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Heuristics for Routing and Spectrum Allocation in Elastic Optical Path Networks

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ABSTRACT: *This paper presents an efficient method for spectrum allocation that uses Integer Linear Programming (ILP) and heuristics. In elastic networks, the WDM rigid frequency grid is replaced by a more flexible structure, where the spectrum is organized in frequency slots, and each traffic flow is assigned to an appropriate set of contiguous slots. This new concept, which is based on Orthogonal Frequency Division Multiplexing (OFDM), is known as Spectrum-Sliced Elastic Optical Path Network (SLICE). In this paper a mathematical formulation and two heuristics are proposed to conveniently route the traffic demand in SLICE Networks. Numerical simulations were performed with the mathematical formulation for small networks, whereas the heuristics were used in large networks, where the processing of mathematical formulation becomes intense. The results suggest the advantage in terms of spectrum economy of the proposed method.*

Keywords: Flexible bandwidth allocation; routing and spectrum allocation; spectrum-sliced elastic optical path network.

I. INTRODUCTION

The rapid growth of Internet and services, such as Internet TV, video-on-demand, peer-to-peer applications and virtual private networks, have been driving an ever increasing bandwidth demand of the communications systems backbones [1]. According to research conducted by Cisco Systems [2], the global Internet traffic will reach 1.6 zettabytes by 2018 with a growth of 21 percent from 2013 to 2018. Presently, the all-optical networks technology is considered one of the main vehicles to undertake this evolution. The reason for this is that a single fiber provides an enormous bandwidth and very low bit error rate. The spectrum-sliced elastic optical path network (SLICE) has been proposed as a promising candidate for future optical transport networks [3].

In SLICE, the finer granularity and elastic right-size bandwidth allocation is achieved by segmenting the ITU-T wavelength grid in frequency slots and allowing the use of multiple slots for a single spectrum path [3,4]. The spectrum is partitioned into frequency slots of either 6.25 or 12.5 GHz [4, 5]. Thus, a spectrum path is established using a given number of frequency slots. In addition, the use of optical orthogonal frequency-division multiplexing (O-OFDM), where the signal may be composed by an arbitrary set of orthogonal sub-carriers that overlap in the frequency domain, enables more flexible allocation and efficient utilization [5].

In O-OFDM, one sub-carrier normally occupies several GHz, and the capacity of one sub-carrier is in the order of Gbps. Specifically, sub-wavelength accommodation can be achieved in the optical domain by fitting a contiguous set of sub-carriers on a contiguous set of slots with total bandwidth narrower than that one of an optical channel in Dense Wavelength Division Multiplexing (DWDM) networks.

In WDM network, the spectrum is divided into wavelengths of specific bandwidth (50 or 100 GHz) and establishing a spectrum path requires the selection of a path and a wavelength on the links that comprise the path. Fig. 1 illustrates the allocation of WDM channels with fixed grid of 50 GHz available spectrum. These guard frequencies are when two spectrum paths share one or more common fiber links. In this example, five allocation are performed with total of 250 GHz of spectrum used.

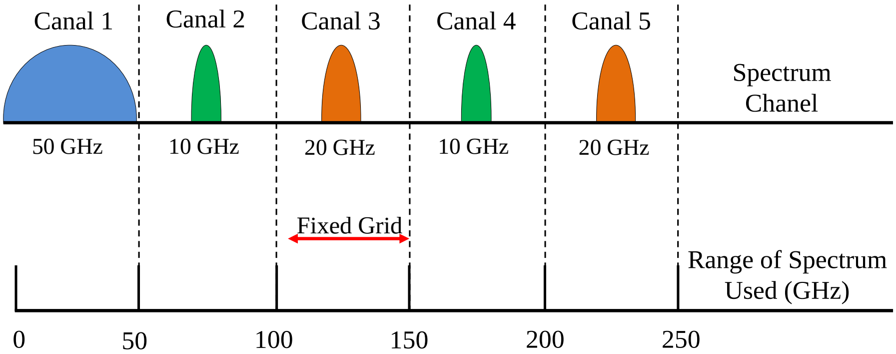


Fig. 1. Spectrum of traditional WDM network.

The SLICE network, to form the spectrum path for the traffic demand using multiple sub-carriers, needs to deploy bandwidth-variable (BV) transponders at the network edge and bandwidth-variable optical cross connects (WXCs) in the network core, which can be built based on the continuous bandwidth-variable wavelength-selective switch (WSS). Note that two spectrum paths that share one or more fiber links have to be separated in the frequency domain to facilitate optical signal filtering. In other words, two sets of sub-carriers within the two spectrum paths have to be isolated by a guard band (GB) of guard-carrier (GC). The width of the guard-band, however, is not trivial and may be the width of one or multiple sub-carrier(s) [6-8].

Fig. 2 illustrates the allocation of spectrum in SLICE network, with slots of 12,5 GHz and one guard-carriers (GC), between two spectrum path that share one or more common fiber links. It can be observed, comparing Figs. 1 and 2, that using SLICE it is possible to reduce from 250 to 175 the amount of used spectra.

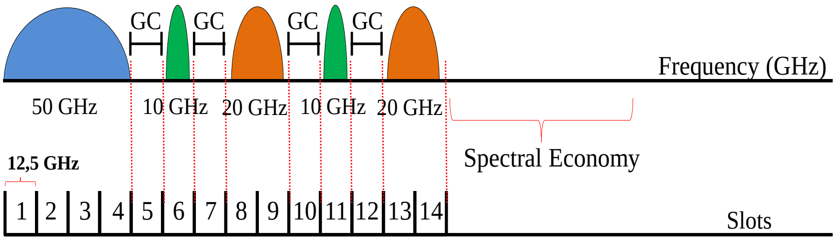


Fig. 2. Spectrum of SLICE network.

