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Migration of elastic optical networks to the C + L-bands subject to a partial upgrade of the number of erbium-doped fiber amplifiers

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Space division multiplexing (SDM) and band division multiplexing (BDM) are considered promising technologies to increase the capacity of optical transport networks. The progressive shortage of available dark fibers and the immaturity of multicore and multimode fibers for multichannel transmission induce network operators to postpone the process of capacity enhancement through SDM. Therefore, capacity increase revolves around BDM by lighting up at least the L-band of the already installed optical fiber infrastructure, which is a practical solution in the short to middle term. However, L-band activation requires the upgrade of network components such as erbium-doped fiber amplifiers (EDFAs). To manage the imposed cost while leveraging the L-band, a network can be partially rather than fully migrated in a single step by upgrading just a subset of the fibers and thus a subset of EDFAs to operate in the C + L-bands. In this paper, the focus is set on determining which fibers in the network should be upgraded to exploit the L-band, subject to a constraint on the maximum number of EDFAs to be upgraded, and analyzing its impact on network performance when facing dynamic traffic in terms of the blocking ratio. To this end, three heuristic algorithms, each pursuing a different objective, and two of them based on an integer linear programming (ILP) formulation, are proposed for the network planning to identify which fibers to upgrade. Simulation results demonstrate that, thanks to the use of these heuristics, the upgrade of a partial set of links to the C + L line system is a viable solution for network operators to circumvent the huge cost associated with migrating the full network. For instance, we demonstrate that a strategic partial upgrade using the proposed methods, subject to upgrading a maximum of 60% of the EDFAs, can significantly boost the supported traffic load in the examined topologies, ranging from 175% to 322%, when compared to the non-upgraded network.

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1. INTRODUCTION

The remarkable growth of traffic demands over the last decade has made it essential to expand the capacity of optical networks. The increased size of data-center networks (e.g., 100 times increase of Google's data centers in 10 years [1]) is an instance of this rapid growth. The introduction of advanced technologies in optical communication, like digital signal processing (DSP) and coherent transceivers employing multilevel modulation formats [2,3], provides network operators with spectral efficiency enabling capacity scaling. However, this type of capacity scaling is not enough to cope with the growth rate in bandwidth demand [4]. Two solutions that are currently receiving a great deal of attention from the research community are space division multiplexing (SDM) [5,6] and band division multiplexing (BDM) [7–9].

By benefitting from parallel signal transmission, the deployment of SDM technology yields dramatic capacity improvement compared to elastic optical networks (EONs) [5]. SDM-enabled EONs can be realized through several strategies, including multifiber (MF) transmission, the use of multicore fibers (MCFs) or the use of multimode fibers (MMFs) [10,11]. Although the utilization of MCFs or MMFs increases the transmission capacity to the range of petabit/s/fiber [12], their implementation relies on installing new optical fiber infrastructures, which imposes a substantial capital expenditure (CAPEX). Furthermore, MCF and MMF technologies have not yet been commercialized and are still in the research phase. Regarding the use of MF transmission, it is a practical solution if unused optical fibers are available (although it requires enabling C-band line systems in those fibers). Nevertheless, in the event of shortage or lack of available dark fibers, leasing and rolling out new cables may cause huge CAPEX cost and delays [13].

As an attractive and practical solution to increase the capacity of optical fibers, multiband elastic optical networks (MB-EONs) come into play. In MB-EONs, the goal of increasing network capacity is ensured by using other spectral bands in addition to the conventional C-band [14]. The main motivation behind promoting the MB-EON technology is that scaling the network capacity can be done through the efficient utilization of the available spectrum at already installed fibers, thus maximizing the return on investment of the existing optical fibers [15]. The implementation of MB-EONs requires the deployment of new amplifiers, transceivers, and reconfigurable optical add-drop multiplexers (ROADMs) able to operate in spectral bands beyond the C-band (in the O-, E-, S-, L-, and/or U-bands). For instance, lighting up the L-band increases the available bandwidth of a network that initially uses only the C-band by more than two times, from ∼5 to ∼11.5 THz [13]. Also, thanks to the L-band-ready erbium-doped fiber amplifiers (EDFAs), C + L-band systems are commercially available, which is another main reason for deploying C + L systems.

To manage the costs imposed on the network operator by the extension of spectral bands beyond the C-band, network planning and design should be done carefully. The high cost of the components required to upgrade a network to C + L-band optical line systems leads network operators to postpone the deployment of a complete upgrade and to adopt a partial migration strategy instead. In this way, it is necessary to identify which fibers (and associated equipment) should be migrated first. On the other hand, once a network has been fully or partially migrated, the use of different spectral bands brings another dimension to the operation mechanisms of EONs, moving from the routing, modulation level, and spectrum assignment (RMLSA) problem [16] to the routing, band, modulation level, and spectrum assignment (RBMLSA) problem in MB-EON [17,18].

In this paper, we focus on the partial migration of EONs. We assume a traffic model where optical connections (lightpaths) are dynamically established and released over time. We propose and compare three different methods to determine the set of fibers to upgrade, each targeted to address a different objective, and we then assess the impact on performance in terms of reduction of the blocking ratio or, equivalently, in terms of the increase of the traffic load supported by the network. In contrast with previous works on this topic, we consider that the cost of upgrading different fibers is different, as the number of amplifiers in each fiber of the network may be different. Therefore, we focus on analyzing which fibers to upgrade subject to a constraint on the maximum number of amplifiers that can be upgraded (due to cost considerations) to support both the C- and L-bands. Nevertheless, it is worth noting that the final objective is to improve the dynamic performance (minimization of the blocking probability).

The rest of the paper is organized as follows. In Section 2, related works on multiband networks and partial migration strategies are reviewed. Then, Section 3 defines the problem, and the proposed methods for partially upgrading the network are discussed. The simulation scenario to analyze the performance of the different methods is described in Section 4, while Section 5 is dedicated to presenting and discussing the numerical results. Finally, the conclusions of the present study and some future work directions are given in Section 6.

2. RELATED WORKS

Several works have compared the replication of C-band line systems with the exploitation of different spectral bands to analyze the advantages of MB-EONs. Thus, Shariati *et al.* [19] have shown that the exploitation of the C + L + S-bands improves the network capacity by 8%–14% compared to the deployment of MF transmission with three C-band fibers. Ferrari *et al.* [20] have presented a comprehensive comparison between SDM and BDM technologies. They conclude that in case of availability of dark fibers, the employment of pure SDM technology is better, and if the availability of dark fibers is limited, the most practical solution relies on the mixed employment of BDM and SDM technologies. In [21], the network performance under three different methods, namely, C-band single-mode fiber transmission, SDM technology in which two fibers enable MF transmission, and a C + L-band system, is analyzed. Simulation results demonstrate that the C + L-band system doubles the network capacity while its application does not lead to severe physical penalties compared to MF transmission over two fibers. From a techno-economic perspective, Jana *et al.* [22] conclude that the application of SDM technology using available dark fibers enabled by MF transmission technique forces network operators to devote more expenditures compared to the C + L-band systems for long-haul networks.

Other works have analyzed the impact of physical impairments in multiband networks. Multiband systems impose a nonlinear interference, known as inter-band stimulated Raman scattering (ISRS), which induces power transfer between spectral bands [23,24]. D'Amico *et al.* [23] evaluated the quality of transmission (QoT) in C + L-band systems and concluded that the degradation in generalized signal-to-noise ratio (GSNR) is related to SRS. Mitra *et al.* [25] employed an optical SNR (OSNR) model considering ISRS as well as amplified spontaneous emission (ASE) noise, which is generated by the amplifiers in the C + L-bands, and Cantono *et al.* [26] concluded that the application of the generalized Gaussian noise (GGN) model is the most appropriate solution for the prediction of QoT of wideband optical line systems.

