Superchannel Multicasting Module Placement Algorithm Applied to Elastic Optical Networks

Bruno V. de A. Correia, Raul C. Almeida Jr., Helder A. Pereira and Daniel A. R. Chaves

***Abstract*—The spectral fragmentation problem in elastic optical networks decreases the spectral usage provided by this technology. One way to tackle this problem is by the use of the optical inverse multiplexing technique based on superchannel multicasting (SM). This technique allows to fill the fragments presented in the network with requests, by either modifying the original central frequency of the request or by dividing the original request superchannel into discontiguous sets of slots, in part of the route. These two forms of SM usage are investigated in this paper, in order to evaluate the advantage of applying descontiguity. An algorithm for an efficient superchannel multicasting module distribution among the network nodes with this capability is the main subject of this paper. The effectiveness of the heuristics is assessed by comparing its call request blocking probability with that provided by the uniform SM module distribution. We analyze three distinct topologies under multiple network loads and amount of SM modules. In all cases, our proposed module distribution provides reductions of** 25% **to** 48% **in the call request blocking probability when compared to the uniform SM module distribution.**

***Index Terms*—Elastic optical network, optical inverse multiplexing, spectral fragmentation, superchannel multicasting.**

I. Introduction

In elastic optical networks (EON), the bandwidth required to establish a call request depends on both the transmission bit rate and the assigned modulation format [2]. To such required bandwidth, one must assign an integer number of fixed-bandwidth spectrum slices, called slots [3]. This flexibility allows to use higher transmission bit rates, as 400 Gbps and 1 Tbps, which cannot be established through long distances with wavelength division multiplexing (WDM) technology, given its fixed grid spacing [2].

The basic steps to set up call requests in EONs are performed by the routing and spectrum assignment (RSA) algorithm, which consists in: (1) determining an appropriate route between the source and destination nodes of the request; and (2) choosing a set of contiguous slots available in all the links of the route. There are two constraints that the RSA algorithm must comply in this evaluation: the continuity constraint, which arises due to the lack of spectrum conversion along the links, and the contiguity constraint, which is derived from limitation in the multi-carrier generation technique (e.g., frequency shifting) in transmitter and the fact that consecutive OFDM channels (as subbands of superchannel) can save the spectrum guard band required in optical switching [4].

In optical networks under dynamic traffic scenario and heterogeneous traffic demands, it is highly expected that the successive establishment and release of call requests produce spectral fragmentation (SF). The SF corresponds to the presence of vacant and isolated slots either not aligned along the route or not contiguous in the spectrum [5]. If not well assessed, the SF may lead to an inefficient spectral usage and therefore high call request blocking probabilities.

One of the most recent proposals presented in the literature to mitigate spectrum fragmentation is the optical inverse multiplexing (OIM) [6]. This proposal uses the superchannel multicasting technique to create copies of the optical signal, followed by a bandwidth-variable wavelength selective switches (BV-WSS) to select sub-bands of the signal or the replicas [7]. The objective is to allow a superchannel to be split into multiple small subchannels through properly filtering the desired sub-band of the superchannel from one of its copies (or itself) respectively [4].

In this paper, we make use of a heuristic strategy for distributing superchannel multicasting modules (SMM), proposed in [1], along the nodes of elastic optical networks. The main goal is to determine an efficient module concentration ratio to be used on the placement of these modules among the network nodes. The proposal assesses the node usage frequency as intermediate nodes on the routing strategy adopted by the RSA process, and infer an efficient relative importance of including SMMs on the network nodes for SF mitigation. In [1], we have analyzed the SMM distribution found by the proposed heuristic on two network topologies under multiple network loads and numbers of modules. The present paper extends the analysis in [1], providing a more detailed investigation of the technique and an additional algorithm that describes the process of choosing the node of the route where the OIM will be applied. This paper also adds to the previous paper [1] a comparison of the superchannel multicasting technique used only as central frequency conversion, as presented in literature [8], and as OIM [4], [6], [7]. At last, an additional topology was added to our simulations.

This paper is organized as follows: Section II presents the OIM technique, different forms of using the technique and the

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node architecture assumed in the simulations. In Section III, the proposed heuristic is described in details. The simulation scenario is described in Section IV and the obtained results are presented and discussed in Section V. In Section VI, we present our conclusions.

II. Spectral Defragmentation Using Optical Inverse Multiplexing

The optical inverse multiplexing technique based on superchannel multicasting uses the non-linear effect of four wave mixing (FWM) to generate multiple copies of a superchannel by sending it to a highly nonlinear fiber (HNLF) coupled with K co-polarized pumps. The original signal together with the created copies in different spectrum positions may be used to generate new possibilities of spectrum allocation that cannot be performed with conventional devices and methods.

Spectrum conversion is a straightforward application that may be accomplished by selecting one of the signal copies and filtering both the original signal and the remaining copies. With spectrum conversion, the spectrum continuity constraint must be fulfilled in the formed segments of the lightpath, which alleviates the difficulty in finding a free contiguous and continuous end-to-end portion of the spectrum. Although spectrum conversion brings an interesting application for the OIM modules, there is still other possibilities of using them in the network.

Zhu et al. [9] proposes that the generated signal copies may be forwarded to different node outputs through filtering and switching processes in order to perform optical multicasting. Optical multicasting brings the advantage of spectrum saving since the network can use a lower number of links to distribute the signal among different destinations. Notice that such application still uses the fact that the super-channels are kept identical to the original, just shifted in frequency.

In this paper, a more extensive application for the superchannel multicasting technique is used. It is based on the fact that the superchannels are usually composed by several sub signal carries. Therefore, slices of both original signal and generated copies can be properly extracted to form an optical signal with the same amount of sub-bands, but in a discontiguity form along the frequency spectrum of the remaining route links, as discussed and demonstrated in [4]. These individual slices extracted from the original signal or from the created copies are referred to in this paper as sub-bands.