A fundamental issue in SLICE networks relies on choosing a proper route and necessary number of contiguous frequency slots from end-to-end to accommodate the spectrum path requests, which is referred to as the routing and spectrum assignment (RSA) problem. RSA is different from and more challenging than the traditional RWA (routing and wavelength assignment) problem, as spectrum paths will be established using different spectral granularities, as opposed to WDM. In addition, without spectral conversion, the wavelength continuity constraint is transformed into the spectrum-continuity constraint [9].

In [9] the authors propose an ILP (Integer Linear Programming) formulation to accommodate the traffic into SLICE networks when the problem size (e.g., network topology, traffic demands) is small. For the large scale problem, they proposed two heuristics algorithms to obtain a solution within reasonable time. The heuristics are Shortest Path with Maximum Spectrum Reuse (SPSR) and Balanced Load Spectrum Allocation (BLSA). The objective is minimizing the maximum sub-carrier number on a fiber and maximizes the reuse of sub-carriers in spectrum allocation.

In this paper, we propose a more simple mathematical formulation and the use of two heuristics algorithms, the Best among the Shortest Routes (BSR) [10] and Iterative Load Routing (ILR) [11]. The BSR aims to find the best routes within a set of possible routes. As each pair (source, destination) can have more than one shortest path route (called in this work of Candidate Routes – CR), there are M different solutions. The heuristic ILR has the main objective of balancing the network load. This is done by performing the re-routing of paths on sets of physical links less congested. Thus, one can reduce the number of sub-carriers allocated to a network link.

The rest of the paper is organized as follows. In Section 2 we introduced the problem of routing and spectrum allocation in SLICE network. In Section 3 we describe a more flexible method for spectrum allocation in optical networks and heuristics are presented in Section 4. Section 5 shows some numerical results and how effective is our proposed routing when compared with SPSR and BLSA heuristics. Finally, Section 6 concludes the paper.

II. ROUTING AND SPECTRUM ALLOCATION

The problem of establishing connections in flexible networks is typically referred to as the Routing and Spectrum Allocation (RSA) problem, known to be NP-complete [6-9]. The signal transmitted over the optical path (using the spectrum determined by the volume of client traffic) is routed through bandwidth variable (BV) wavelength cross-connects (WXCs) towards the receiver. Every BV WXC on the route allocates a cross-connection with the corresponding spectrum to create an appropriate-sized end-to-end optical path. To do so, the BV WXC has to configure its switching window in a contiguous manner according to the spectral width of the incoming optical signal [7,12].

The RSA problem may consider static or dynamic traffic. In the static RSA a traffic matrix that represents the set of optical routs that have to remain active for an undetermined period of time is previously defined. In this case, the optical circuits are established off-line and the objective of the static RSA problem's solution is to minimize the number of sub-carriers of network [13].

The dynamic RSA problem must be solved for the network in operation where the requests arrive randomly. If there are not enough resources to satisfy a given request, it is blocked. For this reason, the objective of a transport service provider, vis-a-vis the RSA problem is to maximize the number of accepted optical paths requests minimizing the blocking probability of future optical paths requests [14].

We will focus our study on the planning phase of flexible optical network, namely the offline RSA, which is known to be NP-complete problem [15]. Offline resource allocation is more difficult than online, since it aims at jointly optimizing the establishment of all the connections and minimizing the resources used, giving a more combinatorial character to the problem, in the same way that the multicommodity flow problem is more difficult than the shortest path problem in general networks [13].

III. MATHEMATICAL FORMULATION

In this section we describe a more flexible method for spectrum allocation in optical networks and proposes ways to use it for network planning. The main goal is minimize the number of sub-carriers used in physical links in the networks. We present the formulation ILP as follows:

Notation

- i and j denote originating and terminating nodes, respectively, of a variable bandwidth spectrum path (set of slots).
- m and n denote endpoints of a physical link in the network.

Given

- Number of nodes in the network: N.
- Traffic matrix element: Λ_{ij}, which denotes the traffic intensity (set of slots) from a source node i to a destination node j.
- Physical Topology: F_{mn}, which represents the distance of fibers interconnecting from node m to node n.
- Filter Guard Band: GC, which is the minimum spectrum width between wavebands (in terms of number of slots).
- A larger number K to be used to make some integer variables.

Variables

- Capacity of each fiber: MS, maximum number of slots per link.
- Spectrum path bandwidth V_{ij}: bandwidth or number of slots of an elastic spectrum path from node i to node j.
- Physical topology route P_{mn}^{ij}: amount of bandwidth that a spectrum path from node i to node j uses in a fiber link $m - n$.
- A binary variable A_{mn}^{ij} to indicate whether the spectrum path from node i to node j passes through a link $m - n$. A_{mn}^{ij} equals to 1 if $P_{mn}^{ij} > 0$; equals to 0 if $P_{mn}^{ij} = 0$.

