A Slot-Priority Spectrum Assignment Algorithm for Elastic Optical Networks

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***Abstract*— To overcome the inefficiency of the rigid spectrum allocation in traditional wavelength division multiplexing (WDM) networks, a flexible grid networking paradigm for spectrum allocation has been recently proposed. On these Flexible-Grid Optical Networks, the spectrum is not rigid, but flexible so that spectrum resources can be adaptively provided to client traffic demand. Spectrum allocation is performed by a process known in the literature as the Routing and Spectrum Assignment (RSA). The performance improvement imparted by RSA algorithms on currently proposed Flexible-Grid Optical Networks is a subject of current extensive investigation. In this paper, we propose a spectrum assignment algorithm based on First-Fit spectrum ordering, where slots are prioritized regarding to the number of forms how future variable-bandwidth path requests can be assigned. Case studies were carried out in order to analyze the benefits of the proposal. In the scenarios analyzed the proposed algorithm outperformed traditional First-Fit assignment.**

***Index Terms*—** Bandwidth-Variable Lightpath; Gridless Networks, First-Fit Assignment, Routing and Spectrum Assignment.

I. INTRODUCTION

The emergence of new services on the Internet imposes to future optical networks the capability to transport traffic with different Quality of Service (QoS) and bandwidth requirements. Wavelength Routing Networks (WRNs) introduced several advantages on the support of heterogeneous client layer traffic when compared to point-to-point optical transmission. In a mixed line rate system, however, some user requests may demand more or less spectrum space than a rigid WDM (Wavelength Division Multiplexing) channel. This granularity mismatch between the traffic demand and the rigid bandwidth granularity of WDM networks is leading to inefficient optical spectrum utilization in current Wavelength Routing Networks.

Recently, several authors [1]-[4] have pointed out that it is possible to increase the spectrum efficiency of WDM optical networks if a flexible method of spectrum allocation is accomplished. This new type of optical network is commonly referred to as Elastic Optical Network (EON), SLICE network, Flexible-Grid Optical Network or Gridless Network. At this new type of paradigm, the

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bandwidth assigned to a lightpath can span over a flexible slice of the optical spectrum. Such flexibility allows a finer match between required and provided bandwidths, which improves the network spectral utilization. In EONs, due to cost and operational simplicity, it has been proposed the spectrum partitioning into frequency slots of finer granularity than a WDM channel (for instance 6.25 or 12.5 GHz), whereas a lightpath is established using an appropriate set of contiguous slots. To support the concept of this new type of network, bandwidth-variable optical filters, wavelength-selective switches (WSS) and efficient modulation technologies (such as optical orthogonal frequency-division multiplexing O-OFDM) have been proposed to allow the desired flexible granularity into the optical domain [1]-[4].

A fundamental issue in this new network proposal relies on choosing a proper route and necessary number of contiguous frequency slots from end-to-end to accommodate the traffic demands, which is referred to as the Routing and Spectrum Assignment (RSA) problem [5]-[10]. RSA is different from and more challenging than the traditional RWA (Routing and Wavelength Assignment) problem used in conventional WDM networks, as path requests present heterogeneous bandwidth granularities and the allocated slots shall be consecutive in the spectrum domain. In addition, without spectral conversion, the wavelength-continuity constraint is transformed to spectrum-continuity constraint. In [6], the authors have proved the NP-hardness of the static RSA problem. The use of Integer Linear Programming has been commonly utilized to formulate the RSA problem, together with effective heuristics for the case where ILP is either time onerous or not attainable [6]-[7]. Dynamic routing and spectrum assignment algorithms to achieve high utilization of spectrum resource have also been currently investigated [8]-[10]. The necessity of accommodating connections of heterogeneous bandwidth granularities may incur that existing methods in the literature to optimize spectrum usage in WRNs do not provide good performance when directly applied to EONs. A very interesting example is the poor performance of the Most-Used wavelength assignment algorithm [12] when it is directly applied to EONs [8]. In EONs, the sum of spectrum usage on a range of frequency band does not lead to the known compacting characteristic that makes the Most-Used one of the most efficient wavelength assignment algorithms in WRNs [12].