Regarding the operation of MB-EONs, several works have focused on partially migrated networks, i.e., hybrid C/C + L networks, where just a subset of the links have been upgraded to exploit the C + L-bands. Bao *et al.* [27] proposed a technique called link-oriented resource balancing (LoRB) to select a block of frequency slots for spectrum assignment such that the contiguous available resource separation degree (CARSD) for the transmission path is minimum. Yao *et al.* [18] proposed an RBMLSA algorithm for hybrid C/C + L networks, which is aware of the interactive effect of the ISRS impairment that new requests might have on the existing requests. Moreover, different policies for the spectrum assignment under a hybrid C/C + L network were introduced. However, [27] and [18] do not address how to plan the C/C + L network, i.e., how to determine which subset of links should provide C + L transmission capabilities.

Moving from a C-band only network to a fully upgraded network in which all the links can operate in the C + L-bands is a considerably costly process. Therefore, methods for partially or gradually migrating C-band networks toward C + L have been proposed, as it is of the utmost importance for operators. The work by Uzunidis *et al*. [28] combines and analyzes many of the issues previously mentioned in this section. They first incorporate the main physical impairments of MB systems into an RBMLSA algorithm and use it to assess the performance advantages of MB-EONs (in terms of traffic blocking) compared with the replication of C-band fibers. Then, they demonstrate that upgrading a C-band network to a MB solution can be done in gradual phases in order to reduce the first-day CAPEX. This is because not all fibers and spectral bands have the same level of utilization. Therefore, they conclude that the network operator may plan the deployment of MB systems in specific links as they are needed due to traffic increases. A network planning framework to achieve a cost-effective network upgrade is presented in [29]. In that paper, Moniz *et al*. focus on upgrading a network by combining two strategies. On the one hand, by deploying line interfaces in some of the existing fibers to enable operation in the L-band. On the other hand, by deploying new optical fibers (and associated line interfaces) to operate in the C + L-bands. They combine those two strategies with the aim of minimizing the total cost of the required fibers and line interfaces for the upgrade. A very relevant work on partial network upgrade is that of Ahmed *et al*. [30]. They propose several heuristics to gradually migrate a C-band network toward a fully upgraded C + L-band network in a set of sequential steps. They take into account the traffic evolution and the impact of the physical layer and determine when to perform each migration step and which fibers should be upgraded in each of those steps. The aim is to minimize the total cost of the upgrade until the network is fully migrated to the C + L-bands through those sequential steps. Then, they extend their work in [31] by proposing and comparing several methods to reprovision (or reallocate) the existing lightpaths in the network when it is partially upgraded (in each of those sequential steps) to support the C + L-bands. These last works, [30,31], assume an incremental traffic model, where new connections are established, but once established are never released. In [32], we proposed a heuristic algorithm for gradually upgrading the fibers of a network to support the C + L-bands. In contrast to [30,31], we assumed a dynamic traffic model, where connections are established but also released on user demand, and demonstrated that the supported traffic load can be significantly increased with a partial upgrade of the network links. Moreover, we also proposed and compared two heuristics to solve the RBMLSA problem. Then, in [33], we introduced a novel integer linear programming (ILP) formulation to determine the set of fibers that should be upgraded to the C + L-bands (subject to a constraint on the maximum number of fibers that should be migrated), which generally outperforms the proposal in [32].

In the above studies [29–33], the cost of upgrading an existing fiber to the L-band is assumed to be the same. However, if the EDFAs in the network were originally deployed to support only the C-band, that is not the case. Upgrading a link implies upgrading its EDFAs, and the number of amplifiers can vary from link to link. This implies different upgrading costs. Therefore, in this paper, we focus on determining which fibers should be upgraded, subject to a constraint on the maximum number of C-band amplifiers that can be upgraded to support the C + L-bands, and the final objective is to minimize the blocking probability in a scenario where optical connections are dynamically established and released. For that aim, we propose three heuristics focused on three different auxiliary objectives: a) upgrading the most-used fibers, b) upgrading the fibers that maximize the number of precomputed source-destination paths that benefit from the partial upgrade, and c) upgrading the maximum number of fibers as possible subject to the constraint on the number of EDFAs.

In particular, this paper extends our previous works in [32,33], not only because of the consideration of the maximum number of EDFAs to be upgraded (in contrast to those works), but also because (1) we introduce and analyze two metrics to help understand which heuristic may lead to better performance in different scenarios, (2) we propose an additional (simple) heuristic to compare with, and (3) because we analyze the performance assuming not only uniform traffic but also nonuniform traffic, with the help of weighting factors included in the methods and tuned to operate providing better performance in those scenarios. In fact, the proposal in [32] did not include a weighting factor or method to deal with nonuniform traffic, so its inclusion is another contribution of this paper.

3. NETWORK PLANNING FOR PARTIAL MIGRATION

A. Description of the Problem and Resolution Approach

Let us consider an optical network that is going to be partially upgraded from the C- to C + L-bands, that is, just a subset of the network links will be migrated to support both bands. The topology of the network can be represented by a connected graph $\mathcal{G} = (\mathcal{N}, \mathcal{E})$ where $\mathcal{N}$ denotes the set of nodes and $\mathcal{E}$ the set of bidirectional links. We assume that a link connecting two nodes i and j is composed by two fibers, (i, j) and (i, j), one in each direction. Moreover, each fiber (i, j) is equipped with a certain number of amplifiers a_{ij},. Upgrading a link to support C + L transmission involves upgrading all the EDFAs located in the fibers in both directions of that link.

The objective is to determine which fibers should be migrated subject to a constraint on the maximum number of EDFAs that can be upgraded in the whole network ($A_{\max}$). The selection of the set of fibers to upgrade is done with the final objective of minimizing the connection blocking probability when the network faces dynamic traffic (i.e., when optical connection establishment and release requests are received during network operation).

Nevertheless, rather than directly minimizing the blocking probability, we adopt a simpler but pragmatic approach and propose three heuristics to determine the set of fibers to upgrade during the offline planning phase of the network.

For that aim, the K-shortest paths are precomputed between each source-destination (s-d) pair of nodes in the network. These K-shortest paths will be eventually used for establishing end-to-end optical connections, and for that reason we focus on these paths. To represent these precomputed paths, the binary constants r_{ij}^{sdk} are introduced. If the fiber (i, j) is traversed by the kth shortest path between nodes s and d, then r_{ij}^{sdk} is set to 1, while it is set to 0 otherwise. Additionally, a set of weighting factors (α^{sdk}) can be employed to model the relevance of the different sdk paths when determining the set of fibers to be upgraded. For instance, as we will describe and analyze later, these factors can be used to give more relevance to the end-to-end paths associated with those pairs of nodes (s-d) interchanging more traffic.

Therefore, in summary, the selection of the fibers to upgrade is done based on the following inputs:

- $\mathcal{G} = (\mathcal{N}, \mathcal{E})$, the network topology.
- a_{ij}, the number of amplifiers in each fiber of the network.
- r_{ij}^{sdk}, the set of K precomputed shortest paths for each s-d pair of nodes in the network.
- α^{sdk}, the set of weighting factors for each sdk path.
- $A_{\max}$, the maximum number of amplifiers that the network operator desires to upgrade to operate in the C + L-bands.

The first of the three proposed heuristics, named MostUsed, upgrades the fibers that are most used by the precomputed shortest paths. The second heuristic, MaxPaths, upgrades the fibers that maximize the number of precomputed K-shortest paths that benefit from the partial upgrade toward the L-band. Finally, the third heuristic, MaxFibers, upgrades as many fibers as possible. The last two methods are based on ILP formulations. However, since they optimize a target function that is different from the minimization of the blocking probability, they should also be considered as heuristic approaches to solve the problem.

The MostUsed and MaxPaths methods are extensions of our previous proposals in [32,33], respectively, where we did not consider that different links may have different numbers of amplifiers (and thus different impacts on the cost of the upgrade).