We refer to the module composed by HNLF and K co-polarized pumps as superchannel multicasting module (SMM). The number of generated copies (C) in these modules is related to the number of pumps that compose the module, and is given by [10]:

$$C = \binom{K}{2} 2 = K(K-1) \quad (1)$$

For instance, if two or three pumps are used, two or six copies, respectively, of the original signal are generated. The central frequency (CF) of the i-th copy, $1 \leq i \leq C$, is given by [9]:

$$f_{R_i} = f_s + f_{P_j} - f_{P_k}, \quad (2)$$

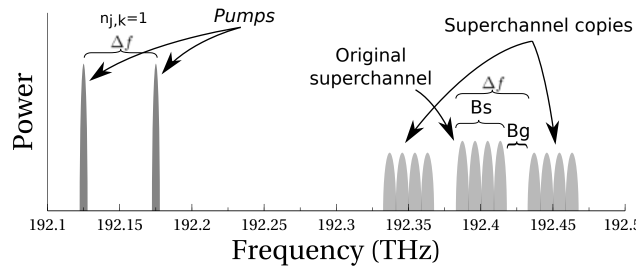
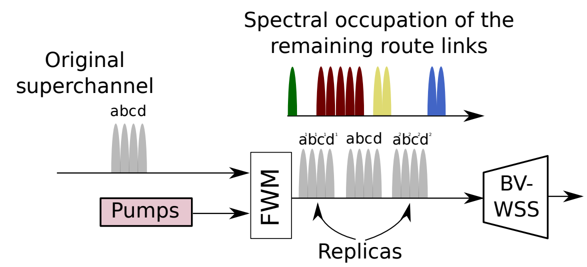
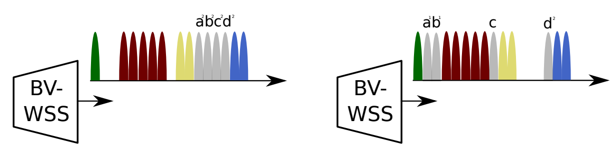


Fig. 1. Example of spectral position of pumps, original superchannel and its copies.



(a)



(b) (c)

Fig. 2. Example of FWM superchannel multicasting (a) used as: (b) central frequency conversion and (c) optical inverse multiplexing.

in which f_s is the central frequency of the original superchannel, f_{P_j} is the frequency of the j-th pump with $j = 1, \ldots, K$, f_{P_k} is the frequency of the k-th pump with $k = 1, \ldots, K$, with $j \neq k$. Fig. 1 illustrates the case of a SMM that uses two pumps, $f_{P_1} = 192.125$ THz and $f_{P_2} = 192.175$ THz, combined with a signal with the central frequency on $f_s = 192.40$ THz [10]. Such configuration generates two signal copies, one centered on $f_{R_1} = 192.35$ THz and the other on $f_{R_2} = 192.45$ THz.

A form to ensure that there is not spectral overlap among the generated superchannel replicas is given in [9] by calculating the spectral spacing between the pumps as:

$$f_{P_j} - f_{P_k} = n_{j,k} \cdot (B_s + B_g) = n_{j,k} \cdot \Delta f \quad (3)$$

in which B_s is the original superchannel spectral width, B_g is the guard band between original superchannels and the closest copies, as the distancies between the copies itself, $n_{j,k}$ is a positive integer variable and Δf is the sum of B_s and B_g. This frequency spacing is known as recursive pump-adding (RPA) [11] scheme. This scheme adopts predetermined values for $n_{j,k}$, in which $n_{1,2} = 1$, $n_{2,3} = 2$, $n_{3,4} = 4$, in a case with 4 pumps. With the right selection of the pump lasers frequencies in the SMM in an intermediary node of a request route, the signal replicas can be placed in the desired spectral position [4].

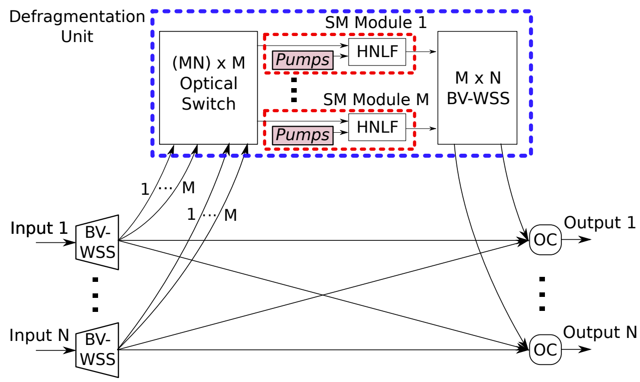


Fig. 3. Node architecture with shared-per-node OIM capability.

The selection of the sub-bands after the superchannel multicasting (Fig. 2a) can be performed in two distinct ways. The former has been proposed by Geisler et al. [8] and is illustrated in Fig. 2b. Using the proposed scheme, all sub-bands of one copy of the superchannel are selected as a whole package, working as simple central frequency conversion (similar to the wavelength conversion in WDM). In the second form (OIM), illustrated in Fig. 2c, each individual sub-band can be freely selected from either the original signal or its generated copies, and then forwarded in the remaining links belonging to the route [4], [6]. Notice that this approach can avoid spectrum collision by separating the contiguous slots of a bulk traffic demand and fitting them into multiple spectrum fragments. Therefore, the first utilization of the modules can relieve only the continuity constraint, whereas the second can relieve both the continuity and contiguity constraints [7].

Despite the advantages generated by the use of SMM for OIM defragmentation, there are also some limitations imposed by this technique. The first one recommends that the OIM should be used at most once per optical path [4]. This recommendation is due to the penalties imposed by the optical multicasting and filtering processes [6]. Other restrictions of using OIM defragmentation are related to: (a) the limitation of allowed spectral position for the generated copies, which must comply with Eq. (2) and Eq. (3); and (b) the number of possible signal copies that can be generated into the usable link bandwidth. This number depends on the signal bandwidth, pump position and number of slots in the network [10].

