A Joint RSA Algorithm for Dynamic Flexible Optical Networking

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***Abstract*— We propose a novel algorithm to solve the Routing and Spectrum Allocation (RSA) problem in dynamic flexible grid optical networks. Unlike most previous proposals, the algorithm solves the R and SA problems jointly by exhaustively searching the solution space and taking the network state into account. As a result, the shortest possible path with enough spectrum availability is allocated to establish the connections. Simulation results show that, in terms of blocking ratio, our proposal significantly outperforms previously proposed algorithms. In some cases, the performance is better by more than one order of magnitude.**

Keywords—dynamic optical networks, flexible grid, Routing and Spectrum Allocation.

I. INTRODUCTION

Currently, DWDM (Dense Wavelength Division Multiplexing) transport networks are the best alternative to face the growing demand of Internet data traffic. Data transmission in DWDM networks is performed by sending different information signals in different modulated optical carriers (wavelengths) in the same optical fiber. The central frequency of each wavelength is defined by the G.694.1 Recommendation of ITU (International Telecommunications Union), where a fixed spectral separation between optical carriers around the 1550 nm must be chosen: 100 GHz, 50 GHz, 25 GHz or 12.5 GHz. The most commonly used spectral separation between optical channels is 50 GHz, which allows transmitting signals at rates of 2.5, 10, 40 and 100 Gbps [1]. Figure 1.a shows an example of the spectrum usage of a DWDM link including 7 channels at multiple bit rates (100, 40 and 10 Gbps) using an spectral separation equal to 50 GHz.

Although transmission capacities over 1 Tbps have been reached in experimental settings in DWDM networks [2], the exponential growing of Internet data traffic (with reported growing rates of 35 to 50% annually [3]) and its heterogeneity (connection requests with different bit rates [4]) will challenge this type of fixed-spectral-separation networks to ensure the accommodation of all data traffic in a near future [5]. For example, according to the traffic forecast analysis in [6], heterogeneous bit rates from 2.5 Gbps to 1000 Gbps are expected in the next years. The heterogeneous use of the spectrum in networks with fixed spectrum assignment (typically with 50 GHz spacing) would not allow an efficient use of the spectrum. As shown in Fig. 1a, it might be observed that a 10 Gbps channel uses a very narrow portion of its assigned spectrum whilst a 50 GHz of spectral separation would not be enough to deploy connections of 400 Gbps or higher. To allow higher bit rates, it would be necessary to increase the spectral separation. Nevertheless, if the same spectral separation is used for all the channels, a large amount of spectrum would be under-utilised for connection requests under 100 Gbps that would require a lower bandwidth than assigned.

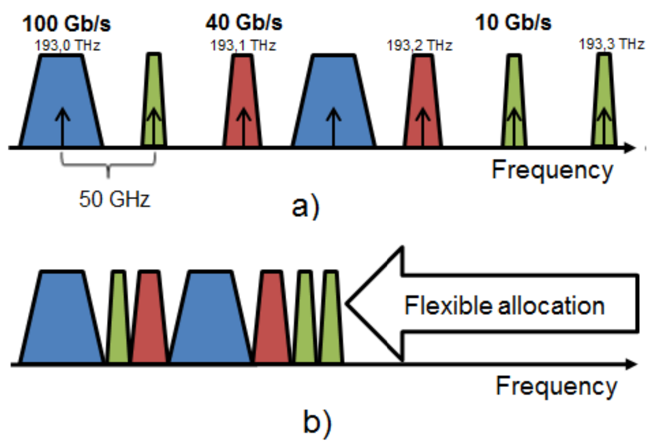

Fig. 1: Spectrum in a DWDM link a) with fixed grid and b) with elastic/flexible grid.