ILP formulation

Minimize: *MS* (3.1)

$$\sum_n P_{mn}^{ij} - \sum_n P_{nm}^{ij} = \begin{cases} V_{ij} & m = i \\ -V_{ij} & m = j \\ 0 & m \neq i,j \end{cases} \quad \forall \text{ m-n} \in \text{E} \tag{3.2}$$

$$\sum_{ij} (P_{mn}^{ij} + GC.A_{mn}^{ij}) - GC \leq MS.F_{mn} \quad \forall \text{ i,j} \in \text{N e } \forall \text{ m-n} \in \text{E} \tag{3.3}$$

$$A_{mn}^{ij} \geq P_{mn}^{ij}/K \qquad \forall \text{ i,j} \in \text{N e } \forall \text{ m-n} \in \text{E} \tag{3.4}$$

Eq. (3.1) denotes the objective function, i.e., minimization the spectrum utilization. It is a maximum number of sub-carriers in any fiber in the network, with the GC interval. Eq. (3.2) is the flow conservation constraint for the demands. Eq. (3.3) represents variables that make up the spectrum capacity of each fiber. Eq. (3.4) represents a variable that assists in the calculation of GCs, on each physical link.

IV. HEURISTICS

Heuristic algorithms are the most practical way to produce sub-optimal feasible solutions. A heuristic algorithm is not guaranteed to find optimal solutions but often gives near-optimal solutions at acceptable times, trading off optimality for speed.

In [9] were reported two heuristics for solving the RSA problem. The Shortest Path with Maximum Spectrum Reuse (SPSR) uses two parameters to the routing and allocation: 1) the optical paths are ranked in order of increasing traffic demand, 2) the optical paths allocated, according to the constraint of continuity of the sub-carrier. In this allocation, the optical path chosen is the first available. The Balanced Load Spectrum Allocation (BLSA) determines the routing through load balancing within the network, aiming to reduce the maximum number of sub-carriers in a fiber. This algorithm can be divided in three steps:

Step 1: Path generation. In this step is used the k-shortest path algorithm [16], to generate the k (k >= 1) path(s) for each node-pair (s, d).

Step 2: Path selection. In this step is decided the path for each spectrum path with the goal of balancing the load among all the fibers within the network. The load of a fiber is estimated using eq. (12) in [9].

Step 3: Spectrum allocation. In this step is use the Maximum Reuse Spectrum Allocation (MRSA) [9] to accommodate all the spectrum paths.

In this paper, it is proposed two heuristics for SLICE network, the Best among the Shortest Routes (BSR) and Iterative Load Routing (ILR). The results were compared with SPSR and BLSA heuristics.

a) Best among the Shortest Routes (BSR)

This section presents the BSR that belongs to the fixed-routing class and is proposed for elastic optical networks. The algorithms use the results of an iterative process in the attempt of finding the best solution for the set of fixed shortest paths to be used during network operation. The aim of BSR is to balance the load among the network links in order to reduce the number of sub-carriers of network. It is important to emphasize that, since we are working with fixed routing algorithms, they are executed off-line, i.e., during a planning phase.

Consider the following set of variables used in the BSRs algorithms:

- L is the set of all network's links;
- l is a link that belongs to L;
- $c(l)$ is the cost of link l;
- $c(l)_i$ is the cost of link l at the i-th iteration;
- $u(l)_i$ is the utilization (occupied slots) of link l at the i-th iteration, i.e., the sum of the number of slots allocated on link;
- T is the number of iterations in the process.
- R is the maximum number of slots that can be requested;

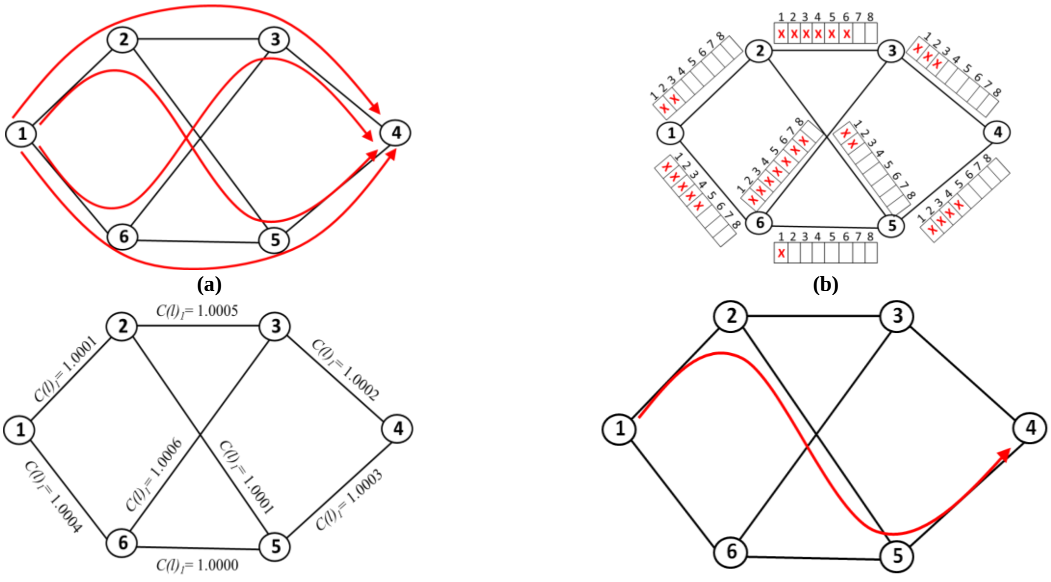
Each iteration i of BSR simulates one routing solution S_i of the universe of S possible solutions. The results of the i-th iteration are the utilization values for each network's link $(u(l)_i)$ and the network's sub-carriers number performance obtained with the routing solution S_i. The basic idea of this algorithm is to adjust, at iteration i+1, the cost of link by means of a small weighting factor ($1 - \alpha$) that is proportional to the link's utilization value obtained in the previous iteration. The cost of each link is adjusted by:

$$c(l)_{i+1} = \alpha \,.\, c(l)_i + (1-\alpha) \,.\, u(l)_i \tag{4.1}$$

in which $1 \leq i \leq T$ and α is assumed very close to one to modify minimally the links' costs as function of their respective utilization and to ensure that the new routes that will be found continue to be shortest path routes. The value of $\alpha = 0.9999$ has been empirically determined, after trying different alternatives. It is a matter of further investigation how the reduction of its precision impacts the quality of the solutions.