Fig. 3 shows a possible node architecture with M shared SMM, assumed in this paper. This architecture is based on the one proposed by Zhu et al. [7]. For a N-degree node, the architecture is composed by N $1 \times (N + M)$ WSSs (in the node inputs), and N optical couplers in the node outputs. The architecture is also composed by an $MN \times M$ optical switch responsible for forwarding each signal to one of the M superchannel multicasting modules, K co-polarized pumps for each SMM and an $M \times N$ WSSs to forward each selected sub-bands to the right output. With this structure, the superchannel multicasting modules are shared among all input/output links.

III. Heuristic Algorithm for Superchannel Multicasting Module Placement

In a network planning stage, how to choose the distribution of SMMs among the network nodes is not a trivial task. First notice that there is no reason to use OIM in the destination node of a route and it is usually assumed that it is not used in the source node as well. In addition, in real networks, it is expected that some nodes receive a larger amount of traffic than others and require a higher concentration of resources to improve some network metric under analysis.

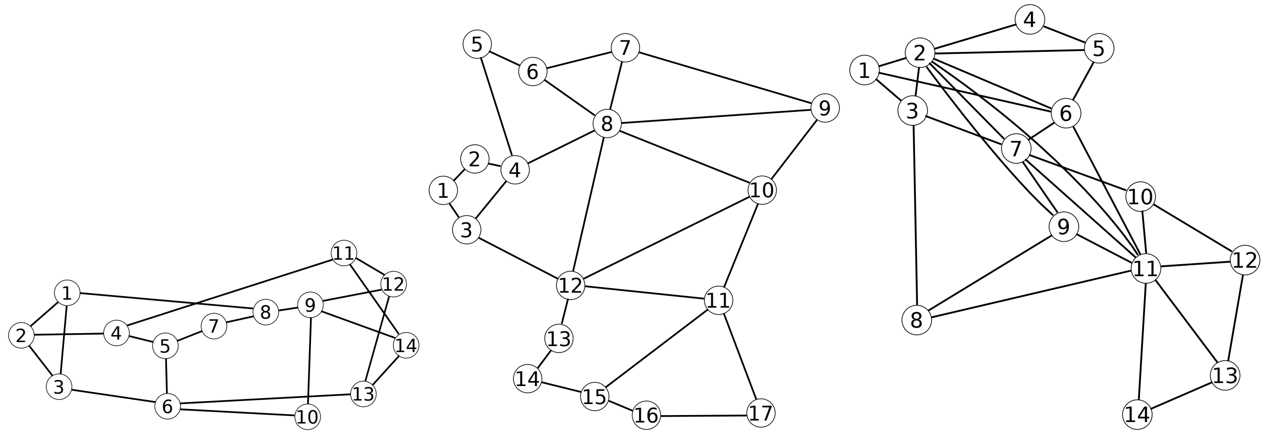
It is therefore reasonable to think that nodes which appear in high frequency as intermediary nodes in the set of routes used in the routing process should receive a high concentration of SMMs. However, directly taking into account the node frequency as an intermediate node of the network routes to decide how to distribute the modules among the network nodes is possibly not the most efficient strategy. This occurs because a route with a large number of nodes has a higher chance, when compared to shorter routes, of not presenting a set of available slots end-to-end (due to not attending the continuity and contiguity constraints) and therefore shall require OIM defragmentation with higher frequency. On the other hand, since long routes are formed by a larger number of intermediary nodes, it presents more options to perform OIM when compared to shorter routes. An optimized manner to place the modules in the network should observe all these aspects.

A straightforward manner to distribute the SMMs in the network would be an equal placement of these modules in all network nodes, named henceforth as uniform distribution. However, the uniform distribution of modules cannot contemplate all the aspects discussed in the previous paragraph and shall, therefore, not generate an efficient usage of the SMM during the network operation. Consequently, another technique shall be sought to properly distribute the SMM so that the network call request blocking probability may be reduced.

In this paper, we used the proposed heuristic [1], which is capable of finding an appropriate distribution of SMM among the network nodes. The proposal is based on not just take into account the node's usage-frequency as intermediary nodes in the routes, as previously discussed, but also infer in which proportion the SMM distribution shall be performed according to such frequency.

We have assumed in this paper a fixed shortest-path routing procedure, which is commonly assumed in network planning strategies that must have a simple and fast routing procedure [12], [13]. Thus, the node-usage frequency may be calculated in an off-line manner from the set of routes returned by the chosen routing algorithm. Then, the algorithm distributes the SM modules in an iterative way using the inferred importance of the node usage-frequency as intermediate node.

The pseudocode of the proposed SMM placement strategy is described in Algorithm 1. The first part of Algorithm 1 (from line 5 to line 6) consists in initializing all the elements of vector A with 0 and each element of vector U with the total number of times that the respective node appears as an intermediary node in the set of routes provided by the



(a) (b) (c)

Fig. 4. Network topologies used in our simulations: (a) NSFNet, (b) German and (c) Italy.

Algorithm 1 SMM distribution based on intermediary node ratio.

Require: Set of routes responsible for connecting every node pair in the network, as provided by the routing algorithm;
Require: T {Total number of SM modules};
Ensure: $M = (M_1, M_2, ..., M_D)$ {Best module distribution};
1: $U = (U_1, U_2, ..., U_D)$; {U is the node-utilization vector and D is the number of nodes in the network};
2: $A = (A_1, A_2, ..., A_D)$ {Auxiliary module distribution};
3: $Pb_{best} \leftarrow 1$;
4: **for** $\alpha = 0.01$ to 0.99 **do**
5: $A \leftarrow \{0, 0, ..., 0\}$;
6: $U \leftarrow$ nodes usage frequency as intermediary node in the set of total routes;
7: $L \leftarrow$ highest value in vector U;
8: **while** $\sum_{i=1}^{D} A_i < T$ **do**
9: $i \leftarrow$ index of the highest value in vector U;
10: $A_i \leftarrow A_i + 1$; {Assign one SM module to the i-th node}
11: $U_i \leftarrow U_i - \alpha \cdot L$; {Update the vector U}
12: **end while**
13: $Pb_{aux} \leftarrow$ call request blocking probability with module distribution A;
14: **if** $Pb_{aux} < Pb_{best}$ **then**
15: $Pb_{best} \leftarrow Pb_{aux}$;
16: $M \leftarrow A$;
17: **end if**
18: **end for**

routing algorithm. In the next step, variable L receives the maximum value of the elements in vector U (i.e. the largest number of times that a node appears as intermediary node). From line 8 to line 12, the SMM distribution policy occurs, in which one module is placed per iteration. First, the index i of the element in vector U of highest value is selected, which represents the next network node to receive an SMM. After an SMM is placed to this node, its intermediary-node ratio, U_i, is upgraded according to a fraction α of L, and this process continues until all modules are distributed among the network nodes.