To overcome this drawback of fixed grid networks and face the future volumes of data traffic in optical networks, flexible usage of the spectrum has been proposed. That is, the spectrum of the different channels is allocated according to the requested bit rate and the distance to be covered [7]. This type of networks have been termed "elastic" or "flexible DWDM Optical Networks" [8,9] and it is expected to render obsolete the fixed spectrum assignment operation based on the G.694.1 Recommendation of the ITU.

An elastic optical network consists of a group of nodes and optical fiber links, where the devices work in an "elastic" or "flexible" way [10,11,12]. That is, the different optical devices (e.g., transmitters, receivers, transponders and optical switches [13]) are dynamically configurable in such a way that they can generate, operate, and receive optical signals at different digital bit rates (from 2.5 Gbps to 1000 Gbps), modulation formats (a

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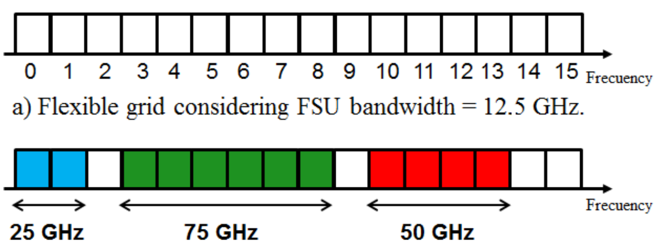
characteristic that determines de bandwidth) and carrier central frequencies according to the distance the signal must travel [14]. Fig. 1b shows an example of the spectrum usage of an elastic optical network link, where the spectral separation and the carrier frequencies can be assigned flexibly. It can be seen that the elastic operation makes a more efficient use of the optical spectrum than current DWDM networks since the unused bands of the fixed assignment of the optical carriers are eliminated. As a result, a higher number of channels can be accommodated, solving the problem of the potential increase of traffic demand in a near future.

Flexible optical networking also raises new challenges. One of the most important is that of the routing and spectrum allocation (RSA), that consists of finding available spectrum paths. That is, finding a route and enough contiguous spectrum (central frequency and spectral width in terms of FSUs or Frequency Slots Units) in each link of that route for each arriving connection. FSU refers to the minimum slice of spectrum for communications into optical fiber (for example, 12.5 GHz). Fig. 2a shows the spectrum of a single flexible grid network link. The spectrum is divided in 16 FSUs, each with a bandwidth equal to 12.5 GHz. Fig. 2b shows an example of flexible spectrum allocation, where 3 connections with different bandwidth requirements are assigned a different number of FSUs.



a) Flexible grid considering FSU bandwidth = 12.5 GHz.

b) Flexible spectrum allocation.

Fig. 2. a) Illustration of the FSU concept and b) example of flexible FSUs allocation.

On solving the RSA problem, 3 constraints must be met. First, the FSUs allocated to a connection must be contiguous in the spectrum. Second, the same FSUs (number and position in the spectrum) must be allocated along all the links of the route. Third, one FSU in a particular link cannot be allocated to more than 1 connection at a time.

There are two approaches for solving the RSA problem: in the static approach connections are permanently established and the main goal is minimizing the spectrum usage; in the dynamic approach connections are established only when and where required with the main goal of minimizing the number of blocked requests. Because dynamic operation adapts better to traffic or topology changes and it has the potential of using the spectrum more efficiently than the static approach, in this paper we focus on dynamic operation.

The RSA problem in dynamic elastic optical networks is typically solved in two stages: firstly, a route is assigned (for example: the shortest path) and then, a portion of the available spectrum is assigned along the links of the route (for example: the first portion of the spectrum available in all the links of the route). Generally speaking, in terms of blocking, the performance of this kind of algorithms (that solve the RSA problem by sequentially solving the routing first and the spectrum allocation second) is lower than algorithms that address the route and spectrum allocation problem jointly, as in [15]. In this paper, a novel algorithm that solves the RSA problem in a joint and adaptive manner is proposed. Simulation results show that the blocking probability of this new algorithm is significantly lower than algorithms previously proposed in the literature.