B. MostUsed Method: Upgrading the Most-Used Fibers

The MostUsed method [32] prioritizes the fibers to be upgraded based on the number of times that they are utilized in the shortest path of all s-d pairs. The number of times that a certain fiber (i, j) appears in the first precomputed shortest path (i.e., $k = 1$) of all s-d pairs (w_{ij}) is

$$w_{ij} = \sum_{sd} r_{ij}^{sd1}, \quad \forall i \in \mathcal{N}, \quad \forall j \in \mathcal{N}. \tag{1}$$

In contrast to [32], that definition can be enhanced by including the set of weighting factors, α^{sd1}, to take into consideration the traffic associated with each s-d pair and improve performance when facing nonuniform (but more realistic) traffic:

Algorithm 1. MostUsed—Upgrade the Most-Used Fibers

Input: $(\mathcal{G}, \boldsymbol{a_{ij}}, \boldsymbol{r_{ij}^{sd1}}, \boldsymbol{\alpha^{sd1}}, \boldsymbol{A_{\max}})$
Output: Set of fibers to upgrade to L-band, F_{upgrade}
1 Compute w_{ij} using Eq. (2)
2 $F_{\text{not\_upgraded}}$ = list of fibers in the network in decreasing order of w_{ij}
3 $F_{\text{upgrade}} = \varnothing$ # set of fibers selected for migration to L-band
4 *upgraded_EDFAs* = 0
5 **for each** fiber (i, j) in $F_{\text{not\_upgraded}}$:
6 **if** *upgraded_EDFAs* + $a_{ij+}a_{ij} \leq A_{\max}$:
7 # The fibers composing the link can be migrated
8 Add fibers (i, j) and (j, i) to F_{upgrade}
9 Delete fibers (i, j) and (j, i) from $F_{\text{not\_upgraded}}$
10 *upgraded_EDFAs* = *upgraded_EDFAs* + $a_{ij+}\,a_{ji}$
11 **end if**
12 **end for**

$$w_{ij} = \sum_{sd} \alpha^{sd1} r_{ij}^{sd1}, \quad \forall i \in \mathcal{N}, \quad \forall j \in \mathcal{N}. \tag{2}$$

In this way, w_{ij} represents the traffic that would traverse fiber (i, j) if all the traffic between each s-d pair were successfully routed through its first precomputed shortest path. Thus, from now on, we will consider Eq. (2) as the general definition of w_{ij}, since Eq. (1) is a particular case of Eq. (2) where $\alpha^{sd1} = 1$.

Algorithm 1 shows the operation of the MostUsed method. First of all, the fibers of the network are sorted in a list from the most used to the least used one, i.e., in decreasing order of w_{ij} (lines 1–2). Then, the algorithm works in an iterative fashion using that list, checking if each link can be upgraded without exceeding the maximum number of EDFAs that can be upgraded due to cost considerations, $A_{\max}$ (lines 5–12). It should be noted that for a link to be upgraded, both fibers composing the link must be migrated. For that reason, the number of amplifiers required in each direction of the link is considered (line 6). The abovementioned process is repeated until all the fibers have been analyzed.

C. MaxPaths Method: Upgrading the Fibers That Maximize the Number of Precomputed *K*-Shortest Paths That Benefit from the Upgrade

The aim of the MaxPaths method is to maximize the number of precomputed paths that can use the L-band to establish optical connections (or lightpaths). As in most of previous works, we consider the spectrum continuity constraint. Therefore, each lightpath should use the same spectral resources in all the fibers of the path from the source to the destination node. That implies that a lightpath can be established in the L-band only if all the fibers traversed by that connection have been upgraded. Taking this issue into account, the aim of the MaxPaths method is to determine which fibers should be upgraded with the objective of maximizing the number of precomputed paths (which will be used by the connections) that can benefit from the upgrade. Note that this approach is equivalent to minimizing the number of precomputed s-d paths that cannot benefit from the upgrade.

In order to achieve this objective, a new ILP formulation is presented. It takes at inputs $(\mathcal{G}, a_{ij}, r_{ij}^{sd1}, \alpha^{sdk}, A_{\max})$.

In the formulation we also introduce a big constant U, which represents an upper bound on the length (in hops) of the precomputed paths. The longest path between a source and destination node could traverse all the unidirectional links in the topology. Therefore, the value of U must be set to a value equal or higher than the number of unidirectional fibers in the network. We also introduce M, a very small constant, which is used to break ties if there is more than one solution that minimizes the number of precomputed *s-d* paths that cannot benefit from the upgrade.

The outputs of the ILP formulation, i.e., the decision variables, are defined as follows:

- f_{ij} are the main output of the formulation, as these decision variables identify the fibers selected for migration. They are binary variables, where a value of 1 means that the fiber (i, j) should be upgraded, i.e., equipped with C + L-band EDFAs. On the other hand, a value of 0 means that no upgrade is performed. Thus, transmission through that fiber can only use the C-band.
- Δ^{sdk} is an auxiliary integer variable (≥ 0) that represents the number of fibers in the k precomputed path between nodes s and d that have not been upgraded. When the ILP formulation is solved, if Δ^{sdk} is 0, it means that all fibers along that path *sdk* have been equipped with multiband devices, and therefore the path benefits from the upgrade as connections using that path can work over the C + L-bands. On the contrary, if Δ^{sdk} is higher than 0, it means that at least one of the fibers of the path has not been upgraded. Therefore, the path cannot benefit from the L-band, since connections using that path must necessarily use the C-band to comply with the spectrum continuity constraint.
- δ^{sdk} is an auxiliary variable that converts Δ^{sdk} into a binary value by clipping its value. Thus, if $\Delta^{sdk} = 0$, then δ^{sdk} is also 0, which means the path *sdk* benefits from the upgrade. If $\Delta^{sdk} \geq 1$, then $\delta^{sdk} = 1$, which means that the path cannot benefit from the upgrade.

The ILP formulation for the MaxPaths method is as follows:
Minimize

$$\sum_{sdk} \alpha^{sdk} \delta^{sdk} - M \cdot \sum_{ij} w_{ij} f_{ij} \tag{3}$$

subject to

$$\sum_{ij} a_{ij} f_{ij} \leq A_{\max}, \tag{4}$$

$$f_{ij} = f_{ji}, \quad \forall i \in \mathcal{N}, \quad \forall j \in \mathcal{N}, \tag{5}$$

$$\Delta^{sdk} = \sum_{ij} r_{ij}^{sdk} - \sum_{ij} r_{ij}^{sdk} f_{ij}, \quad \forall s, d \in \mathcal{N}, \quad \forall k \in K, \tag{6}$$

$$\Delta^{sdk} \leq U \delta^{sdk}, \quad \forall s \in \mathcal{N}, \quad \forall d \in \mathcal{N}, \quad \forall k \in K, \tag{7}$$

$$f_{ij} \in \{0, 1\}, \quad \forall i \in \mathcal{N}, \quad \forall j \in \mathcal{N}, \tag{8}$$

$$\delta^{sdk} \in \{0, 1\}, \quad \forall s \in \mathcal{N}, \quad \forall d \in \mathcal{N}, \quad \forall k \in K. \tag{9}$$

Equation (3) shows the objective function of the formulation. The main objective (modeled by the first term of the equation) is to minimize the number of precomputed paths that cannot benefit from the partial migration of the network. As previously mentioned, if $\delta^{sdk} = 1$, it means that the path *sdk* cannot benefit from the upgrade, so adding these variables constitute the core of the objective function. The objective function also includes the set of weighting factors α^{sdk}. On the one hand, it can be used to give a higher weight to the end-to-end paths associated with those pairs of nodes (s, d) interchanging more traffic. On the other hand, when the network is operated dynamically, the usual strategy consists of using the first precomputed path ($k = 1$) if possible and only resorting to higher-order paths if there are no resources on the first path. Therefore, it seems reasonable to set a higher weight for $k = 1$ than for higher-order paths. Equation (3) has a second term, which is used to break ties if there is more than one solution that minimizes the number of precomputed paths that cannot benefit from the upgrade. In that case, the tie is broken by selecting the solution that upgrades the most-used set of fibers, i.e., the set of fibers that appear in a highest number of precomputed shortest paths ($k = 1$). As the aim is to break ties, M is set to a very small constant.