After obtaining the new link costs, $c(l)_{i+1}$, a simple shortest path algorithm (Dijkstra's algorithm [17]) is used to find the routing solution S_{i+1} that will be used in the simulation's (i+1)-th iteration. This small adjustment serves as a tiebreak criterion for the Dijkstra's algorithm (DJK) to find a solution S_{i+1} with a better load balancing among the network's links and, consequently, decreases the sub-carriers number of network.

For exemplification, see Fig. 3. If we have to choose among these four paths the best routing between nodes 1 and 4 (Fig. 3a). Note that the weight of each links is equal to 1. We illustrate the current state the SLICE network (Fig. 3b) with number of slots allocated. In this example, each link contains 8 available slots and "X" represented the busy slots. Then we have that choose one paths for route the connection request. To $c(l)_0 = 1$, so applying Eq. (4.1) we have the value $c(l)_1$ for each link Fig. 3c. To choose one paths, we do the sums of routes between nodes 1 and 4, and choose the lowest path. The best result is illustrated in Fig. 3d.



(a) **(b)**

(c) **(d)**

Fig. 3. BSR heuristic (a) four paths between nodes 1 and 4 (b) number of slots allocated in SLICE network (c) value of c(l)$_1$ for each link (d) chosen paths.

The flow chart of our proposed algorithm is shown in Fig. 4. Verify among the T iterations which solution has the lowest sub-carriers number. The solution of fixed routes used in the simulation of this iteration represents the routes chosen by the BSR algorithm.

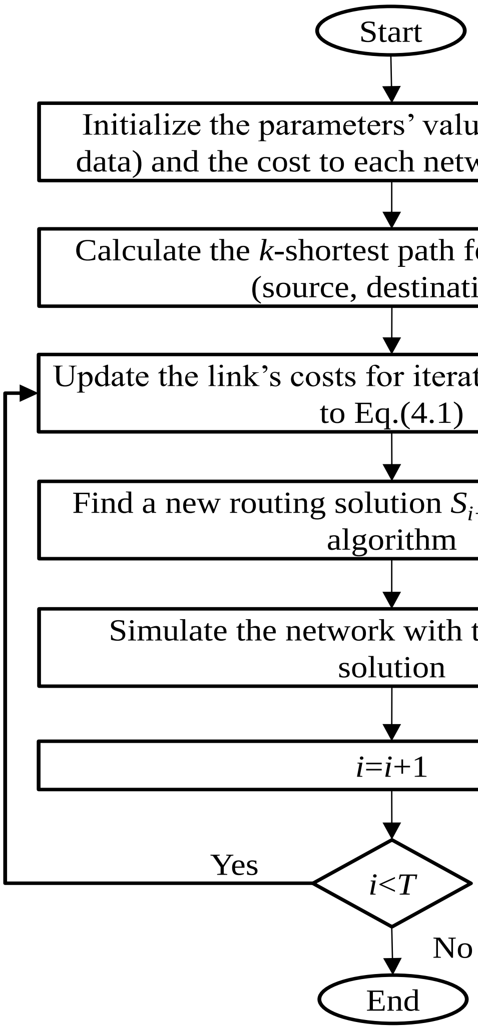


Fig. 4. Flow chart of YBS algorithm.

b) Iterative Load Routing (ILR)

The heuristic ILR has the main objective of balancing the network load. This is done by performing the re-routing of paths on sets of physical links less congested. Thus, one can reduce the number of sub-carriers allocated to a network link. Thus, it is possible to reduce the number of sub-carriers allocated in a physical link. Below we describe a summary of the steps followed in the ILR algorithm and an exemplification is illustrated in Fig. 5.

Step 1: Route all paths using Dijkstra's algorithm [17]. Fig. 5a shows an example of the allocated routes.

Step 2: Find the spectrum paths with higher amount link-sharing and remove. Fig. 5b illustrate that blue path have the higher amount link-sharing, path 6-5-2.