The rest of this paper is as follows: Section II describes previous proposals for the RSA problem, Section III presents the traffic and network models assumed in this paper to then propose, in Section IV, the new RSA algorithm. Section V presents the simulation results and conclusions are drawn in Section VI.

II. RELATED WORKS

RSA algorithms can be classified in two categories:

-R+SA algorithms.

This type of algorithms separates the RSA problem in two simpler problems: they solve the routing (R) problem first and then, on the route found by the R algorithm, they perform a spectrum allocation (SA) algorithm. The most common R algorithm is k-SP (k-Shortest Path), where the k shortest paths between every node pair are calculated beforehand and stored in a routing table. Concerning SA algorithms, the most mentioned in the literature are Random Fit (RF) and First-Fit (FF). RF allocates the spectrum randomly, which leads to a higher spectrum fragmentation. FF instead, allocates the spectrum in an ordered manner (first portion of spectrum available, from left to right). As a result, RF exhibits a higher spectrum fragmentation, which leads to a significantly worse performance than FF in terms of blocking probability [15,16]. Recently, Best Fit (BF) and Bit Rate Aware Fit (BRAF) algorithms have been proposed in [16] with the aim of taking into account the different bit rates (i.e. different number of requested FSUs) of the different connections requests. They exhibit lower blocking probability than FF and RF, as shown in [16]. BF diminishes the route spectrum fragmentation by allocating the smallest portion of the spectrum capable of accommodating the requested demand. BRAF divides the spectrum in two zones. Connections are allocated spectrum on a FF basis on their corresponding zone (from left to right for low bit rate connections and from right to left for high bit rate connections). By doing so, spectrum fragmentation is decreased.

Being computationally simple, these algorithms limit their search for a feasible spectrum path to the stored routes. As a result, they achieve lower performance than algorithms that make a joint search of routes and spectrum portions.

-Joint RSA algorithms.

This type of algorithm searches available spectrum in several routes simultaneously. This search technique makes the algorithm computationally more complex than R+SA algorithms, but with a better performance. In [15] a joint RSA algorithm called MPSC (*Maximize Path Spectrum Consecutiveness*) was proposed. The algorithm evaluates the impact that establishing different spectrum paths (considering different parts of available spectrum on k routes) have on the network spectrum consecutiveness (SC). The spectrum path with the highest value of SC is then selected. In [15] is shown that the performance of this algorithm is better than FF and RF.

All previous RSA proposals consider a fixed number of routes that are pre-calculated (normally, no more than 5 [17]), without taking into account the network state when the connection request arrives. Given the dynamic nature of the traffic, not taking the network status into account can limit the performance of the RSA algorithm.

In this paper, we propose a new algorithm that does not limit its search to a predetermined set of routes. Instead, every possible spectrum path is evaluated on the fly and the one utilizing the lowest number of resources is allocated to the connection.

III. NETWORK AND TRAFFIC MODELS

A. Network Model

The flexible optical network is represented by a graph $\mathcal{G} = (\mathcal{N}, \mathcal{C})$, where $\mathcal{N}$ is the set of optical nodes and $\mathcal{C}$ the set of links connecting the optical nodes. The number of elements in sets $\mathcal{N}$ and $\mathcal{C}$ is denoted by $|\mathcal{N}|$ and $|\mathcal{C}|$, respectively. Each optical node $n \in \mathcal{N}$ is locally attached to an electronic device through a pool of transmission and reception Bandwidth Variable Transponders (BVTs). The number of reception BVTs is assumed equal to the number of transmission BVTs and equal to $(|\mathcal{N}| - 1)$ per node. That is, every node is equipped with a pair of BVTs (one for reception, one for transmission) per every possible destination node.

Each link $c \in \mathcal{C}$ is made of two optical fibers, one in each direction. The set of optical fibers is denoted by $\mathcal{L}$ and the number of elements in $\mathcal{L}$ is denoted by $|\mathcal{L}|$. The number of FSUs in each optical fiber *l* is denoted by $|FSU|_{max}$.

