 to 50 nodes.

works from 5 to 50 nodes regarding to the best strategies in literature (Simmons, 2014). These are:

Decreasing Bandwidth First Fit (DB-FF): We use the same routing strategy explained in section 3. The users are sorted by their bandwidth requirements in a decreasing order, and sequentially searching for a spectrum available using the usual First-Fit technique.

Decreasing Length First Fit (DL-FF): Again, we use the same routing than before. The users are sorted in decreasing order according to their route length, and follows the First-Fit scheme to solve the spectrum allocation.

The methods here presented are executed using three bandwidth requirements strategies: proportional, inversely proportional to the route length and arbitrarily, counting 117 scenarios total. Due to lack of space, only the proportional scenario is presented in the text.

We can see in Figure 2, the total cost obtained by all the heuristic method analyzed here (DB-FF, DL-FF and our proposal DB-SFF) is presented. Despite the algorithm, the total network cost increases similarly (order N^4) as the number of network nodes increases on the ring topologies.

Even though Figure 2 helps us to see the relation between C_{net} and the number of nodes, we can not clearly visualize the performance of our proposal against the DB-FF and DL-FF. Thus in Table 3 we illustrate the mean savings (*Savings*), measured in percentage, obtained by our proposal respect to the best approaches in literature (DB-FF and DL-FF) for the three bandwidth requirements strategies. The *Savings* are obtained according to the following equation:

$$Savings[\%] = 100 \cdot \frac{C_{net}(Ref) - C_{net}(DB-SFF)}{C_{net}(Ref)}, \quad (3)$$

where Ref is the method to be compared to.

In Table 3 we can see that DB-SFF presents consistent savings in all cases respect to DB-FF and DL-FF, obtaining in the worst case scenario mean savings of 4.83% in all the compared scenarios.

4.2.1 Spectrum Fragmentation

Finally, in this section we analyze the spectrum fragmentation obtained by the methods compared in here.

Figure 3 shows the spectrum fragmentation obtained by the DB-SFF, DB-FF and DL-FF for ring

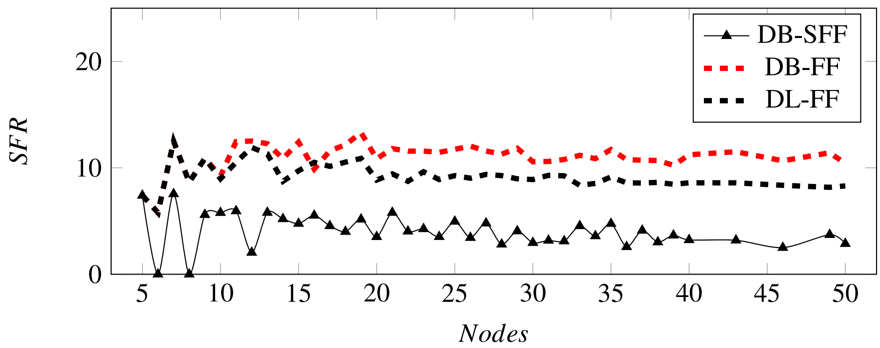

Figure 3: SFR comparison between DB-SFF and DB-FF according to the number of nodes.

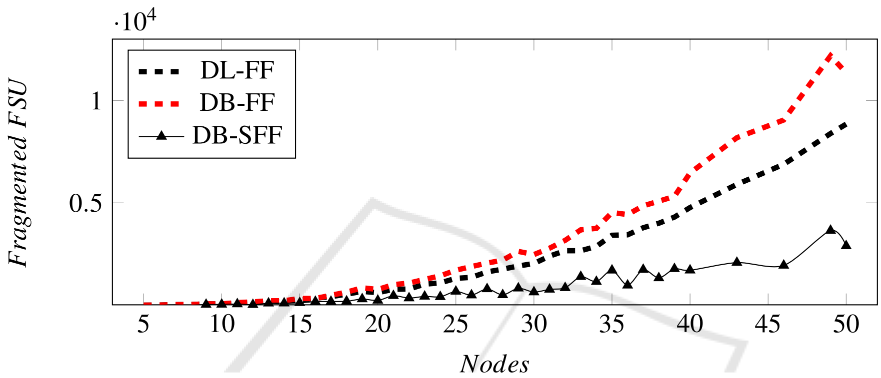

Figure 4: Number of empty FSU according to the number of nodes for DB-FF and DB-SFF.

Table 3: Mean C_{net} savings obtained by DB-SFF respect the reference algorithms.

Reference	Proportional	Arbitrary	Inversely
DB-FF	6.92%	6.14%	13.06%
DL-FF	4.83%	7.57%	5.60%

Table 4: Mean $\overline{SFR}$ obtained by the three algorithms on the three bandwidth requirements scenarios.

Algorithm	Proportional	Arbitrary	Inversely
DB-SFF	3.96%	7.57%	8.4%
DB-FF	9.24%	9.47%	13.99%
DL-FF	11.03%	13.27%	20.57%

topologies between 5 and 50 nodes for the proportional bandwidth requirements scenario. In Figure 3 is shown that for all network topologies the spectrum fragmentation of DB-SFF is lower than DB-FF. In comparison to the DL-FF in Figure 3 there is a tighter difference. However, except a few cases, our proposal obtains better results than DL-FF. The prior can be shown in Table 4 where the mean spectrum fragmentation (SFR) is presented for all the methods and all the bandwidth requirements strategies previously presented.

Finally, in Figure 4 we present the total number of slots fragmented on the network obtained by the three methods analyzed in this article. It is clear that our methods obtains much better results in terms of spectrum fragmentation than the commonly used RSA solutions, obtaining in the worst-case scenario an 8.4% percentage of spectrum fragmentation.