The First-Fit (FF) wavelength assignment algorithm has been extensively utilized in WRNs because of its inherent simplicity and favorable capacity of leaving end-to-end free wavelengths in the network for future path requests [12,13]. This occurs due to its wavelength-usage compacting characteristic, which mitigates lightpath request blocking probability. FF consists of numbering all wavelengths and searching for available ones in the order they are numbered. The first available wavelength in the ordered list is then selected. In WRNs, where lightpaths are comprised by a single wavelength channel, if just wavelength availability is taken into consideration, the accommodation of a lightpath into a specific wavelength does not change the capability that future lightpaths be established in a distinct wavelength. Consequently, the path blocking probability is indifferent to the selected wavelength ordering (Notice, however, that this is not true when some physical impairments

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is taken into consideration [14]-[16]). A direct adaptation of conventional first-fit algorithm to Gridless networks is trivial and several works have used it by just numbering existing slots in a frequency-value sequential form [9,10]. However, such sequential numbering of slots for lightpath accommodation may not be the most efficient way to define the First-fit algorithm in Gridless networks. This may be understood by the fact that the accommodation of a lightpath in a contiguous set of slots will change the capacity that future heterogeneous-bandwidth requests are accommodated into the remaining set of slots, which was not the case in WRNs. Consequently, it is important to leave open capacity in distinct set of slots to future bandwidth-variable lightpaths. In this paper we show that by carefully defining priorities to some slots regarding to others it is possible to leave a higher number of free contiguous slots and consequently have a more efficient First-Fit spectrum assignment algorithm, which we refer to as Optimized First-Fit (FFO). A heuristics to generate an optimized First-Fit list for each traffic demand granularity is presented and the performance of the proposed algorithm is compared with traditional First-Fit assignment. In the cases analyzed, the proposed algorithm outperformed the traditional First-Fit method. The optimized lists are generated in an off-line manner, which incurs in RSA operational complexity similar to that of traditional FF.

II. The Proposed Algorithm

If conventional FF assignment is applied to EON, the beneficial behavior of leaving open capacity for future requests is not completely achieved. This is because slot usage and availability must both be though in chunks whenever distinct-bandwidth lightpaths must be established. Therefore, in this work, we propose a more efficient way of assigning slot priorities under the FF list construction, so that future spare capacities are though in chunks of slots.

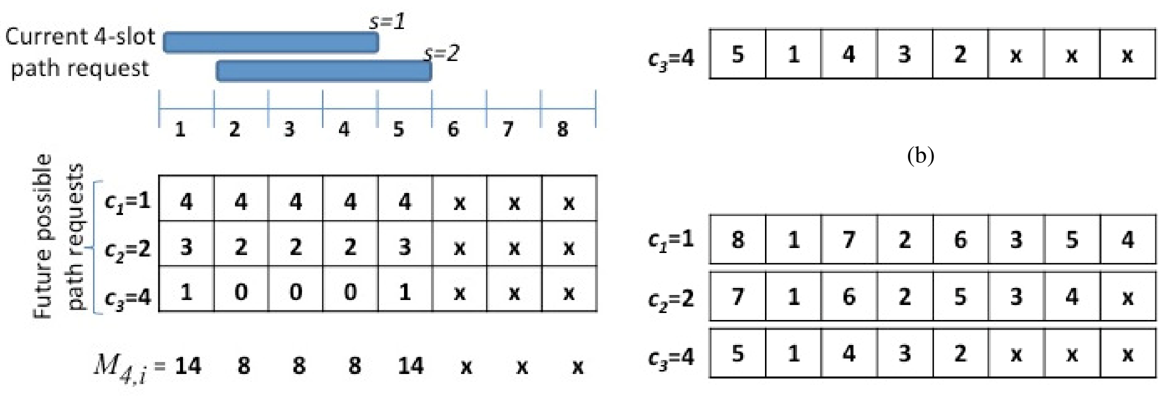
In the following analysis, let us assume that each fiber can transport at most S slots (indexed as $1,2,\ldots,S$) and that any given request which demands c_n slots is defined as a c_n-slot request. Without loss of generality, the vector of N different allowed number of slots that may be demanded by a request is defined as $C=\{c_1,c_2,\ldots,c_N\}$. Serving a request for c_n slots ($n \in 1,2,\ldots,N$), one should find a starting slot s_i ($1 \leq i \leq S - c_n + 1$) such that slots $s_i, s_{i+1}, \ldots, s_{i+c_n-1}$ are all free in every link of the path.