To determine the best distribution for a fixed number of SMM, we vary α (for loop in line 4) and, for each α, we run a network simulation to obtain the resulting call request blocking probability (line 15) related to the current candidate module distribution, A_i, $i = 1, 2, \dots D$. If the probability value is lower than the one obtained so far, the SMM distribution and the call request blocking probability are stored (line 16 to line 19). Otherwise, it is disregarded. To ensure a fine-tune in search for the best value for α, values from 0.01 to 0.99 with a 0.01 step have been tested. Note that the closer α is to 0, the higher is the concentration of modules among the nodes with high incidence as intermediary node. On the other hand, the closer α is to 1, the modules tend to be distributed more uniformly. Notice that using a low step for α allows the check of several SM modules distributions, with a trade-off between computational effort and number of explored solutions.

IV. Simulation Setup

The network topologies used in the simulations are shown in Fig. 4. They are: NSFNet [14], composed by 14 nodes and 21 bidirectional links, Germany [15], composed by 17 nodes and 26 bidirectional links, and Italy [16], composed by 14 nodes and 29 bidirectional links. We assumed in our simulations 128 slots per link, 10^8 call requests, dynamic traffic with Poisson arrival process and Exponential holding time, uniform selection of source-destination nodes and number of slots of each call request varying between 2 and 5 slots uniformly distributed. The shortest-path routing algorithm was used, with hop as cost metric, along with first-fit (FF) algorithm used as spectral assignment policy.

The heuristic process presented in Algorithm 1 was performed under the specific network loads: 260 erlangs for NSFNet, 162 erlangs for Germany and 210 erlangs for Italy topologies. For each topology, we have assumed the quantities of SMM to be distributed among the nodes multiples to the number of nodes, so the heuristic can be adequately compared to the uniform distribution of SMM, with quantities equivalent to 1, 2, 3 and 5 modules per node.

During the process of establishing a call request, in case the continuity or contiguity constraints is not fulfilled in the selected route, an intermediate node with an available SM module may be used to perform either spectrum conversion or optical inverse multiplexing. At this point, it is required to perform a combined spectrum assignment: in the first segment of the route formed from the source node to the selected intermediate node, as well as in the second segment formed from the selected intermediate node to the destination node. The first segment requires a set of contiguous and continuous slots. The second segment may use either one of the copies generated in the SM process, if spectrum conversion is adopted, or the sub-bands extracted from the original signal and its generated copies, if inverse multiplexing is performed.

Algorithm 2 presents the process used in this paper of choosing: (a) the node where the process of OIM is applied; (b) the contiguous slots set (i.e central frequency) of the first segment of the route; and (c) either the chosen signal copy or the possible discontiguous slots to form the second route segment. The algorithm steps are the following: after discovering the set of nodes with available SMM, the candidate nodes to apply the OIM are selected at random, as presented in line 2. Then, the algorithm lists all possible central frequencies for assigning the spectrum in the first segment (line 3) following the FF order. For each of such possible central frequencies, the algorithm calculates the largest possible pump spacing, Δf (line 5), as described in eq.(3), which, together with eq.(2), defines the frequency of the pumps. After the copies are defined, at the output of the SMM it is possible to choose several combinations of slots to form the second segment of the connection. The selection of the sub-bands is also based on the FF algorithm, so that the available slots with the lowest indexes are always preferred (line 8). If there is a combination of subbands extracted from either the superchannel or its generated copies that is available in all links belonging to the second part of the route, the algorithm returns true and the call request is established using the slots picked in the first and second segments. If all sub-band combinations cannot be used for establishing the request, the guard band (B_g) is decreased by one slot (line 13) and the pumps frequencies are recalculated. The minimum distance between the central superchannel and the closest copy is one slot, as stated in [9]. After all possible nodes are tried and no possible combination of signal central frequency in the first segment and slot combination after OIM in the second segment is found, the algorithm returns false and the call request is blocked. In all results presented in this paper, we have assumed that the modules use one-to-three superchannel multicasting, i.e., 2 pumps for each module.

Algorithm 2 Process of selecting the node where to apply the OIM process and the spectrum assignment of the two formed segments

Require: S {Set of nodes of the call request route that presents a free SMM for possible OIM};
Ensure: Return true if the algorithm finds a possible allocation for the call request using OIM;
1: **while** S is not empty **do**
2: Randomly choose a node of S;
3: $V \leftarrow$ all possible central frequencies for the first segment of the route ordered by FF algorithm {Subroute from source node to the intermediary node chosen};
4: **while** V is not empty **do**
5: $B_g \leftarrow$ larger possible value {This parameter depends on the central frequency position of the first part of the route};
6: **while** $B_g \geq 12.5$ GHz **do**
7: Find Δf and calculate the pumps frequencies;
8: Check if there is a combination of possible slots allocation considering the original superchannel and the copies {FF ordering};
9: **if** combination found **then**
10: Keeps the central frequency of the first part of the route and the slots combination for the second part;
11: **return** true;
12: **else**
13: $B_g \leftarrow B_g - 12.5$ GHz;
14: **end if**
15: **end while**
16: Remove the current central frequency tried of V;
17: **end while**
18: Remove the current node tried of S;
19: **end while**
20: **return** false;

V. RESULTS

In this section, we describe the results obtained in our simulations. The first analysis we have carried out is a comparison of the following cases: 1) without any module installed (named as WO-SMM), 2) the use of the SMMs only working as central frequency converter (henceforth named as SMM-FC) and 3) working as OIM (henceforth named as SMM-OIM). To perform this analysis, each node of the network is equipped with a single SMM (for cases 2 and 3).