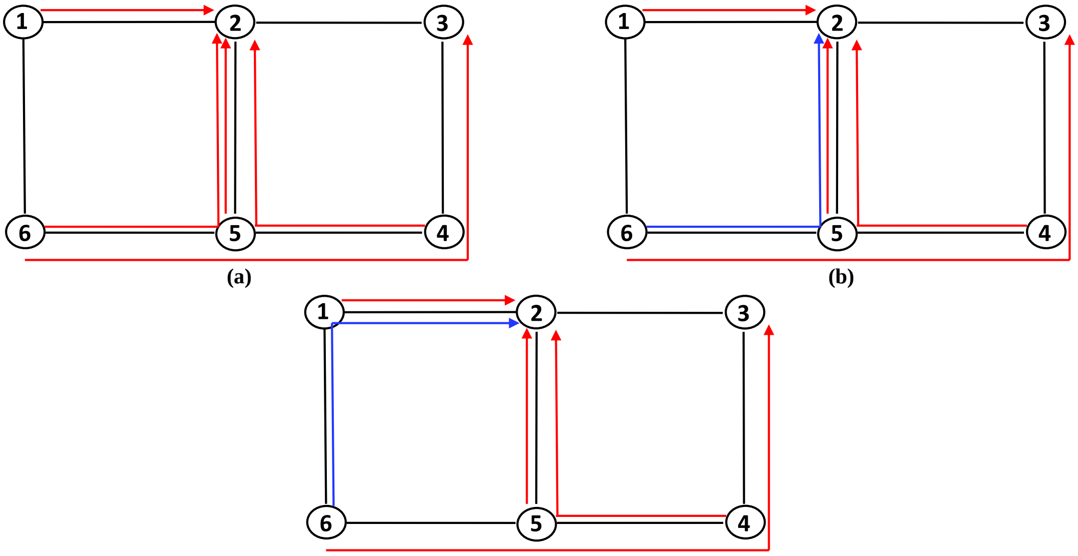
Step 3: Set sumLOAD as the sum of loads (busy slots) of each physical link along the path over which the removed spectrum path was routed.

Step 4: Find among all possible paths to the removed spectrum path the one with the smallest sum of loads (busy slots) of its physical links, we call this sum as minLOAD.

Step 5: if sumLOAD > minLOAD then reroute the removed spectrum path over the path with minLOAD and go back to Step 2. Else reroute the removed spectrum path over the same path over which it was routed before. In Fig. 5c the blue spectrum path was relocated for new route 6-1-2.

Step 6: Find the next spectrum path in descending order of link-sharing, remove it from the routing and go back to Step 3. If all spectrum path have been tested without to go back to Step 2, then the algorithm is finished.

The idea behind this heuristic is that rerouting spectrum path on sets of little congested physical links we can significantly minimize the number of sub-carriers of network.



(a) **(b)** **(c)**

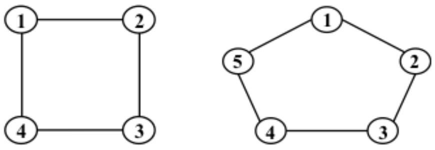
Fig. 5. ILR heuristic (a) Route all paths using Dijkstra's algorithm (b) blue path have the higher amount link-sharing (c) blue path was relocated for new route.

V. NUMERICAL RESULTS

For evaluating the effectiveness of the proposed optimization, we will analyze five different network topologies. We use IBM ILOG CPLEX v.9.0 [18] on an Intel i3 2.13GHz 4GB computer to solve ILP. We first evaluate the performance of small networks in detail and then analyzed the results from moderate large networks with heuristics.

5.1 Small Network

To validate the proposed mathematical formulation was used a ring network with four (R_4) and five nodes (R_5), as shown in Fig. 6 and available in [9], and a mesh network (Fig. 7). The ILP obtained the same results of [9]. However, the formulation is simpler and faster in terms of simulation time.



(a) (b)

Fig. 6. Ring networks with (a) 4 and (b) 5 nodes.

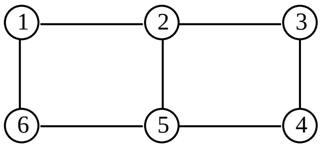


Fig. 7. Mesh network (R_6)

We can see in Table 1 that the networks with large amount of nodes require more simulation time. In the simulations, we varied the number of guard bands or guard carriers (GC) and the traffic demand (X), ie, the number of sub-carriers. The BSR and ILR heuristics obtained optimal solutions for R_5 and R_6 networks, with less simulation time than BLSA heuristic. The delay time of the simulations is due the stage of routing of traffic network. In this are chosen the paths in which the sub-carriers shall be allocated posteriorly.

For large network the ILP model is intractable and the analysis becomes computational intensive, then analyze the proposed heuristic results.

Table 1. Results of Simulations for Small Networks: R_4 and R_5 (ring), R_6 (mesh)

		X =1, GC=1					X =1, GC=2					X =2, GC=1				
Network		**ILP**	**BSR**	**ILR**	**BLSA**	**SPSR**	**ILP**	**BSR**	**ILR**	**BLSA**	**SPSR**	**ILP**	**BSR**	**ILR**	**BLSA**	**SPSR**
R_4	MS	3	5	5	3	5	4	7	7	4	7	5	8	8	5	8
	Time	(7ms)	(63ms)	(13ms)	(169ms)	(35ms)	(7ms)	(63ms)	(13ms)	(169ms)	(35ms)	(7ms)	(63ms)	(13ms)	(169ms)	(35ms)
R_5	MS	5	5	5	7	5	7	7	7	10	7	8	8	8	11	8
	Time	(17ms)	(92ms)	(38ms)	(220ms)	(40ms)	(20ms)	(92ms)	(38ms)	(220ms)	(40ms)	(15ms)	(92ms)	(38ms)	(220ms)	(40ms)
R_6	MS	7	7	7	9	9	10	10	10	13	13	11	11	11	14	14
	Time	(32s)	(125ms)	(79ms)	(286ms)	(44ms)	(473s)	(125ms)	(79ms)	(286ms)	(44ms)	(13s)	(125ms)	(79ms)	(286ms)	(44ms)

5.2 Large Networks

5.2.1 NSFNet network

We initially investigated the performance of an NSFNet network (Fig. 8) with 14 nodes and 21 bidirectional fiber links, unidirectional path requests and uniform and non-uniform traffic demand between each node pair.