As mentioned before, the central idea of the proposed FFO is to define a proper slot priority assignment for each c_n-slot request in order to increase the number of future diverse-bandwidth requests that can still be set up after the establishment of the current c_n-slot request. The proposed algorithm is based on assessing the number of forms how future heterogeneous-bandwidth requests can still be admitted after the starting slot i is assigned to a c_n-slot request. For each c_n-slot request, priorities are given to those slots that provide the highest number of forms how future heterogeneous-bandwidth requests can be set up in the network.

The metrics described above can be calculated by defining, for each c_n-slot traffic demand, a matrix $A^{<c_n>}$, so that element $A^{<c_n>}_{j,i}$ (line j and column i) quantifies the number of forms how future c_j-slot requests can still be admitted after the starting slot i is assigned to the current c_n-slot request. Finally, the number of slots that will be available to future requests once a c_n-slot request is assigned to slot i can be assessed by $M_{c_n,i} = \sum_{\forall j}(c_j \cdot A_{j.i}^{<c_n>})$, $n = 1,2,\ldots,N$. For each c_n-slot request, an optimized FF list is formed by giving priority to slot i according to $M_{n,i}$.

To exemplify such concept, suppose a scenario in which the number of available slots per link is $S=8$ and lightpath requests are for either *1, 2* or *4* slots (i.e., $N=3$ and $c_1=1$, $c_2=2$ and $c_3=4$). Fig. 1a illustrates the *8* existing slots in the network and two possible slot assignments ($s=1$ and $s=2$) for a *4*-slot request in this scenario. The table shows the values for $A^{<4>}$, i.e, the future assignment forms for c_1, c_2 and c_3 under any possibility of a *4*-slot request admittance. For instance, the first row shows that there will be at most four ways to admit future *1*-slot requests whatever is the slot assignment to the *4*-slot request. On the other hand, three or two are the number of forms how future *2*-slot requests may be admitted if either starting-slot 1 or 2, respectively, is assigned to the current *4*-slot request. The *x* mark in the table informs to which slot the request cannot be assigned. Finally, the values for $M_{4,i}$ are shown on the bottom of figure 1a and the 4-slot request optimized FF list, as shown in figure 1b, is obtained by giving priority to slot i according to $M_{4,i}$. Fig. 1c shows the complete First-Fit lists found using the same procedure described above for all c_n-slot traffic request.

The pseudocode of the proposed algorithm is shown in Algorithm 1. It is important to mention that the list formation is realized off-line and it will depend only on the allowed number of slots that may be demanded by a request. Once the lists are formed, the same spectrum prioritization is used during all the spectrum assignment process in any dynamic traffic scenario. This incurs in no additional overhead in the spectrum assignment process apart from the fact that searching for slots that are not in sequence (as done for FFO) may be slightly more time onerous than sequentially. In addition, the fact that we have one list per traffic demand may increase the storage capacity, but not the operational complexity of the algorithm. Therefore, any performance improvement by the proposed method is achieved with slight additional operational effort. To organize the list, however, we can notice a big-O complexity of $O(S^3)$. Therefore, in situations where one needs to recalculate the lists, this value must be taken into consideration.