Regarding the constraints, Eq. (4) guarantees that the number of EDFAs to be upgraded to operate in the C + L-bands does not exceed the bound imposed by the network operator $A_{\max}$. As a bidirectional link is composed by two fibers in different directions, Eq. (5) ensures that either both fibers of the link are upgraded or neither of them. Equation (6) defines the auxiliary variable Δ^{sdk}. The first term in the right-hand side of that equation computes the length in hops of the path *sdk*. The second term counts the number of fibers of that path that have been selected to be upgraded. Therefore, the difference is the number of fibers of that path that will not be upgraded, i.e., Δ^{sdk}. Then, Eq. (7) is used to determine δ^{sdk}, the clipped binary version of Δ^{sdk}. Since U is a large positive constant, if Δ^{sdk} is higher than 0, the binary variable δ^{sdk} is forced to take the value of 1 to comply with Eq. (7). On the other hand, if Δ^{sdk} is 0, the δ^{sdk} variable could be either 0 or 1 and still satisfy Eq. (7). However, it will take the value of 0, as it leads to minimizing the objective function (sum of δ^{sdk} variables) in Eq. (3). In this way, δ^{sdk} works as a clipped binary version of Δ^{sdk}. Finally, Eqs. (8) and (9) set f_{ij} and δ^{sdk} as binary variables.

D. MaxFibers Method: Upgrading the Maximum Number of Fibers

The third method, MaxFibers, aims at maximizing the number of optical fibers that are migrated (subject to the constraint imposed on the number of upgraded EDFAs). An algorithmic implementation of this method can be done by selecting the links to upgrade in increasing order of the number of amplifiers that they have. Equivalently, the MaxFibers method can be defined by means of an ILP formulation (which is, in fact, a simplified version of the MaxPaths formulation, with fewer constraints and a different objective function):

Maximize

$$\sum_{ij} f_{ij} - M \cdot \sum_{ij} a_{ij} f_{ij} \tag{10}$$

subject to

$$\sum_{ij} a_{ij} f_{ij} \le A_{\max}, \tag{11}$$

$$f_{ij} = f_{ji}, \quad \forall i \in \mathcal{N}, \quad \forall j \in \mathcal{N}, \tag{12}$$

$$f_{ij} \in \{0, 1\}, \quad \forall i \in \mathcal{N}, \quad \forall j \in \mathcal{N}. \tag{13}$$

4. SIMULATION SETUP

In the previous section, we have proposed three different strategies for network upgrading. They determine the set of links to be migrated from the C-band to the C + L-band, subject to a constraint on the maximum number of EDFAs that can be upgraded. The three proposed methods employ different approaches: upgrading the most-used fibers, upgrading the fibers that maximize the number of precomputed paths that benefit from the upgrade, and upgrading the maximum number of fibers. However, the final objective is to analyze and compare the performance of the network when it is upgraded according to each of these three strategies and then operates dynamically. Therefore, once the network is partially migrated, we assume lightpath establishment and release requests are dynamically received. Connection establishment requests will be handled by an RBMLSA algorithm, and its performance in terms of the bandwidth-blocking ratio will be assessed.

Three different network topologies, with similar size in terms of number of nodes and links, the American NSFNet [34], the Japanese JPN12 [35], and the European Deutsche Telekom (DT) network [36], have been considered. However, the distances involved in these topologies are very different, being the lowest for the DT and the highest for the NSFNet, which translates into different numbers of required amplifiers. The exact location and distance between amplifiers (and thus the number of amplifiers per link) depends not only on the length of the link but also on other factors of each particular link, like the class of fiber employed or the type and configuration of the amplifiers. However, our aim is not to accurately model amplifier placement but to create a set of simulation scenarios where different links may have different numbers of amplifiers. Therefore, for the sake of simplicity, we have assumed that an amplifier is required every 80 km in all network links. Thus, the total number of C-band amplifiers in these networks (A_{network}) ranges from 86 amplifiers for the DT and 554 for the NSFNet. Table 1 summarizes the characteristics of these three topologies.

The implementation of C + L amplifiers for MB-EONs can be done by means of several architectures [37]. The most common architecture, shown in Fig. 1, is based on the use of a demultiplexer/multiplexer structure and a separate EDFA to amplify each spectral band [37]. This architecture imposes a 400 GHz guard band between the C-band and the L-band. In this work, we consider this architecture when an amplifier is migrated to a C + L system. Moreover, we assume that the 400 GHz guard band is deducted from the beginning of the L-band. We also consider that the spectrum is divided 12.5 GHz frequency slots. Thus, the C-band consists of 320 frequency slots, while the L-band, after the guard band allocation, consists of 516 frequency slots [38].

Table 1. Characteristics of the Evaluated Network Topologies

Topology	Number of Nodes (N)	Number of Bidirectional Links	Number of Amplifiers (A_{network})
NSFNet	14	21	554
JPN12	12	17	172
DT	14	23	86

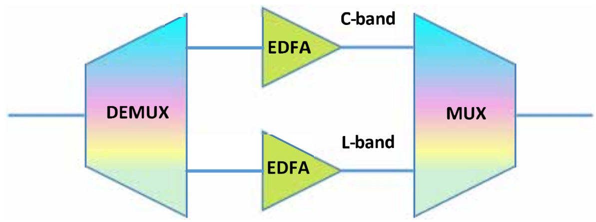

Fig. 1. Architecture with separate amplifiers for the implementation of C + L line systems.

We have analyzed different scenarios in terms of the maximum percentage of network amplifiers that can be upgraded, from no upgrade (0%) to full upgrade (100%), including partial upgrades in steps of 20% (that is, we have set $A_{\max} = p \cdot A_{\text{network}}$, with $p = 0, 0.2, \ldots, 1$). In order to determine which fibers to migrate to the C + L-bands, the three heuristics described in Section 3 have been used.

Regarding traffic, we have assumed two different models:

- Uniform traffic, i.e., all s-d pairs have the same average traffic load.
- Nonuniform traffic, i.e., different s-d pairs have different traffic loads. In particular, we have assumed a population-based traffic matrix, where the average traffic load between nodes s and d is proportional to the product of the population (P) of the cities where nodes s and d are located, i.e., $\nu P_s P_d$, where ν is a proportionality constant. For simplicity, but without loss of generality, we assume $\nu = 1$. The 2023 population data for the cities (or states) where the nodes are located has been obtained from [39]. Additionally, the traffic matrices that we have generated and used in this research have been made accessible on GitHub [40].

Moreover, we have only considered the primary shortest path between each s-d pair (i.e., $K = 1$) to propose the potential fibers for the migration. This approach is consistent with the MostUsed heuristic, which also only considers the shortest path to determine which fibers to upgrade. Therefore, the constants α^{sdk} have been set as $\alpha^{sd1} = 1, \forall s, d$ and $\alpha^{sdk} = 0, \forall s, d,$ and $k > 1$ for the uniform traffic case. The value of the very small constant to break ties, M, has been set to 10^{-5}. For the nonuniform traffic case, the constants α^{sdk} have been set as $\alpha^{sd1} = P_s P_d, \forall s, d$ and $\alpha^{sdk} = 0, \forall s, d,$ and $k > 1$.

Table 2. Maximum Optical Reach for Each Spectral Band in C + L Line Systems

	Multiband Optical Reach (km)	
Modulation Level	**C-band**	**L-band**
QPSK	1800	1600
16QAM	370	330

In this case, M has been set to $1/[F\sum_{sd}(P_s P_d)]$, where F is the number of unidirectional fibers in the network. However, in order to compare the results, we have also analyzed the performance when the network faces nonuniform traffic, but the network has been upgraded using the output of the heuristics when employing the weighting factors of the uniform scenario ($\alpha^{sd1} = 1$).