Fig. 5 shows the resulting network blocking probability of the three compared cases as a function of the network load for the (a) NSFNet, (b) German and (c) Italy topologies. Note that, in all investigated topologies, the possibility of performing optical inverse multiplexing (SMM-OIM) results in lower blocking probability (BP) values (diamonds in the graphs) than the case that allows just spectrum conversion (SMM-FC), which outperforms the case of a network without SMM (squares). The use of SMM-FC results in reduction in BP of at most 46% for NSFNet, 33% for German and 28% for Italy topologies when compared with the case WO-SMM. The comparison between the case of using SMM-OIM against WO-SMM results in reductions of at most 61% for NSFNet, 65% for German and 51% for Italy topologies. Such simulations confirm that the use of OIM capability results in a larger reduction in call request blocking probability then the use of SMM-FC.

Fig. 6 to Fig. 8 present the call request blocking probability of the topologies NSFNet, German and Italy, respectively,

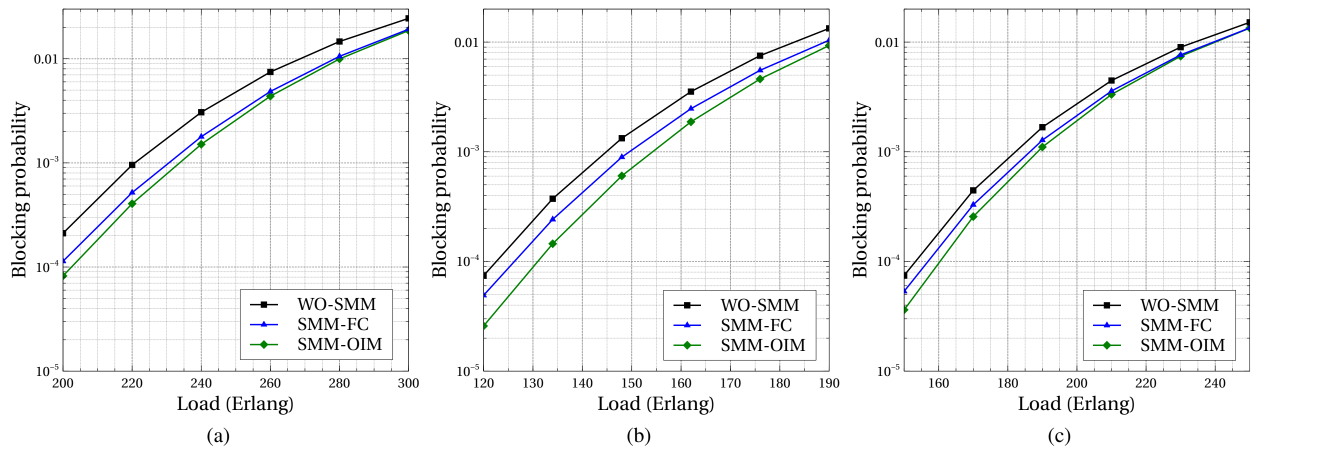


Fig. 5. Blocking probability as a function of load, considering WO-SMM, SMM-FC e SMM-OIM heuristics for the following topologies: (a) NSFNet, (b) German and (c) Italy.

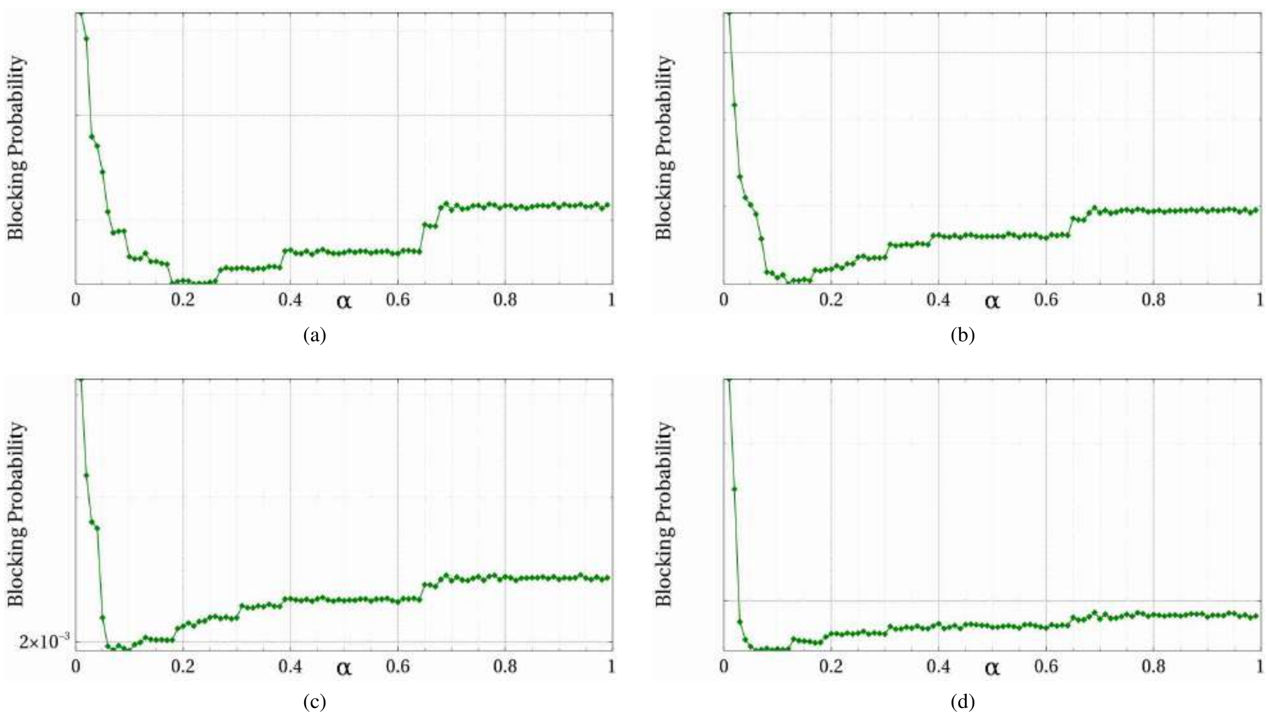


Fig. 6. Blocking probability as a function of α for the NSFNet topology with: (a) 14 modules, (b) 28 modules, (c) 42 modules and (d) 70 modules.