B. Traffic Model

Each connection is identified by a source-destination node-pair (i, j), $i, j \in \mathcal{N}$. Each node pair generates traffic according to an ON-OFF process [18]. That is, during the ON period the source node transmits information at a given bit rate using a specific modulation format. The pair bit rate-modulation format determines the number of FSUs required by the connection [19]. During the OFF period the source node refrains from transmitting information. In this paper, we assume uniform and homogeneous traffic. That is, the mean duration of the ON (OFF) period is denoted by t_{ON} (t_{OFF}) for each connection. In this way, the mean traffic load offered by each connection to the network is given by:

$$\rho = \frac{t_{ON}}{t_{OFF}+t_{ON}} \tag{1}$$

IV. JOINT AND ADAPTIVE RSA ALGORITHM

In this paper we propose a new algorithm, called Dynamic Graph Coloring (DGC), to solve the RSA problem in a joint and adaptive manner.

Upon receiving a request to establish a connection requiring M FSUs between the node-pair (i, j), the DGC algorithm executes the steps shown in the pseudo-code of Fig. 3.

Step 1: Variables initialization
$x = 1$, where x is an index that identifies a FSU in a link. It is assumed that the first FSU from left to right is indexed as 1.
$\mathcal{R}_{i,j} = \{\phi\}$, where $\mathcal{R}_{i,j}$ is the set of spectrum paths for the node pair (i, j).

Step 2: Build a sub-graph of $\mathcal{G}$, denoted by $\mathcal{G}_x(M)$. The sub-graph $\mathcal{G}_x(M)$ is made of the links of $\mathcal{G}$ that comply with having M contiguous FSUs available, starting from FSU x, and the nodes adjacent to these set of links. If it is not possible building this sub-graph, go to Step 5.

Step 3: Run the Dijkstra algorithm on $\mathcal{G}_x(M)$ to find the lowest-number-of-hops path between the nodes i and j. This spectrum path is denoted by $\mathbb{R}_{i,j}[\mathcal{G}_x(M)]$.

Step 4: Add $\mathbb{R}_{i,j}[\mathcal{G}_x(M)]$ to the set $\mathcal{R}_{i,j}$.

Step 5: **If** $x + M - 1 < |FSU|_{max}$ then :

- $x = x + 1$
- go to Step 2

Else:

- Go to Step 6 (the spectrum paths starting at all possible FSUs have been found)

Step 6: **If** $\mathcal{R}_{i,j} \neq \{\phi\}$, then:

- Select $min\{\mathcal{R}_{i,j}\}$ (the shortest path in $\mathcal{R}_{i,j}$) to establish the connection between *i* and *j*.

Else:

- Reject the request.

Fig. 3. Pseudo-code of the DGC algorithm.

As a way of example, we execute the DGC algorithm assuming that $\mathcal{G}$ is the topology shown in Fig. 4 ($|\mathcal{N}|$ = 5 nodes, $|\mathcal{C}|$ = 6 links and $|FSU|_{max}$ = 5 FSUs). When a request

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to establish a connection between nodes i=5 and j=3 with M=3 FSUs arrives, the state of the network is that shown in Fig. 4 (non-available FSUs colored in blue, available ones in white).

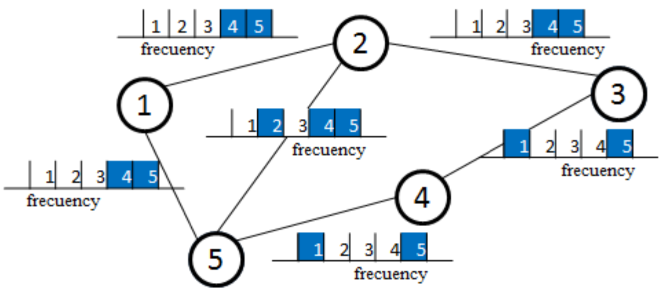

Fig. 4. Small-scale topology example.