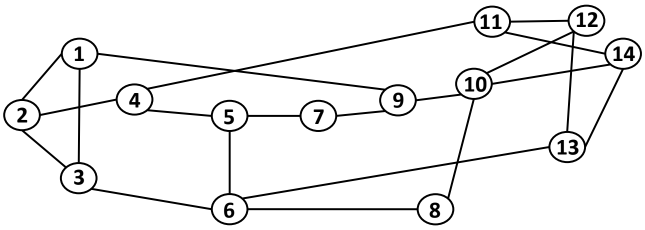


Fig. 8. NSFNet network

a) Uniform Traffic Demand

The Figs. 9, 10 and 11 illustrates the maximum sub-carrier number by *GC* for one, two and three sub-carrier of uniform traffic (X). The x-axis is the guard-band (GC) and y-axis is the maximum subcarrier number among all the fibers in the network. Note Figs. 9, 10 and 11, for the same X, bigger GC implies more overhead for the guard-carrier and thus requiring more sub-carriers.

It can be seen that BSR and ILR heuristics obtained better results than BLSA and ILR heuristics for NSFNet network.

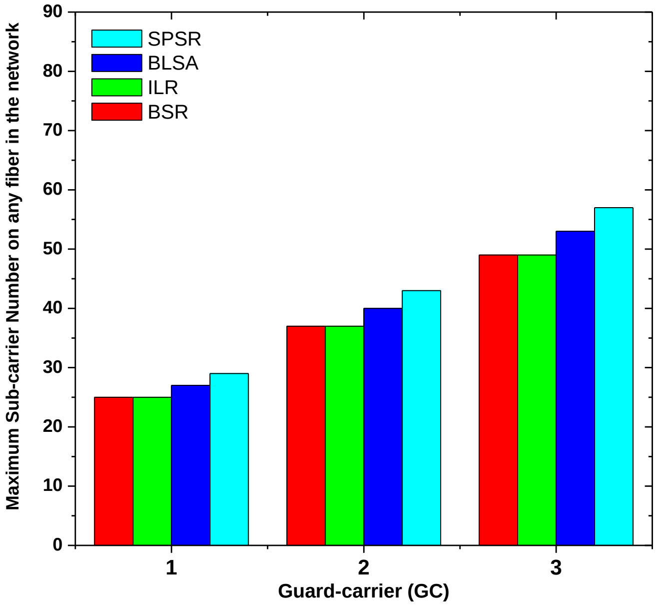


Fig. 9. Maximum sub-carrier number by *GC* for one sub-carrier of uniform traffic (X=1)

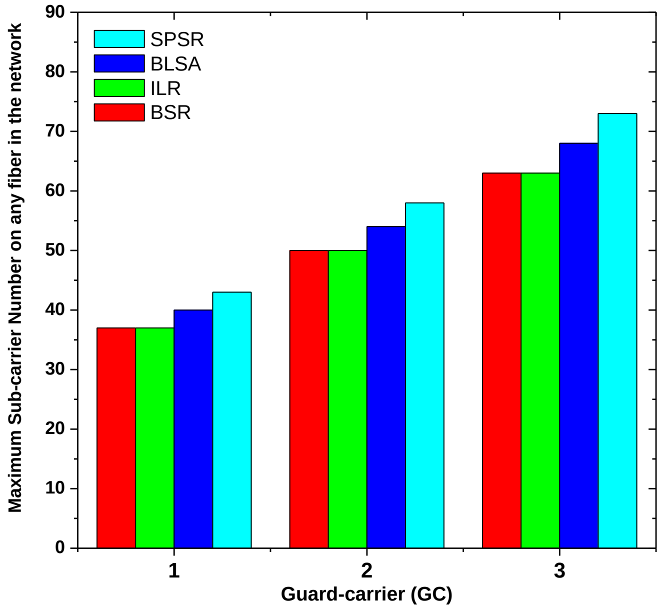


Fig. 10. Maximum sub-carrier number by *GC* for two sub-carriers of uniform traffic (X=2)

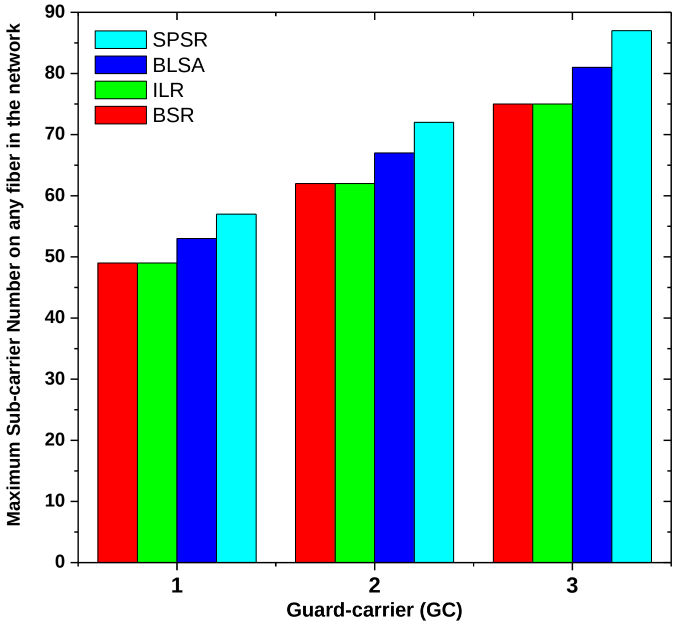


Fig. 11. Maximum sub-carrier number by *GC* for three sub-carriers of uniform traffic (X=3)