when different number of modules are used and α varies from 0 to 1 as assumed throughout the execution of the proposed heuristic. It can be perceived from the graphs that there is a value of α that results in a minimum value of BP. This minimum value varies from topology to topology, and depends on the target number of SMM to be installed. Fig. 6a to Fig. 6d show the results for the NSFNet topology considering a load value of 260 erlangs and different number of SMM: from 14 to 70 in total. Fig. 7a to Fig. 7d show the results for the German topology, considering a load value of 162 erlangs and the total number of modules from 17 to 85. Fig. 8a to Fig. 8d show the results for the Italy topology, considering a load value of 210 erlangs and total number of SMM from 14 to 70. Based on Fig. 6 to Fig. 8, the optimum value of α tends to be closer to 0 than to 1 in all investigated cases, which confirms that the uniform distribution does not represent the best manner to place the modules in the network.

The values of α that achieve the lowest BP as well as the best module placement found for each number of total modules deployed are shown in Tables I to III. Table I show these results for the topology NSFNet, Table II show the results for German topology and Table III for Italy topology.

Using the optimized modules solutions shown in Tables I to III, we have investigated the call request blocking probability as a function of the network load as shown in Fig. 9 to Fig. 11. In the graphs, we compare the resulting BP by deploying SMM-OIM using our proposal against the BP found using the uniform deployment. Fig. 9 performs the comparison for NSFNet topology using 14, 28, 42 and 70 modules, Fig. 10 presents the comparison for German topology using 17, 34,

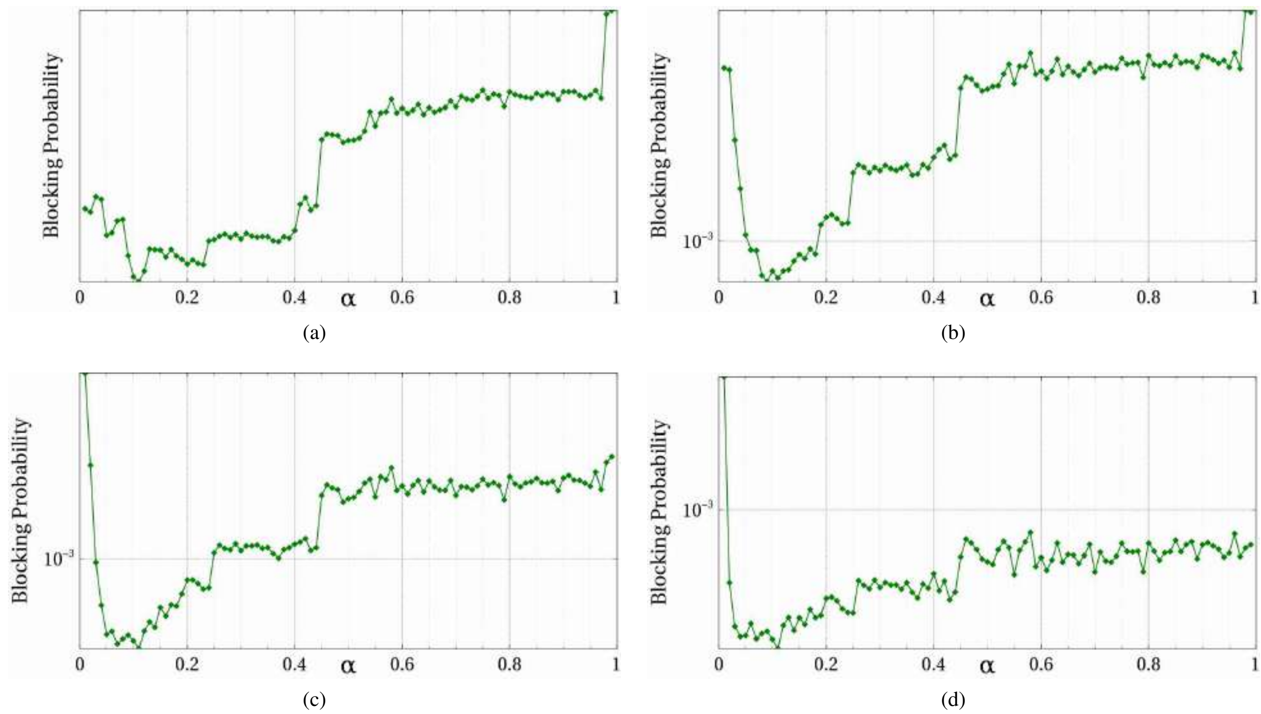


Fig. 7. Blocking probability as a function of α for the Germany topology with: (a) 17 modules, (b) 34 modules, (c) 51 modules and (d) 85 modules.