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(a) (c)

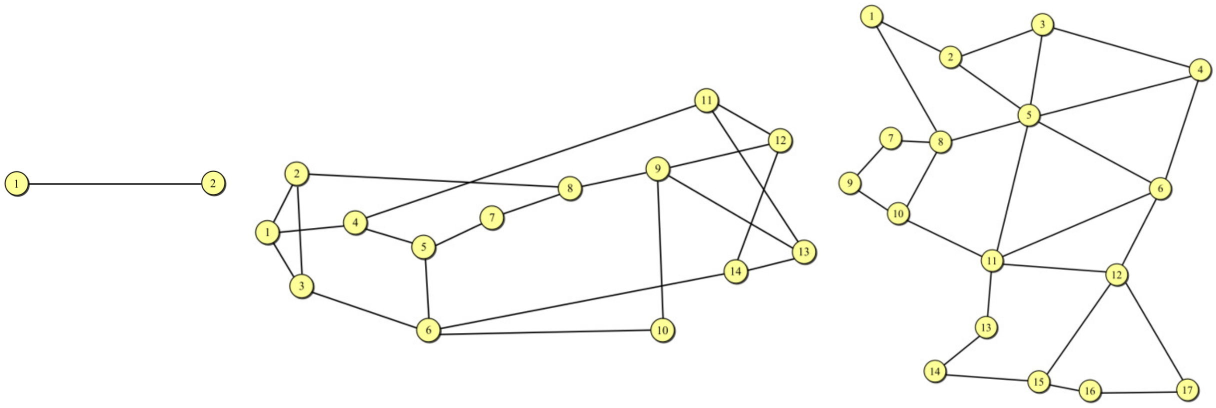
Fig. 1: Example of the FFO algorithm: (a) remaining open capacity after a *4*-slot request admittance; (b) Final optimized First-Fir list for 4-slot path requests; (c) Final optimized First-Fit list for *1*, *2* and *4*-slot path requests.

Algorithm 1: FFO priority list generator.

for $n = 1$ to N **do**
  for $i = 1$ to S **do**
    for $j = 1$ to N **do**
      $sum \leftarrow sum + C_j \cdot [\max(0, S - C_j - i - C_n + 2) + \max(0, i - C_j)]$
    end for
    $M_{n,i} \leftarrow sum$
    $sum \leftarrow 0$
  end for
end for
for $n = 1$ to N **do**
  for $k = 1$ to S **do**
    $list_{n,k} \leftarrow$ the index i which has a greater value of $M_{n,i}$. Ties are broken by taking first the largest values of i.
    $M_{n,i} \leftarrow -1$.
  end for
end for

III. Simulation Setup

In this section, we present the simulation assumptions used in the evaluation of the SA algorithm performance. The simulations were performed in three different topologies: single link (Topology 1- Fig. 2a), NSFNET topology (Topology 2 - Fig. 2b) and German topology (Topology 3 - Fig. 2c). In the single link scenario all communications take place in a pair of optical fibers linking two nodes (bidirectional communication). On the other hand, NSFNET network with *14* nodes and *21* bidirectional fiber links and German network with *17* nodes and *26* bidirectional fiber links are used to simulate a network scenario. The source-destination node pair for a given request is randomly selected with uniform distribution among the existing node pairs of the analyzed topologies. Path requests are assumed to follow a Poisson process with exponential holding time and demand any number of slots in the set *C of* allowed number of slots with uniform distribution. The routing algorithm used is the shortest path and a c_k-slot request between a pair of nodes *s* and *d* is accepted if the same c_k contiguous slots are available in the shortest path linking nodes *s* and *d* in both directions, i.e., if the spectrum continuity constraint is attended. Otherwise the request is blocked. For performance evaluation, we define the *request blocking probability* as the total number of blocked requests divided by the total number of requested calls and the *slot blocking probability* as the total number of blocked slots divided by the total number of requested slots. The request and slot blocking probability curves emphasize, respectively, the absolute number of blocked requests as well the effective utilization of the spectrum resources in the network. All simulations assumed a total of 10^6 call requests.



(a) (b) (c)

Fig. 2: Topologies used for performance evaluation: (a) single link, (b) NSFNET topology and (c) German topology.