b) Non-Uniform Traffic Demand

For the case with non-uniform traffic demands, we generate the traffic randomly within the range [0,3]. Table 2 shows the traffic demand generated randomly for NSFNet Network. The results are shown in Fig. 12. To *GC* = 1, BSR and ILR heuristics allocated 39 subcarriers and BLSA and SPSR heuristics allocated 40 and 44 sub-carriers, respectively. When we increased the amount of guard-band, the number of subcarriers increases between the spectrum paths. Thus, *GC* = 2, we observe that BSR and ILR heuristic allocated 50 sub-carriers and the BLSA and SPSR 53 and 56 sub-carriers, respectively. *GC* = 3, BSR and ILR allocated 61 sub-carriers while BLSA and SPSR allocated 66 and 68 sub-carriers, respectively.

Table 2. Traffic matrix for NSFNet Network

0	1	3	3	0	3	0	3	1	1	3	3	1	0
0	0	0	3	0	0	3	3	0	3	3	2	2	1
3	0	0	3	1	3	2	1	3	2	0	3	3	3
2	0	0	0	1	0	3	1	2	3	0	1	1	0
3	0	2	3	0	1	0	3	3	3	1	0	2	0
0	2	3	3	0	0	2	1	1	1	2	2	1	3
3	0	1	1	2	2	0	1	0	2	2	1	0	2
0	2	2	1	2	0	0	0	3	2	1	0	1	3
0	1	3	3	2	2	0	1	0	0	2	1	3	0
0	2	1	0	2	1	2	1	3	0	0	0	3	3
3	3	1	0	0	0	2	2	3	2	0	3	0	0
2	0	1	2	1	1	2	1	3	2	1	0	0	2
2	1	2	0	2	2	3	2	3	1	1	0	0	0
0	0	1	0	0	2	3	3	3	2	2	2	1	0

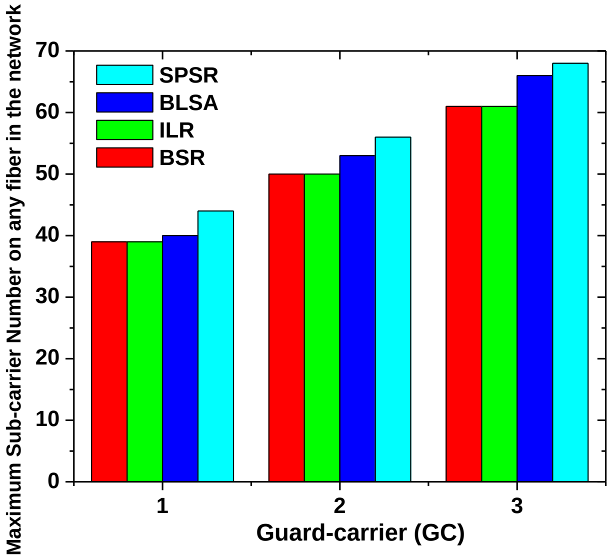


Fig. 12. Maximum sub-carrier number by *GC* for non-uniform traffic

As in all simulations the BSR and ILR heuristics obtained the same results, we analyzed the allocation of sub-carrier number on a fiber. In Fig. 13, the *x*-axis is the *ID* for each fiber link in the 14-node network. The *y*-axis represents the sub-carrier number on the link. We observe that BSR and ILR heuristics make the routing and spectrum allocation of different forms. The link ID 9 (node-pair, 3-6) and 28 (node-pair, 10-9), Fig. 8, allocated in both 39 sub-carriers.

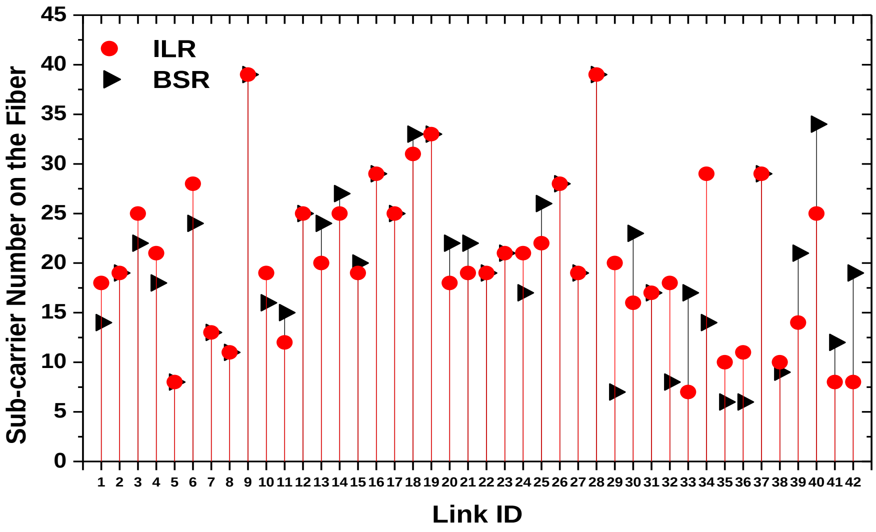


Fig. 13. Sub-carrier number per link

5.2.2 EON network

To show that the results presented before are not isolated cases, we performed simulations for the 19-node and 39-link European optical network (Fig. 14) with unidirectional path requests and uniform traffic demand between each node pair.