5 CONCLUSIONS

In this work, we present a novel method to solve the crucial problem known as Routing and Spectrum Allocation. Our method computes: all the users path by the shortest path algorithm, but balancing the amount of users on the links; and the amount of slots (frequency spectrum) required by each user following the First-Fit strategy. However, the order used to allocate the users is defined in a decreasing order of bandwidth requirements, using a spiral approach to follow the users assignment.

The optimization models obtain results only for small networks, with an execution time prohibitively high. Hence, we consider the optimal as an ideal, but no feasible strategy. On the other hand, our method has results close optimal solutions with approximately a 6,6% of network fragmentation. Moreover, the proposed method shows better results than the best strategies from the literature, with savings in the order of 40% in terms of network fragmentation. Notice that, for the prior comparison we perform 117 scenarios of simulation for each heuristic method, and almost a 100% of the results performed better than the heuristic strategies available in the literature.

Further work would be to solve the RSA problem on mesh network topologies and considering a dynamic network operation, adjusting the strategy of this work to said contexts.

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REFERENCES

Ahumada, R., Leiva, A., Alonso, F., Fingerhuth, S., and Farías, G. (2014). Spectrum Allocation Algorithms for Elastic DWDM Networks on Dynamic Operation. *IEEE Latin America Transactions*, 12(6):1012–1018.

Banerjee, D. and Mukherjee, B. (2000). Wavelength-routed optical networks: Linear formulation, resource budgeting tradeoffs, and a reconfiguration study. *IEEE/ACM Transactions on Networking*, 8(5):598–607.

Chatterjee, B. C., Sarma, N., and Oki, E. (2015). Routing and Spectrum Allocation in Elastic Optical Networks: A Tutorial. *IEEE Communications Surveys and Tutorials*, 17(3).

Chatterjee, B. C., Sarma, N., and Pratim Sahu, P. (2013). Review and Performance Analysis on Routing and Wavelength Assignment Approaches for Optical Networks. *IETE Technical Review*, 30(1):12–23.

Christodoulopoulos, K., Tomkos, I., and Varvarigos, E. a. (2011). Elastic Bandwidth Allocation in Flexible OFDM- based Optical Networks. *Journal of Lightwave Technology*, 29(9):1354 – 1366.

Dijkstra, E. W. (1959). A note on two problems in connection with graphs. *Numerische Mathematik*, 1(1):269–271.

Ellis, A. D., Suibhne, N. M., Saad, D., and Payne, D. N. (2016). Communication networks beyond the capacity crunch. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 374(2062):20150191.

Gerstel, O., Jinno, M., Lord, A., and Yoo, S. J. B. (2012). Elastic optical networking: a new dawn for the optical layer? *Communications Magazine, IEEE*, 50(2):s12–s20.

Iversen Villy, B. (2002). Teletraffic Engineering Handbook.

Jara, N., Vallejos, R., and Rubino, G. (2017). A method for joint routing, wavelength dimensioning and fault tolerance for any set of simultaneous failures on dynamic WDM optical networks. *Optical Fiber Technology*, 38:30–40.

Koganti, R. T. and Sidhu, D. (2014). Analysis of routing and wavelength assignment in large WDM networks. In *Procedia Computer Science*, volume 34, pages 71–78.

Layec, P., Morea, A., Vacondio, F., Rival, O., and Antona, J.-C. (2013). Elastic optical networks: The global evolution to software configurable optical networks. *Bell Labs Technical Journal*, 18(3):133–151.

López, V. and Velasco, L., editors (2016). *Elastic Optical Networks*. Optical Networks. Springer International Publishing, Cham.

Meza, C., Jara, N., Albornoz, V. M., and Vallejos, R. (2016). Routing and spectrum assignment for elastic, static, and without conversion optical networks with ring topology. In *2016 35th International Conference of the Chilean Computer Science Society (SCCC)*, pages 1–8.

Ramaswami, R., Sivarajan, K., and Sasaki, G. (2009). *Optical Networks: A Practical Perspective, 3rd Edition*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 3rd edition.

Sambo, N., Castoldi, P., Cugini, F., Bottari, G., and Iovanna, P. (2012). Toward high-rate and flexible optical networks. *Communications Magazine, IEEE*, 50(5):66–72.

Shirin Abkenar, F. and Ghaffarpour Rahbar, A. (2017). Study and Analysis of Routing and Spectrum Allocation (RSA) and Routing, Modulation and Spectrum Allocation (RMSA) Algorithms in Elastic Optical Networks (EONs).

Simmons, J. M. (2014). *Optical Network Design and Planning*. Optical Networks. Springer International Publishing, Cham.

Takagi, T., Hasegawa, H., Sato, K., Sone, Y., Kozicki, B., Hirano, A., and Jinno, M. (2011). Dynamic routing and frequency slot assignment for elastic optical path networks that adopt distance adaptive modulation. In *2011 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference*, number March 2011, pages 1–3.

Talebi, S., Alam, F., Katib, I., Khamis, M., Salama, R., and Rouskas, G. N. (2014a). Spectrum management techniques for elastic optical networks: A survey. *Optical Switching and Networking*, 13:34–48.

Talebi, S., Alam, F., Katib, I., Khamis, M., Salama, R., and Rouskas, G. N. (2014b). Spectrum management techniques for elastic optical networks: A survey.

Waldman, H. (2018). The Impending Optical Network Capacity Crunch. *Sbfoton Conference*, pages 0–3.

Wen, K., Yin, Y., Geisler, D. J., Chang, S., and Yoo, S. J. B. (2011). Dynamic On-demand Lightpath Provisioning Using Spectral Defragmentation in Flexible Bandwidth Networks. In *2011 37th European Conference and Exhibition on Optical Communication*, volume 1, Washington, D.C. OSA.