IV. Performance Evaluation and Analysis

In this section, we present some simulation results of the proposed optimized First-Fit algorithm (FFO) and we compare its performance with traditional First-Fit ordering. We will initially evaluate a single link, which is a very simple scenario. However, its analysis is interesting because the proposed metric evaluates the loss of future assignment considering just lateral blocking (i.e., blocking that depends only on the lack of a contiguous set of slots and not on the possibility that succeeding links are not free, which is the case for multi-link routes). Afterwards, we simulate the application of FF and FFO to perform the spectrum assignment in both NSFNet and German networks. At such network scenarios, a not appropriate slot assignment for a lightpath will disturb future assignment of all paths that interfere with that lightpath, which stresses the importance of an effective slot assignment.

A. Performance evaluation in a single-link scenario

Let us first compare the performance of the proposed FFO spectrum assignment with traditional FF when both are applied to a single link. Here, we have assumed $S=128$ available slots and a slot traffic demand in the set $C=\{1, 2, 3, \ldots, 32\}$. Fig. 3a and Fig. 3b show, respectively, the path and slot blocking probabilities as a function of the link offered load in erlang. As it can be seen, FFO outperformed FF for both path and slot probabilities at all range of offered load analyzed. For instance, for *1.6* erlang, one can observe a reduction of *15%* in the path blocking probability and *13%* in the slot blocking probability, which is an interesting improvement for a change in the FF algorithm that does not incur in additional operational complexity. Since the proposed metric was derived considering just lateral blocking, this example shows that, in fact, it provides an efficient organization of the connections in order to reduce both path and slot blocking.

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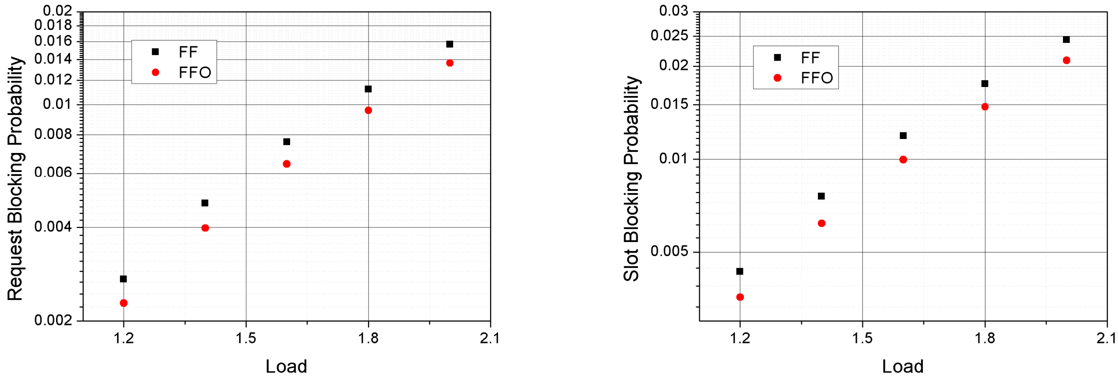
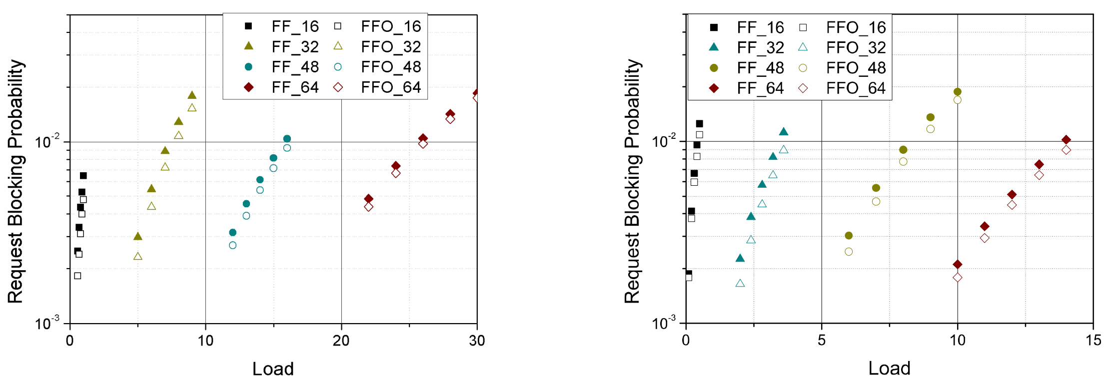


(a) (b)

Fig. 3: Request blocking probability (a) and slot blocking probability (b) as a function of the offered load in erlang evaluated for a single link scenario with S=128 and C={1, 2, 3, …, 32}.