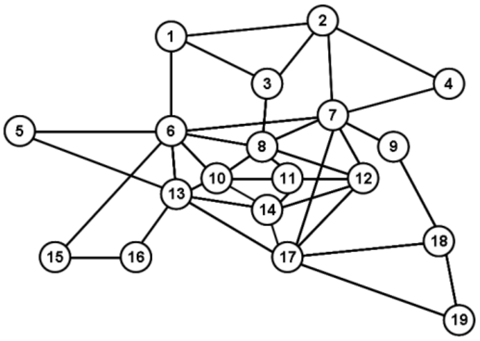


Fig. 14. European optical network (EON) Network.

Figs. 15, 16 and 17 shows the maximum number of sub-carriers by *GC* for one, two and three sub-carriers of uniform traffic, respectively. Similar conclusions can be inferred from this new network scenario. It is important to say that BSR and ILR heuristics are better than BLSA and SPSR, because it can balance the load among the network links in order to reduce the number of sub-carriers of network.

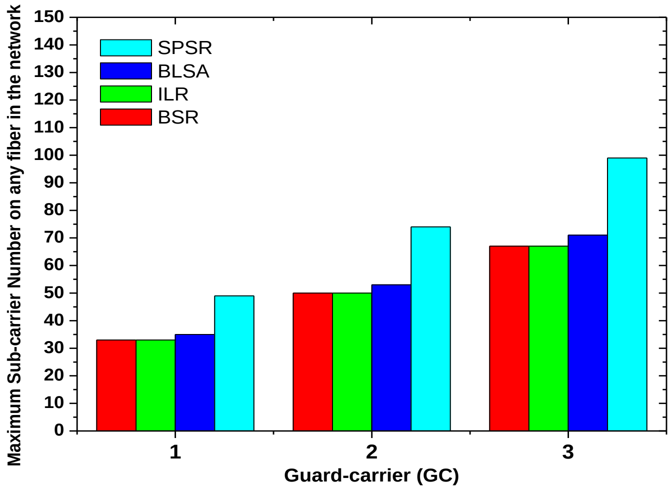


Fig. 15. Maximum sub-carrier number by *GC* for one sub-carrier of uniform traffic (X=1)

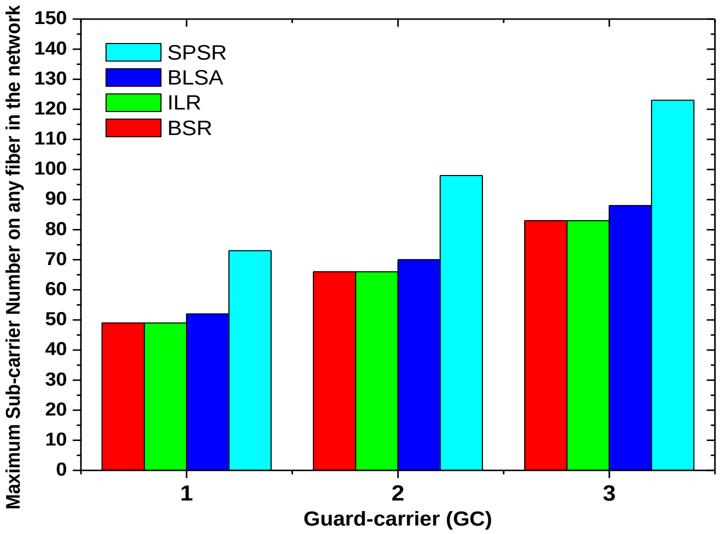


Fig. 16. Maximum sub-carrier number by *GC* for two sub-carriers of uniform traffic (X=2)

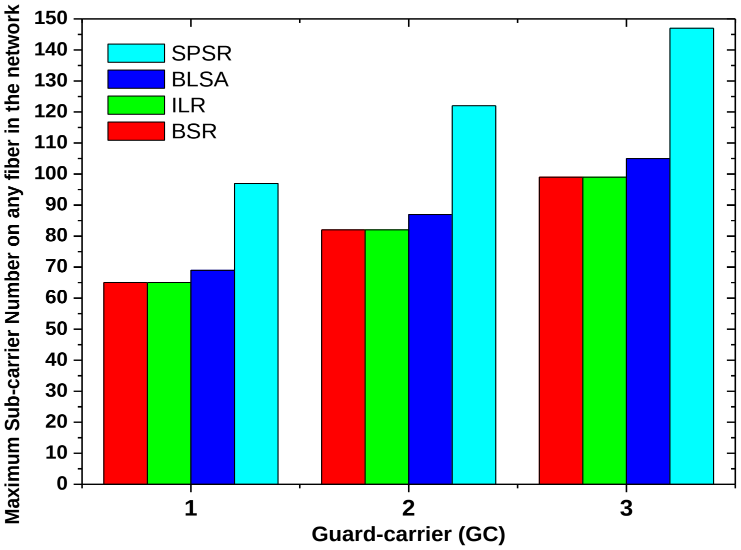


Fig. 17. Maximum sub-carrier number by *GC* for three sub-carriers of uniform traffic (X=3)

VI. CONCLUSION

In this paper was present one efficient method for spectrum allocation and two heuristics that have better results in all simulation that heuristics presented in [9] for NSFNet network with uniform and non-uniform traffic and European optical network with uniform traffic demand. For R_5 (ring) and R_6 (mesh) networks, the BSR and ILR heuristics found optimal solutions in order of milliseconds. The proposed heuristics are efficient to minimize the number of sub-carriers allocated in the network in flexible grid optical networks when compared to BLSA and SPSR assignment.

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