On the first iteration of the DGC algorithm (x = 1), the following steps are executed:

Step 1: $x = 1$; $\mathcal{R}_{i,j} = \{\phi\}$.
Step 2: $\mathcal{G}_1(3)$ is built (as shown in Fig. 5)
Step 3: $\mathbb{R}_{5,3}[\mathcal{G}_1(3)]$, made of nodes 5-1-2-3, is found.
Step 4: $\mathcal{R}_{5,3} = \{\mathbb{R}_{5,3}[\mathcal{G}_1(3)]\}$.
Step 5: x=2, go to Step 2 (to start the second iteration of the algorithm).

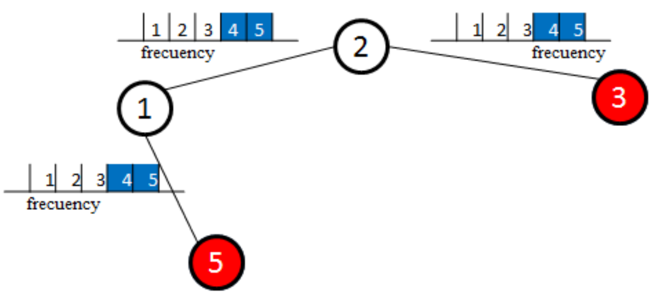

Fig. 5. Sub-graph $\mathcal{G}_1(3)$

Second iteration (*x*=2)

Step 2 : Sub-graph $\mathcal{G}_2(3)$ is built (as shown in Fig. 6)
Step 3 : $\mathbb{R}_{5,3}[\mathcal{G}_2(3)]$, made of nodes 5-4-3, is found.
Step 4 : $\mathcal{R}_{5,3} = \{\mathbb{R}_{5,3}[\mathcal{G}_1(3)],\ \mathbb{R}_{5,3}[\mathcal{G}_2(3)]\}$.
Step 5: x = 3, go to step 2.

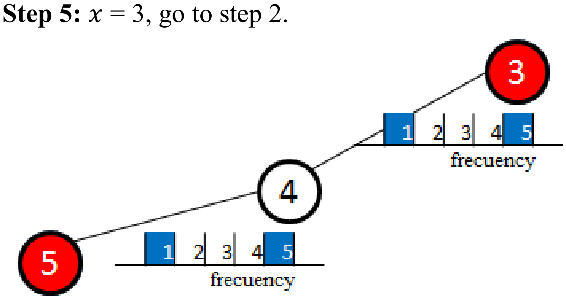

Fig. 6. Sub-graph $\mathcal{G}_2(3)$.

Third iteration (*x*=3)

Step 2: Go to step 5 (as no sub-graph is built because none of the links in the network has M=3 contiguous available FSUs starting at FSU 3).
Step 5: Go to step 6 (given that $x + M - 1 = 5 = |FSU|_{max} = 5$) .
Step 6: $min\{\mathcal{R}_{5,3}\} = \mathbb{R}_{5,3}[\mathcal{G}_2(3)]$. FSUs 2, 3 and 4 are allocated to the connection on the links between the node pairs 5-4 and 4-3.

V. NUMERICAL RESULTS

The performance of the DGC algorithm was evaluated by means of simulation. To do so, an ad-hoc event-driven simulator programmed in C++ was developed.

The topology used for the simulation was the NSFNet (*National Science Foundation's Network*), made of 14 nodes and 21 cables, as shown in Fig. 7. Each cable is made of 2 uni-directional optical fibers. Each link was assumed to have a total spectrum of 1350 GHz, centered at 193,1 THz. Assuming a bandwidth for each FSU equal to 12,5 GHz, in the simulation each link has 108 FSUs.