Then, the IBM ILOG CPLEX solver has been used to solve the ILP formulations. An interesting point regarding all the proposed methods, including the ILP formulations, is that they provide the solution very quickly. The list fibers to be upgraded in each scenario when using any of the three methods is obtained in less than 5 s in a laptop with an Intel Core i7-4720HQ CPU processor, 2.60 GHz, and 16 GB RAM.

As previously mentioned, once the network is upgraded, we evaluate its performance under dynamic traffic. The arrival of connection requests is modeled as a Poisson process with arrival rate (λ). The holding time of each connection is modeled by an exponential distribution with an average of T. For the uniform traffic case, a uniform random distribution is used to select the source and destination node for each connection. For the nonuniform case, the probability of selecting a s-d pair is proportional to the traffic between those nodes, in particular, $P_s P_d / \sum_{s,d}(P_s P_d)$. On the other hand, the requested data rate for each connection is determined according to a uniform distribution, ranging from $C_{\min} = 12.5$ Gb/s to $C_{\max} = 300$ Gb/s in steps of 12.5 Gb/s. Therefore, these data rates translate in a bandwidth requirement ranging from 1 frequency slot to 24 frequency slots, assuming the BPSK modulation format used. Nevertheless, if the length of a certain lightpath does not exceed the maximum optical reach over the C-band or the L-band (Table 2 [41]), a more spectrally efficient modulation format (QPSK and even 16QAM) is used. For instance, if the length of a connection using the L-band is higher than 1600 km, BPSK should be used. If the length is between 330 and 1600 km, QPSK would be used, and if it is lower or equal to 330 km, 16QAM would be used. On the other hand, the capacity of a spectral slot is 12.5 Gb/s for BPSK, twice that for QPSK, and four times that (50 Gb/s) for 16QAM.

As the data rates demanded by different incoming connection requests are different, we employ a normalized version of the classic definition of the traffic load in erlangs (λT). The normalized traffic load considers three additional parameters, namely, the average data rate of the connections (C_{avg}), the maximum data rate of the connections ($C_{\max}$), and total number of nodes in the network (N). The normalized traffic load is calculated using Eq. (14) [42]:

$$\text{Load} = \frac{\lambda T}{N(N-1)} \times \frac{C_{\text{avg}}}{C_{\max}}, \tag{14}$$

where $C_{\text{avg}} = (C_{\min} + C_{\max})/2$.

When a connection request is received, the RBMLSA algorithm that we introduced in [32] is employed. The K-shortest precomputed paths (with $K = 3$) are considered as potential solutions to route the connection. These paths are precomputed in terms of the length in kilometers (km) but are sorted in terms of increasing number of hops, as that approach led to the best results in the tests we did in [32]. Then, the first path of the list is selected, and it is checked if it has been fully migrated to the L-band (i.e., all its links have been upgraded) and has available resources in that band fulfilling the spectrum continuity constraint. If that is the case, the lightpath is established using that route and those L-band spectral resources. Otherwise, the availability of resources in the C-band of that path is assessed. If there are no resources, then the following paths of the list are considered, evaluating for each one of them the availability of resources in the L-band first and then in the C-band. If no resources are available for any of the paths in the list, the connection is blocked. During this procedure, the Best-Fit policy [42] is used for spectrum allocation. When using this policy, the entire spectral band under consideration (L- or C-band) is checked, and the set of contiguous unoccupied frequency slots whose size best matches the bandwidth required by the connection is assigned.

5. PERFORMANCE EVALUATION

In order to evaluate the performance of the partially upgraded network when facing dynamic traffic, a simulator has been developed in Python. In the simulation, no metrics are retrieved for the first 10^4 connection requests, as they are used for warming up the network simulator. Then, data gathering is done for the following 10^5 connection requests. The main metric that we consider is the bandwidth-blocking ratio (BBR). In this regard, it should be noted that different connection requests require different bandwidths (taking into account the requested data rate and the modulation format employed) and thus different numbers of frequency slots. The BBR is computed by dividing the total number of blocked frequency slots by the number of total requested slots throughout the simulation. We first analyze the uniform traffic scenario and then the nonuniform traffic case.

A. Uniform Traffic

When assuming uniform traffic, the BBR versus traffic load is depicted for the three employed topologies, NSFNet [Fig. 2(a)], JPN12 [Fig. 2(b)], and DT [Fig. 2(c)]. Different colors in these figures correspond to different scenarios in terms of the maximum percentage of network amplifiers that can be upgraded, from no upgrade (0%) to full upgrade (100%) in steps of 20%. The type of line (dashed, solid, or dotted) represent the results associated with the heuristics employed for fiber selection, MostUsed, MaxPaths, or MaxFibers, respectively.

Obviously, as the percentage of upgraded amplifiers increases, the BBR decreases, since a higher number of network links have additional spectral resources in the L-band. Anyway, before commenting Fig. 2 in detail, Fig. 3 summarizes

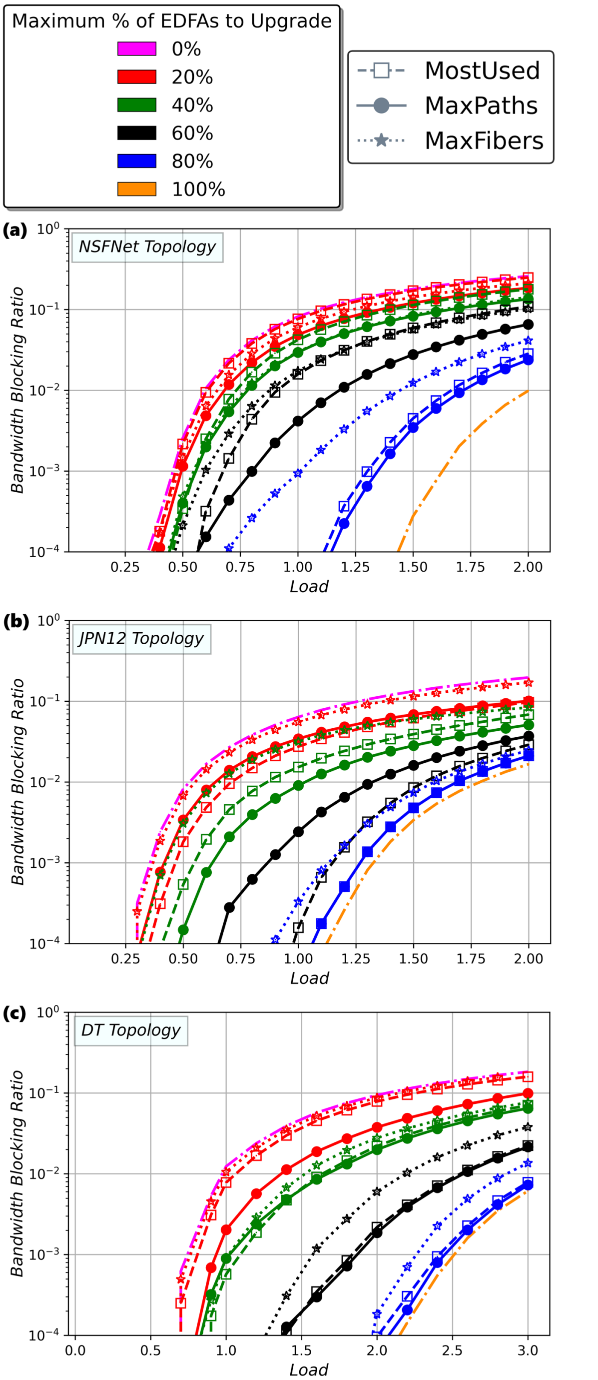

Fig. 2. Bandwidth-blocking ratio depending on the network traffic load considering uniform traffic in the (a) NSFNet, (b) JPN12, and (c) DT-network topologies.