B. Performance evaluation for distinct network topologies

For this scenario, let us first analyze the performance of the NSFNET network under four different values for S (*S=16,32,48* and *64*) and three different set of allowed number of slots per demand: $C_1=\{1,2,4,8\}$, $C_2=\{3,4,6,10\}$ and $C_3=\{3,5,7,11\}$. Each symbol in the graph stands for a different number of slots in the network: *S=16* (squares), *S=32* (triangles), *S=48* (circles) and *S=64* (diamonds), where the traffic demand is analyzed separately per figure. Fig. 4 shows the path blocking probability for the three traffic demands analyzed: C_1 (Fig. 4a); C_2 (Fig. 4b) and C_3 (Fig. 4c). One can notice that the FFO algorithm achieves a lower request blocking probability for all traffic scenarios and offered loads. A similar notation is used to plot the graph presented in Fig.5, in which it is shown the slot blocking probability as a function of the network offered load. The FFO algorithm also achieves a lower slot blocking than FF for all investigated cases. Notice that all curves present are in the same range for the request and slot blocking probabilities, although they represent different load conditions. This is because, as one increases the number of available slots (S) in the network, more offered traffic is required do provide similar slot occupancies as before.



(a) (b)

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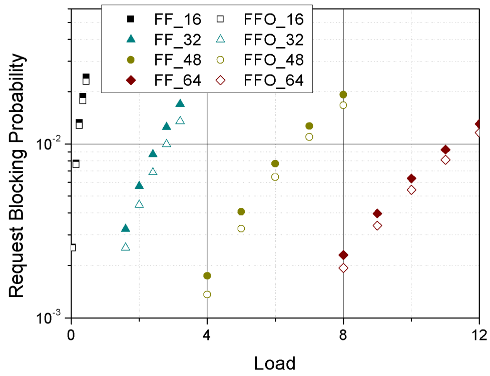
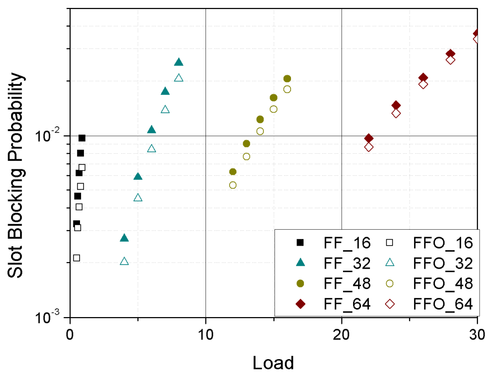
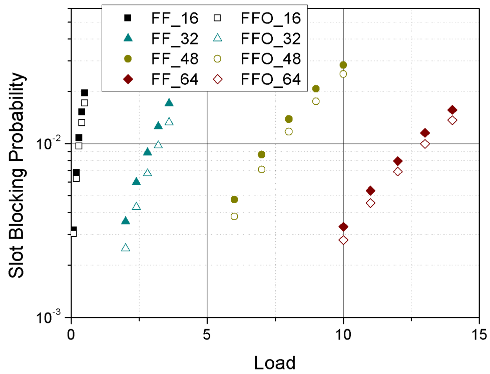


(c)

Fig. 4: Request blocking probability as a function of the network load for FF and FFO considering the request of (a) $C_1=\{1,2,4,8\}$ slots; (b) $C_2=\{3, 4, 6, 10\}$ slots and (c) $C_3=\{3, 5, 7, 11\}$ slots.