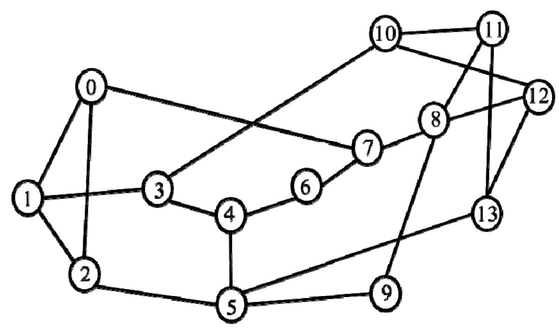

Fig. 7: NSFNet topology

We model the duration of the ON and OFF periods distributed according an exponential distribution. The mean value of the ON period was set equal to $t_{ON} = 1\,ms$. The mean value of the OFF period was varied, according to Eq. (1), to evaluate the system under different values of traffic loads, ranging from 0.1 to 0.9.

We assume that connections can request one of the following 5 bit rates (uniformly distributed): 10, 40, 100, 400 y 1000 Gbps. Depending on the required bit rate and modulation format, a different number of FSUs must be required. In this paper, we assume the values shown in Table 1.

As a way of comparison, the performance of 5 additional RSA algorithms is also evaluated.

Four of these RSA algorithms solve the routing problem (R) first and then the spectrum allocation (SA) problem. The routing problem is solved using the algorithm 3-SP. That is, a set $\mathcal{R}_{i,j} = \{r_{i,j}^1, r_{i,j}^2, r_{i,j}^3\}$ with the 3 shortest paths for the node pair (i, j) is stored in a routing table. Upon receiving a connection request of M FSUs, the first route of this set is entered as an input to the spectrum allocation (SA) algorithm. If the SA algorithm returns successfully, the first route is allocated on the FSUs found available by the SA algorithm. Otherwise, the second route is tried and so on. If the SA returns unsuccessfully after trying the 3 routes, the request is rejected. Each of these 4 RSA algorithms differ on the SA algorithm used. To define each SA, consider the set $S(r_{i,j}^h) = \{s_1, s_2, \ldots, s_n\}$ of blocks with at least M contiguous FSUs along the route $r_{i,j}^h$. The block s_1 is the block in the most left position in the spectrum, block s_2 is the second most left and so on. Let $|s_q|$ be the size of the block q, in number of FSUs. Each SA algorithm works as follows:

First Fit (FF) [20]: Scanning the set $S(r_{i,j}^h)$ from left to right, the first block is allocated. If $S(r_{i,j}^h) = \phi$, the SA algorithm returns unsuccessfully.

Random Fit (RF) [20]: A block is randomly selected from $S(r_{i,j}^h)$. If $S(r_{i,j}^h) = \phi$, the SA algorithm returns unsuccessfully.

Best Fit (BF) [16]: The block complying with the minimum value of $(|s_q| - M)$ is allocated. If $S(r_{i,j}^h) = \phi$, the SA algorithm returns unsuccessfully.

Bit Rate Aware Fit (BRAF) [16]: For low bit rate requests (10, 40 and 100 Gbps) the set $S(r_{i,j}^h)$ is scanned from left to right and the first block is allocated. For high bit rate requests (400 and 1000 Gbps) the first block, the set $S(r_{i,j}^h)$ is scanned from right to left and the first block is allocated. If $S(r_{i,j}^h) = \phi$, the SA algorithm returns unsuccessfully.

Table 1: Number of FSUs required per bit-rate

Bit rate	Required spectrum width [GHz]	Number of FSUs
10 Gbps	25	2
40 Gbps	50	4
100 Gbps	50	4
400 Gbps	75	6
1 Tbps	150	12

Thus, the 4 R+SA algorithms used as a comparison in this paper are called 3SP-FF, 3SP-RF, 3SP-BF and 3SP-BRAF.