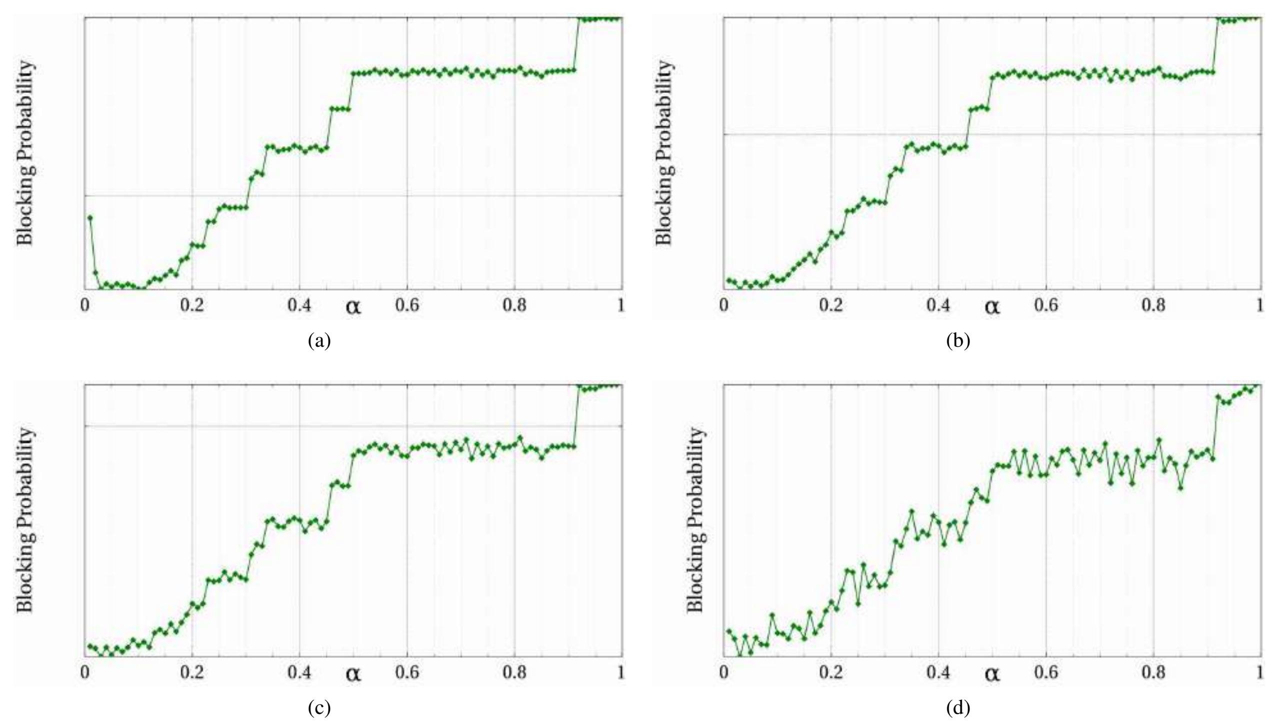


Fig. 8. Blocking probability as a function of α for the Italy topology with: (a) 14 modules, (b) 28 modules, (c) 42 modules and (d) 70 modules.

51 and 85 modules and Fig. 11 performs the comparison for the Italy topology using 14, 28, 42 and 70 modules. One can observe that, in all investigated cases, the BP decreases as the number of SMM-OIM increase. However, there is a number of deployed modules beyond which no further reduction in BP is achieved due to the installation of extra modules. It can also be observed that the lower is the number of modules installed, the higher is the reduction in BP obtained by our proposal in comparison with the uniform distribution. On the other hand, when a large number of modules are used, the importance of the proposed method is observed mainly under high load conditions.

In order to quantify the call request blocking probability reduction between the proposed and the uniform methods, we consider initially the lowest value of the investigated load for each topology. At this point, the obtained gain in the call

TABLE I
OPTIMUM VALUE OF α AND THE RESPECTIVE OIM MODULES DISTRIBUTION AMONG THE NSFNET TOPOLOGY NODES.

Total	α	Distribution (Node 1 to 14)
14	0.22	1-0-1-2-1-3-0-2-2-0-1-1-0-0
28	0.12	2-1-2-4-3-6-0-3-4-0-2-1-0-0
42	0.10	3-2-3-6-4-8-0-5-6-0-2-2-1-0
70	0.06	4-3-4-10-7-14-0-8-10-0-4-4-2-0

TABLE II
OPTIMUM VALUE OF α AND THE RESPECTIVE OIM MODULES DISTRIBUTION AMONG THE GERMANY TOPOLOGY NODES.

Total	α	Distribution (Node 1 to 17)
17	0.11	0-0-1-2-0-0-0-4-0-1-4-5-0-0-0-0-0
34	0.09	0-0-3-5-0-0-0-7-0-3-7-8-0-0-1-0-0
51	0.11	1-1-5-6-1-0-0-9-0-5-8-9-2-0-4-0-0
85	0.11	3-3-7-8-3-3-3-11-2-7-10-11-4-2-6-2-2

TABLE III
OPTIMUM VALUE OF α AND THE RESPECTIVE OIM MODULES DISTRIBUTION AMONG THE ITALY TOPOLOGY NODES.

Total	α	Distribution (Node 1 to 14)
14	0.11	0-7-0-0-0-0-0-0-0-0-7-0-0-0
28	0.03	0-15-0-0-0-0-0-0-0-0-13-0-0-0
42	0.03	0-22-0-0-0-0-0-0-0-0-20-0-0-0
70	0.03	0-32-0-0-0-0-0-0-0-0-29-0-0-0

request blocking probability is 25 % for NSFNet topology, with a total of 14 SMM, 46 % for Germany topology, with a total of 17 SMM, and 48 % for Italy topology, with a total of 14 SMM. On the other hand, the gain achieved under the highest load value was 20 % and 23 %, when 28 and 42 modules are used in the NSFNet topology, 33 % and 30 % when 34 and 51 SMM are used in the Germany topology, and 40 % and 42 % when 14 and 28 modules are used in the Italy topology.

It is important to point out that, in the NSFNet topology (Fig. 9), the same performance is achieved by the uniform distribution with 42 modules and the proposed heuristic with 28 modules, which results in capital expenditure (Capex) reductions of more than 33%. A similar trend is observed in the Germany topology (Fig. 10), where the same performance is observed when the uniform distribution with 51 modules is compared to the proposed heuristic with just 17 modules. This results in a Capex reduction of more than 66%. More prominent Capex reductions are observed in the Italy topology (Fig. 11) under low and middle load points, as similar blocking probabilities are achieved for the uniform distribution with 70 modules and the proposed heuristic with 14 modules, which results in a Capex reduction of 80%. Also in Fig. 11, one may perceive that just 14 modules are enough to provide low blocking probability, since there is no reduction in the call request blocking probability when additional modules are installed in the network nodes, except for slight reductions under high load values. This indicates that the proposed heuristic was able to distribute the SMM in a very efficient way so that they are installed in positions where they are effectively used.