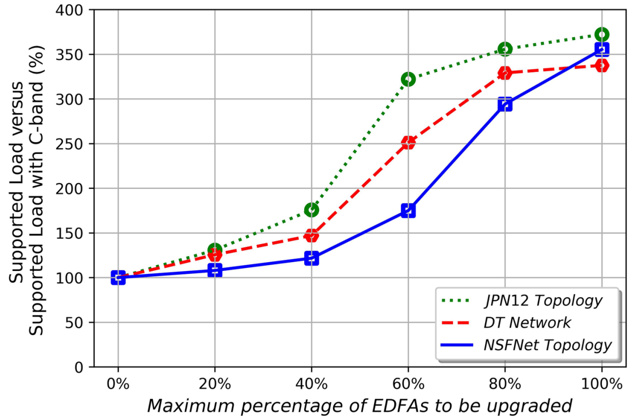

Fig. 3. Maximum supported traffic load in a partially upgraded network with blocking probability $\leq 10^{-3}$, considering uniform traffic.

and quantifies this improvement. It represents the increase of the traffic load supported by the upgraded network, compared to a C-band-only network, if we assume that the maximum acceptable BBR is 10^{-3}, and considering different percentages of upgraded amplifiers. When the network is fully upgraded to the L-band (100% upgrade), the traffic load increase supported by the network, for the three topologies, is around 350% when compared to the C-band-only counterpart. However, the figure demonstrates that even with a partial upgrade of the network, significant increases in the supported traffic loads can be achieved. The most significant rise in improvement is obtained when 60% to 80% of the EDFAs in the network are upgraded. Nevertheless, the amount of improvement on supported traffic load depends on the percentage of upgrade, but also on the topology, ranging from 175% for the NSFNet to 322% for the JPN12 (both for a 60% upgrade). In order to obtain Fig. 3, for each percentage of upgrade we considered the solution provided by the heuristic leading to the lowest BBR (which is an issue that we analyze next, coming back to Fig. 2).

Figure 2 shows the BBR results when the three heuristics to select which fibers to upgrade (MostUsed, MaxPaths, and MaxFibers) are used, considering different scenarios in terms of the maximum percentage of network amplifiers that can be upgraded. As shown in Figs. 2(a)–2(c), the MaxFibers heuristic never obtains the best results in terms of BBR when compared with the other two algorithms. Therefore, we will focus on the comparison between the MostUsed and the MaxPaths methods.

For the NSFNet topology [Fig. 2(a)], the solution provided by the MaxPaths method leads to lower values of BBR in all the partial upgrade scenarios (from 20% to 80%). In contrast, for the JPN12 topology [Fig. 2(b)], the MostUsed method obtains better or similar BBR than MaxPaths except for the 40% upgrade, where MaxPaths leads to lower BBR. Finally, for the DT network [Fig. 2(c)], the MaxPaths method provides lower or at least similar BBR than MostUsed. Therefore, the MaxPaths method, which maximizes the number of precomputed paths that benefit from the upgrade, usually leads to better results. However, in some cases, as we have seen in the JPN12 topology (mainly for the 60% upgrade), the MostUsed method, which prioritizes the upgrade of the fibers that are most used by the precomputed paths, can lead to a lower BBR.

In the following, we explain why in some cases one of the heuristics leads to better results than the other. For that aim, we compute two metrics for each of the solutions (i.e., for the sets of fibers to upgrade that are provided by each heuristic):

- number of precomputed shortest paths that benefit from the upgrade, i.e., $N(N-1) - \sum_{sd} \delta^{sd1}$,

• congestion in not upgraded fibers, defined as the number of times that the most-used but not upgraded fiber appears in the list of precomputed shortest paths, i.e., $\max_{(i,j)} w_{ij}$, such that $f_{ij} = 0$.

It should be noted that the MaxPaths method always obtains the optimal (maximum) value for the first metric, as it is the objective of the associated ILP formulation, while the MostUsed method obtains the optimal (minimum) value for the second metric. Tables 3–5 report the values of these metrics for the different heuristics and the NSFNet, JPN12, and DT topologies, respectively. Although the focus is on the comparison between the MaxPaths and MostUsed heuristics, we also provide the results for MaxFibers for completeness. The values in bold in Tables 3–5 correspond to the solution that provides the best results in terms of BBR. If two different solutions provide very similar results, both of them are marked in bold.

The congestion metric for the solutions of the MostUsed and MaxPaths methods is the same or nearly the same for the NSFNet topology (Table 3) for the 20% and the 40% upgrades. However, the number of paths that benefit from the upgrade is much higher for the MaxPaths method in those two cases (around 20 percentage points more than MostUsed in the first case and 26 in the second). This translates into a lower BBR for the solution provided by the MaxPaths methods.

In contrast, in the 20% upgrade for the JPN12 network (Table 4), the number of paths that benefit from the upgrade when using the solutions provided by the MaxPaths and the MostUsed method are very similar, as they only differ in 2.3 percentage points. However, the congestion in not upgraded fibers is much higher for MaxPaths (22) than for MostUsed (11). Therefore, a highly congested link in the

Table 3. Metrics of the Upgrade Solutions for NSFNet (Uniform Traffic)

		Maximum % of EDFAs to Upgrade			
Metric	**Method**	**20%**	**40%**	**60%**	**80%**
# of paths that benefit from the upgrade	MostUsed	8	26	52	117
		4.4%	14.3%	28.6%	64.3%
	MaxPaths	**44**	**74**	**111**	**144**
		24.2%	40.7%	61%	79.2%
	MaxFibers	30	65	91	130
		16.5%	35.8%	50%	71.5%
Congestion in not upgraded fibers	MostUsed	14	13	10	8
	MaxPaths	**14**	**14**	**14**	**13**
	MaxFibers	14	14	14	14

Table 4. Metrics of the Upgrade Solutions for JPN12 (Uniform Traffic)

		Maximum % of EDFAs to Upgrade			
Metric	**Method**	**20%**	**40%**	**60%**	**80%**
# of paths that benefit from the upgrade	MostUsed	**29**	60	**90**	**118**
		22%	45.5%	68.2%	89.4%
	MaxPaths	32	**70**	98	**118**
		24.3%	53.1%	74.3%	89.4%
	MaxFibers	27	60	98	100
		20.5%	45.5%	74.3%	75.8%
Congestion in not upgraded fibers	MostUsed	**11**	10	**7**	**6**
	MaxPaths	22	**11**	10	**6**
	MaxFibers	24	22	10	10

Table 5. Metrics of the Upgrade Solutions for DT (Uniform Traffic)

		Maximum % of EDFAs to Upgrade			
Metric	**Method**	**20%**	**40%**	**60%**	**80%**
# of paths that benefit from the upgrade	MostUsed	18	**62**	**108**	**153**
		9.9%	34.1%	59.4%	84.1%
	MaxPaths	**36**	**84**	**114**	**159**
		19.8%	46.2%	62.7%	87.4%
	MaxFibers	24	48	82	129
		13.2%	26.4%	45.1%	70.9%
Congestion in not upgraded fibers	MostUsed	16	**12**	**7**	**5**
	MaxPaths	**20**	**18**	**10**	**5**
	MaxFibers	20	20	20	20

MaxPaths solution is becoming a bottleneck, compared to the solution provided by MostUsed, and translates into a higher BBR for the MaxPaths solution.

Therefore, these two metrics that we have introduced are indicators of the performance that can be expected when operating the network dynamically, and they provide a hint of which planning method may provide a lower BBR in dynamic operation without the need of performing a simulation. If the congestion metric is similar, but there is a significant difference in the number of paths that benefit from the upgrade, the MaxPaths method will generally lead to lower BBR. If the number of paths that benefit is similar, but there is a significant difference in terms of congestion, the MostUsed method will usually lead to better results. Nevertheless, as shown in the table, there are many situations where the two metrics are different for the MostUsed and MaxPaths methods, and thus there is a trade-off between the impact of congestion and the number of precomputed paths that benefit from the upgrade on BBR. MaxPaths generally leads to lower (or at least similar) BBR results than MostUsed. However, a network operator desiring to upgrade the network should run a simulation to assess the performance of the upgrades provided by MostUsed and MaxPaths in order to make the final decision.