The fifth algorithm evaluated as a comparison solves the R and SA problems jointly. It works as follows:

Maximize Path Spectrum Consecutiveness (MPSC) [15]: Upon receiving a connection request, the algorithm calculates the impact of establishing the connection in k different routes using First Fit in all the available blocks of spectrum which could contain the demand. The impact is measured using the spectrum consecutiveness factor [15]. The spectrum path that achieves the highest value of the spectrum consecutiveness factor is selected to establish the connection. If no set of contiguous FSUs is found in any route, the request is rejected. In this paper, we evaluate this algorithm using $k = 3$.

Fig. 8 shows the request rejection rate (blocking probability) for the proposed algorithm (DGC) and the 5 algorithms selected for comparison as a function of the traffic load.

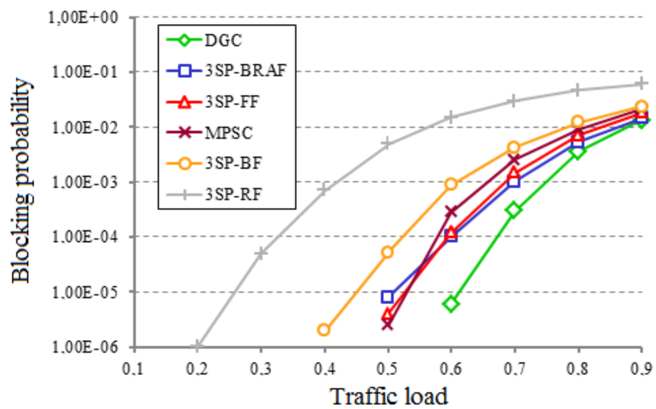

Fig. 8. Blocking probability as a function of the traffic load for the NSFNet topology.

It can be seen that DGC outperforms the rest of the algorithms for all traffic load values due to its ability to find the spectrum paths adaptively, taking the network state into account when serving a connection request.

Second bests are the algorithms 3SP-BRAF and 3SP-FF, which aim to avoid fragmentation of the spectrum space by allocating resources in a "packed" manner. It is worthy to note that, in spite of the higher complexity of the MPSC algorithm in trying to minimize spectrum fragmentation, it does not achieve a better performance than the computationally simpler 3SP-FF, although it gets close.

Finally, the worst performing algorithm is 3SP-RF which, by randomly allocating FSUs, achieves a high spectrum fragmentation. This poor performance of 3SP-RF was already shown in the context of routing and wavelength (RWA) algorithms in fixed grid WDM networks.

The better performance of DGC comes at expenses of a higher computational complexity. By executing the Dijkstra algorithm for every possible graph, its computational complexity raises to $O(|FSU|_{max} \cdot |\mathcal{N}|^2)$. Instead, the 3-SP-based algorithms exhibit a much lower computational complexity of $O(|\mathcal{L}| + |FSU|_{max})$.

All algorithms evaluated showed the same relative performance when evaluated in the Eurocore topology, made of 11 nodes and 21 cables. Due to space restrictions, these results are not shown here.

VI. CONCLUSIONS

In this paper a new RSA algorithm, called Dynamic Graph Coloring (DGC), was proposed. DGC aims at a low rejection ratio of connection requests by exhaustively searching the best spectrum path. To do so, the shortest possible path (i.e. the lowest-number-of-hops path with enough FSUs to accommodate the connection request) is searched for by taking the network state into account. The performance of DGC was evaluated by means of simulation and compared to the performance of other 5 previously proposed algorithms. Simulation results showed that DGC outperformed all the previous algorithms. In some cases, by at least one order of magnitude.

Future research should focus on improving the weak aspects of the proposal:

- designing an algorithm with almost as good performance as DGC but with lower computational complexity;
- considering the modulation format to determine the number of FSUs required and the optical reach of a connection. That is, transforming the RSA algorithm to a RMLSA (RMLSA: Routing, Modulation Level and Spectrum Assignment) algorithm.
- taking into account non-uniform distributions for the bit rate of the connection requests.

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