(a)



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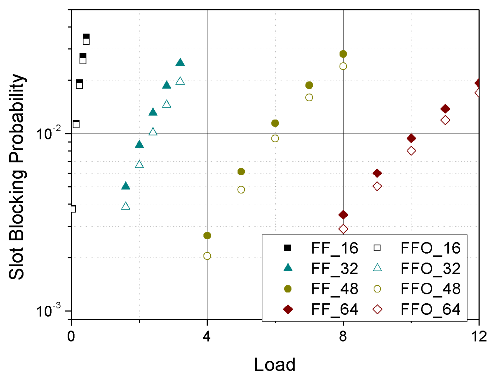

(c)

Fig. 5: Slot blocking probability as a function of the network load for FF and FFO considering the request of (a) $C_1=\{1,2,4,8\}$ slots; (b) $C_2=\{3, 4, 6, 10\}$ slots and (c) $C_3=\{3, 5, 7, 11\}$ slots.

Fig. 6 shows the performance of the FF and FFO spectrum assignment algorithms on the path (Fig 6a) and slot (Fig. 6b) blocking probabilities as a function of the network load for the NSFNET

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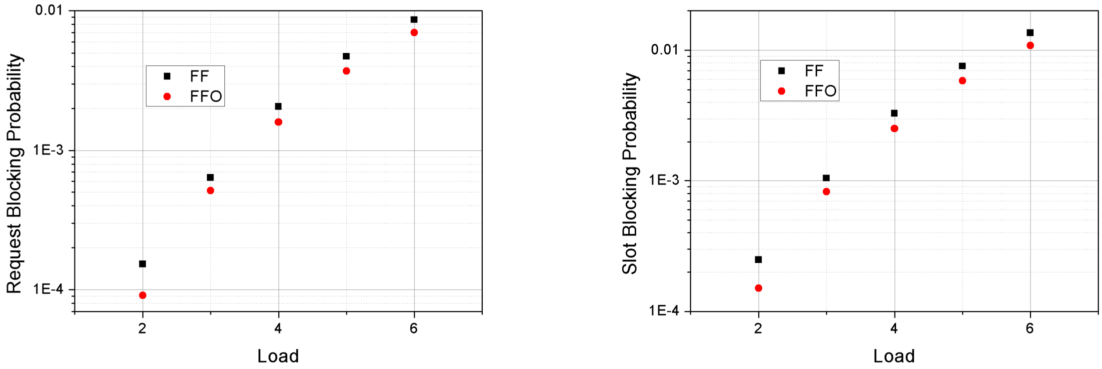
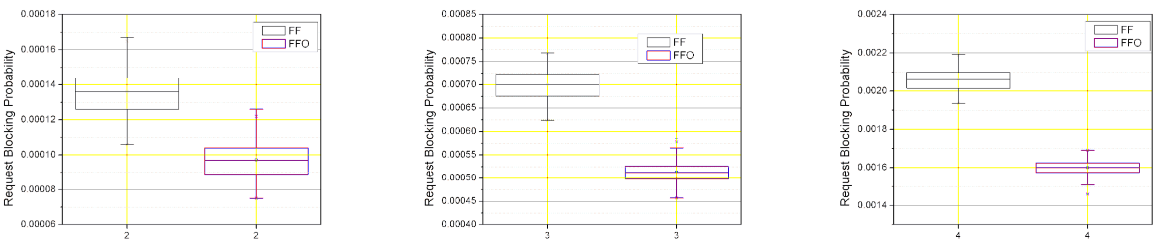
network with *S=128* and under a traffic demand *C={1,2,...,32}*. Again, the proposed FFO outperforms FF for all investigated network loads.



(a) (b)

Fig. 6: Request blocking probability (a) and slot blocking probability (b) as a function of the network load in erlang evaluated for NFSET topology with C={1, 2, 3, …, 32} and S=128.

In order to evaluate the confidence level of the obtained results, we have plotted the request blocking probability for each network load in terms of a box and whiskers chart. The box stands for 50% of the obtained data, the whiskers correspond to 100% of the obtained data, the symbols stand for the mean value and the horizontal line inside the box is the median value. We compare FFO and FF for a network load of 2 (Fig. 7a), 3 (Fig. 7b), 4 (Fig. 7c), 5 (Fig. 7d) and 6 (Fig. 7e) erlang, an NSFNET network with *S=128* and under a traffic demand *C={1,2,...,32}*. The box plots are obtained from a set of 100 independent simulations. The results shown in Fig 7 indicate that the improvement accomplished with the utilization of FFO instead of FF is statistically consistent since for all investigated loads the boxes found for both algorithms show no overlap in vertical axis. Notice that, for a network load of 4 erlang, the request blocking probability reduction between FF and FFO is around 22%, which is, again, an appreciable blocking reduction, mainly because we have assumed just spectrum assignment. Further blocking reduction is usually achieved by considering both routing and spectrum assignment, which shall be analyzed in future works.