B. Nonuniform Traffic

We now analyze the performance of the methods when considering a nonuniform traffic matrix. We will focus on MaxPaths and MostUsed methods since they obtained better results than MaxFibers (and they can be tuned by means of the α^{sdk} parameters to consider nonuniform traffic). As previously mentioned, we assume a population-based traffic matrix, where the average traffic load between nodes s and d is proportional to the product of the population of the cities where nodes s and d are located, i.e., $P_s P_d$. Our aim is to answer two research questions here. First of all, to determine whether setting the weights α^{sdk} according to the associated load of each s-d pair really improves the selection of fibers to upgrade, that is, it leads to a reduction of the BBR when the network operates dynamically. Second, to analyze whether the MaxPaths heuristic also usually leads to better results than MostUsed in this scenario.

In order to answer the first question, we have focused on the MaxPaths method and have compared the dynamic performance when the network is upgraded like in the previous subsection, that is, setting $\alpha^{sd1} = 1, \forall s, d$ (and 0 for other values of k), and when setting the weights so that $\alpha^{sd1} = P_s P_d, \forall s, d$ (and $\alpha^{sdk} = 0, \forall s, d$, and $k > 1$). It should be noted that in the latter case, due to using those weights, the objective function of the MaxPaths method is not really the maximization of the number of paths that benefit from the partial upgrade of the network but the maximization of the amount of end-to-end traffic that benefits from the upgrade (or equivalently, the minimization of the amount of end-to-end traffic that cannot benefit from the partial upgrade of the network).

Figure 4 shows the results for the NSFNet, JPN12, and DT-network topologies. In nearly all cases, the results are always better when α^{sd1} is set proportional to the load of each s-d pair than when it is set to 1 for all pairs of nodes. The only exceptions have been obtained for the NSFNet [Fig. 4(a)] when 80% of EDFAs are upgraded and for the JPN12 network [Fig. 4(b)] for the 20% upgrade. Nevertheless, in those cases the results are quite close with both methods. However, it can be seen that setting α^{sd1} proportional to the load leads to significant improvements in many cases. For instance, for the NSFNet [Fig. 4(a)], the dynamic performance when upgrading 40% of the amplifiers according to the solution obtained when setting $\alpha^{sd1} = P_s P_d$ is even better than when upgrading 60% of the amplifiers according to a solution obtained with $\alpha^{sd1} = 1$. A similar behavior can be observed in the DT network [Fig. 4(c)]: the performance for the 40% amplifiers

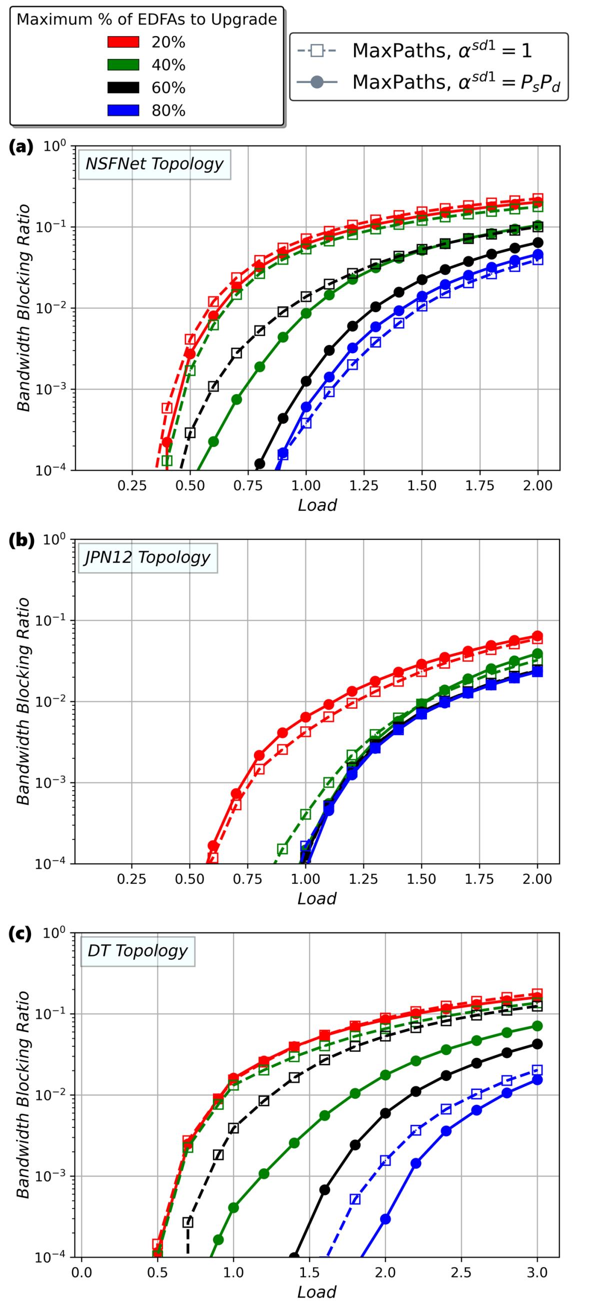

Fig. 4. Bandwidth-blocking ratio depending on the network traffic load considering nonuniform traffic in the (a) NSFNet, (b) JPN12, and (c) DT-network topologies for MaxPaths when different policies to set the α^{sd1} weights are used.

upgrade using $\alpha^{sd1} = P_s P_d$ is again better than for the 60% upgrade using $\alpha^{sd1} = 1$.

In summary, the impact of the value of α^{sd1} on the performance of the MaxPaths method considering nonuniform traffic has been analyzed in 12 different configurations. In only two of the cases, $\alpha^{sd1} = 1$ provides slightly better results. However, in the rest of cases, setting the value of $\alpha^{sd1} = P_s P_d$ leads to better results, and the improvement is very significant in several cases.

Although not shown in the paper due to lack of space, we have also compared the performance of the MostUsed method, considering nonuniform traffic, when setting $\alpha^{sd1} = 1$ and $\alpha^{sd1} = P_s P_d$. The results are consistent with those obtained for MaxPaths. In all cases except two, the use of α^{sd1} proportional to the traffic load between each pair of nodes leads to better results in terms of BBR (the exceptions are for the 20% upgrade of the JPN12 and the 80% upgrade of the DT network).

In conclusion, setting α^{sd1} proportional to the load carried by each *s*-*d* pair generally results in a selection of fibers to upgrade that leads to better dynamic performance. In this regard, if the real traffic deviates from the traffic that has been considered when determining which fibers to upgrade (e.g., assuming uniform traffic but having nonuniform traffic, as in the simulation just presented), a decrease in the dynamic performance is to be expected.

We now address the second question and compare the MaxPaths and MostUsed methods when considering the nonuniform population-based traffic and setting in both algorithms $\alpha^{sd1} = P_s P_d, \forall s, d$ (and $\alpha^{sdk} = 0, \forall s, d$, and $k > 1$). When using these weights, the MostUsed method prioritizes those fibers that carry more traffic to be upgraded, while the MaxPaths method minimizes the amount of end-to-end traffic that cannot benefit from partial upgrade.

The results in terms of BBR are shown in Fig. 5. For the NSFNet topology [Fig. 5(a)], MaxPaths leads to lower BBR than MostUsed in all the analyzed scenarios except for the 80% upgrade. For the JPN12 topology [Fig. 5(b)], MaxPaths and MostUsed obtain very similar BBR in all cases, while in the DT network [Fig. 5(c)], MaxPaths works better (or similar) than MostUsed in all scenarios, except for the 20% upgrade (where it is just slightly worst).

In summary, when dealing with nonuniform traffic, again MaxPaths usually provides better, or at least equal, results compared to MostUsed (when both methods use weights set according to the traffic load).