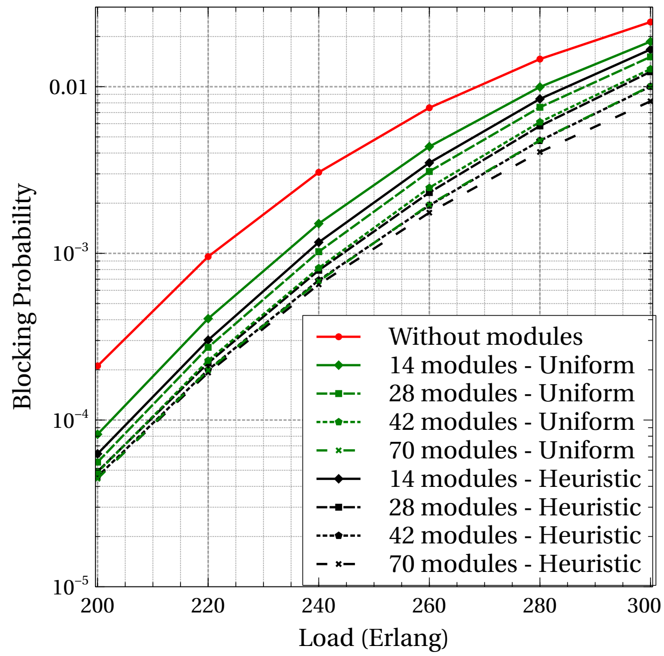


Fig. 9. Call request blocking probability as a function of network load for NSFNet topology considering simulations with: (1) Without modules. Uniform distribution with: (2) 14 modules; (3) 28 modules; (4) 42 modules; (5) 70 modules. Heuristics with: (6) 1 modules; (7) 28 modules; (8) 42 modules; (9) 70 modules.

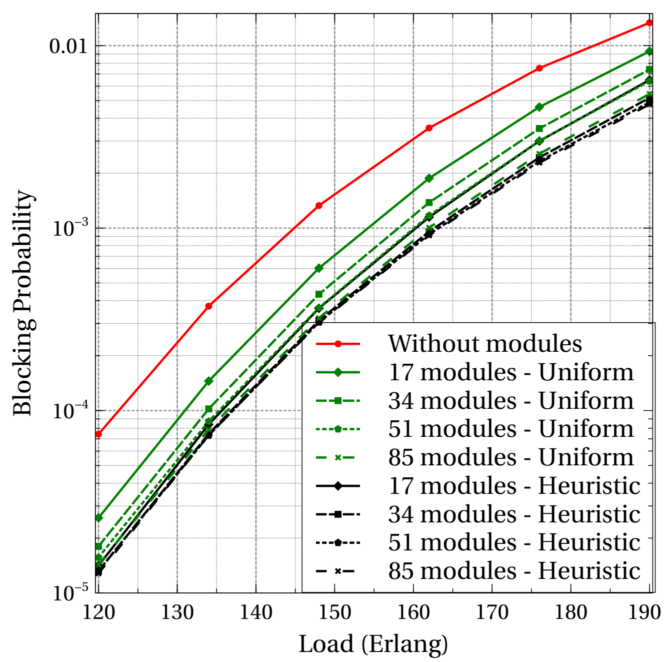


Fig. 10. Call request blocking probability as a function of network load for Germany topology considering simulations with: (1) Without modules. Uniform distribution with: (2) 17 modules; (3) 34 modules; (4) 51 modules; (5) 85 modules. Heuristics with: (6) 17 modules; (7) 34 modules; (8) 51 modules; (9) 85 modules.

VI. CONCLUSIONS

This paper explore a heuristic strategy for superchannel multicasting module placement in elastic optical networks. The modules are used to mitigate the effect of spectrum fragmentation. We compare the use of SMM either as only central frequency converters or as using the OIM capability. The

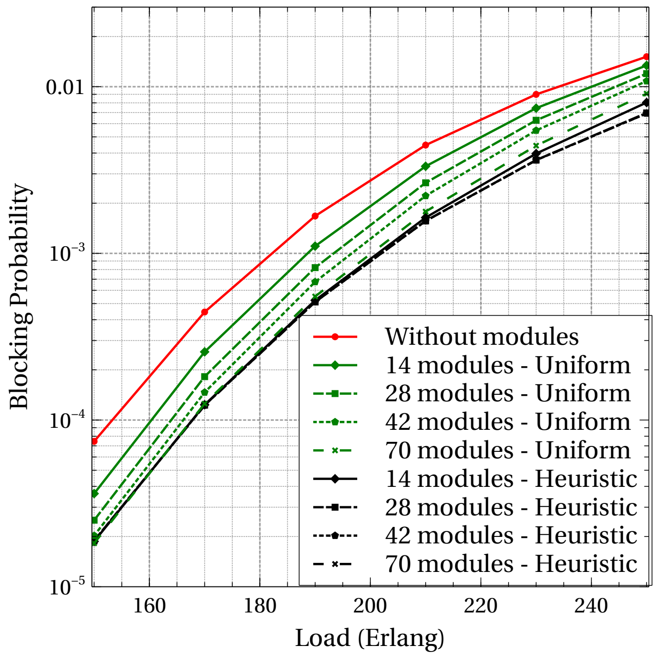


Fig. 11. Call request blocking probability as a function of network load for Italy topology considering simulations with: (1) Without modules. Uniform distribution with: (2) 14 modules; (3) 28 modules; (4) 42 modules; (5) 70 modules. Heuristics with: (6) 14 modules; (7) 28 modules; (8) 42 modules; (9) 70 modules.

analysis has shown that the OIM can be more efficient than the central frequency conversion on mitigating the fragmentation problem, as it achieves superior reductions of the overall call request blocking probability. In addition, we have shown that the heuristic strategy provides significant reductions in the call request blocking probability when it is compared to the uniform module distribution. For the same number of installed SMMs, reductions in the call request blocking probability close to 50% was achieved for the Germany topology, 40% for the Italy topology and 25% for the NSFNet topology. Such reductions show that the proposed technique presents an efficient way to distribute this type of devices among the network nodes.

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