(a) (b) (c)

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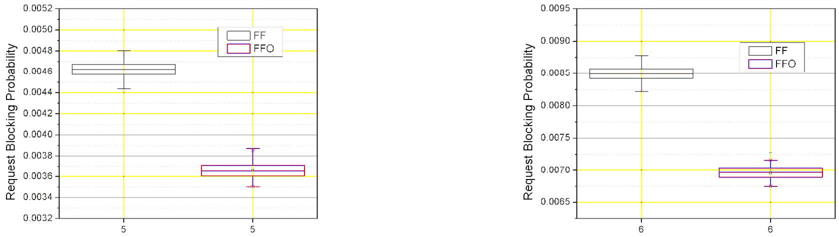
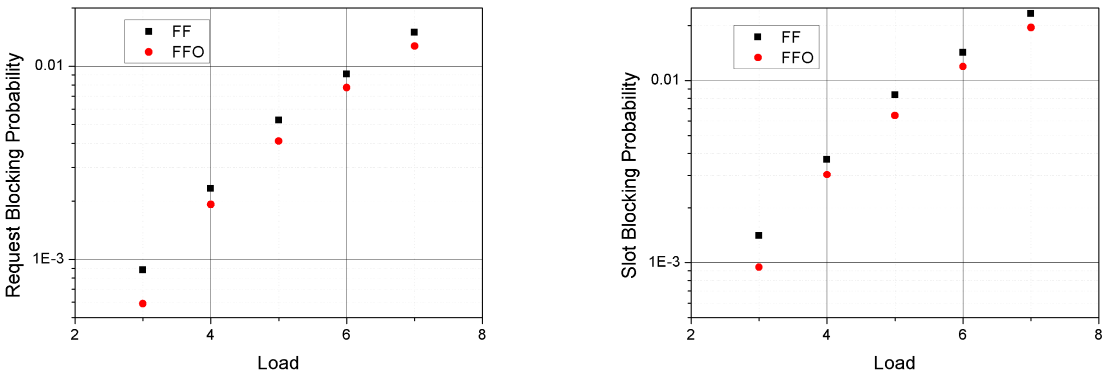


(d) (e)

Fig. 7: Slot blocking probability as a function of the network load for FF and FFO considering the request of (a) $C_1=\{1,2,4,8\}$ slots; (b) $C_2=\{3, 4, 6, 10\}$ slots and (c) $C_3=\{3, 5, 7, 9\}$ slots.

Fig. 8 shows the performance of the FF and FFO spectrum assignment algorithms on the path (Fig 6a) and slot (Fig. 6b) blocking probabilities as a function of the network load for the German network with $S=128$ and under a traffic demand $C=\{1,2,\ldots,32\}$. Again, the proposed FFO outperforms FF for all investigated network loads.



(a) (b)

Fig. 8: Request blocking probability (a) and slot blocking probability (b) as a function of the network load in erlang evaluated for German topology with $C=\{1, 2, 3, \ldots, 32\}$ and $S=128$.

V. CONCLUSIONS

In this work we presented an efficient slot ordering for FF spectrum assignment that reduces the impact that bandwidth-variable requests will incur in the assignment of future lightpaths. The use of an adequately planned optimized FF ordering does not impact the computational cost of the RSA and the examples analyzed showed superior performance than traditional FF in both path and slot blocking probabilities. For instance, reductions of about 20% were achieved in some analyzed scenarios. Future works will aim in analyzing both routing and spectrum assignment with the proposed First-Fit optimization as well as in building the list in an adaptive way, taking into account the network state to account for the number of possible future bandwidth-variable path accommodations.

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