As we did in the uniform traffic case, in order to analyze in more detail this comparison, we compute the same metrics, but we normalized them by the total traffic in the traffic matrix, i.e., $\sum_{s,d}(P_s P_d)$ in order to avoid having very big numbers, and taking into account that α^{sd1} is not 1 but $P_s P_d$. Thus, we will analyze

- the fraction of end-to-end traffic that benefits from the upgrade, defined as $1 - \sum_{sd}(\alpha^{sd1}\delta^{sd1}) / \sum_{sd}(P_s P_d)$,
- the traffic congestion in not upgraded fibers, defined as, $\max_{(i,j)} w_{ij} / \sum_{sd}(P_s P_d)$, such that $f_{ij} = 0$ (note that w_{ij} is computed using Eq. (2) and thus considers $\alpha^{sd1} = P_s P_d$).

These metrics are reported in Tables 6–8. Again, the values in bold correspond to the solutions that provide the best results

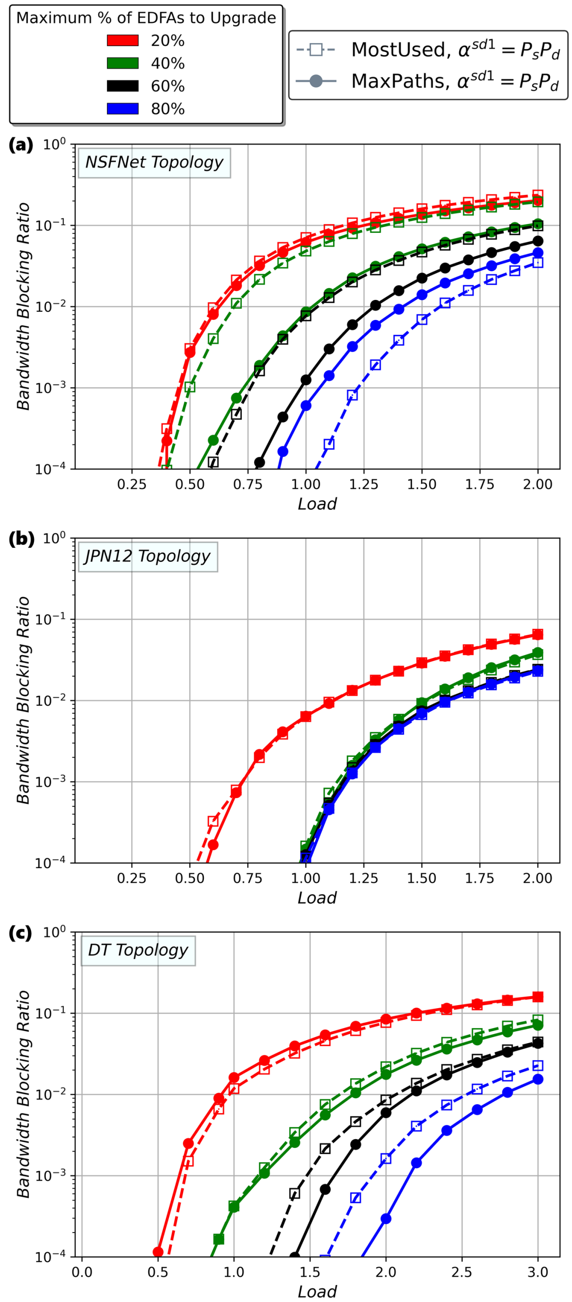

Fig. 5. Bandwidth-blocking ratio depending on the network traffic load considering nonuniform traffic in the (a) NSFNet, (b) JPN12, and (c) DT-network topologies for MostUsed and MaxPaths.

in terms of BBR. If two different solutions provide very similar results, both of them are marked in bold.

Similar conclusions can be drawn from these metrics as in the uniform case. If the congestion metric is very similar for the two heuristics, and also does the other metric, then the dynamic performance is, in general, very similar for the two heuristics. This is what happens, for instance, for all the upgrade scenarios for the JPN12 topology, where the metrics are identical or very similar in all cases (Table 7) and thus the performance results for MostUsed and MaxPaths are also very similar [Fig. 5(b)]. If the congestion metric is similar for both

Table 6. Metrics of the Upgrade Solutions for the NSFNet (Nonuniform Traffic, $\alpha^{sd1} = P_s P_d$)

Metric	Method	Maximum % of EDFAs to Upgrade 20%	40%	60%	80%
Fraction of traffic that benefits from the upgrade	MostUsed	0.06	0.17	0.41	**0.72**
	MaxPaths	**0.22**	**0.48**	**0.63**	0.81
Traffic congestion in not upgraded fibers	MostUsed	0.07	0.06	0.05	**0.03**
	MaxPaths	**0.12**	**0.07**	**0.07**	0.07

Table 7. Metrics of the Upgrade Solutions for the JPN12 (Nonuniform Traffic, $\alpha^{sd1} = P_s P_d$)

Metric	Method	Maximum % of EDFAs to Upgrade 20%	40%	60%	80%
Fraction of traffic that benefits from the upgrade	MostUsed	**0.56**	**0.85**	**0.94**	**0.98**
	MaxPaths	**0.56**	**0.86**	**0.94**	**0.98**
Traffic congestion in not upgraded fibers	MostUsed	**0.09**	**0.02**	**0.016**	**0.011**
	MaxPaths	**0.09**	**0.03**	**0.016**	**0.011**

Table 8. Metrics of the Upgrade Solutions for the DT (Nonuniform Traffic, $\alpha^{sd1} = P_s P_d$)

Metric	Method	Maximum % of EDFAs to Upgrade 20%	40%	60%	80%
Fraction of traffic that benefits from the upgrade	MostUsed	**0.19**	0.39	0.59	0.80
	MaxPaths	0.25	**0.50**	**0.64**	**0.84**
Traffic congestion in not upgraded fibers	MostUsed	**0.10**	0.06	0.04	0.03
	MaxPaths	0.14	**0.10**	**0.07**	**0.04**

heuristics, but there is a significant difference in the fraction of traffic that benefits from the upgrade, the MaxPaths method will generally lead to lower BBR. That happens in the 40% and 60% upgrade of the NSFNet (Table 6). However, in the DT network (Table 8), according to the obtained metrics one would expect a more similar performance for both heuristics for 60% and 80% upgrades, but MaxPaths provides better results. That is, as previously mentioned, these two metrics are indicators of the performance, but obviously a simulation is more trustworthy.

6. CONCLUSIONS

As fully upgrading a C-band EON toward the use of the C + L-bands in all links imposes a high cost to network operators, we have focused on strategies for a partial upgrade. We have analyzed which fibers should be upgraded in an EON with the aim of improving the performance when the network operates dynamically. In contrast with previous works, we have considered that the cost of upgrading different fibers is different, as the number of amplifiers in each link may be different.

In particular, we have proposed three different heuristics to select which fibers to upgrade subject to a constraint on the maximum number of EDFAs that can be upgraded. The heuristics are MostUsed, which upgrades the most-used links; MaxPaths, which upgrades the links that maximize the number of precomputed *s-d* paths that benefit from the upgrade; and MaxFibers, which upgrades as many fibers as possible. All these methods, even those based on ILP formulations, can be solved in a few seconds in networks with around a dozen nodes. Among them, MaxPaths is the method that generally leads to lowest BBR when the upgraded network operates dynamically, although in some scenarios the MostUsed method can obtain better results. We have defined two metrics, the number of paths that benefit from the upgrade and the congestion in not upgraded fibers, which provide an indicator of which of the proposed methods may lead to best performance. Moreover, we have demonstrated that a partial upgrade of the network can lead to significant increases in the supported traffic load by the network. The most significant rise in improvement is obtained when 60%–80% of the EDFAs are upgraded.

Besides analyzing the performance of the heuristics when dealing with uniform traffic, we have also analyzed the case of nonuniform traffic patterns. The MostUsed and MaxPaths heuristics incorporate weighting factors that effectively consider the traffic load associated with each *s-d* pair and use this information to determine which set of fibers should be upgraded. We have demonstrated that when the weights of the heuristics are tuned considering the expected traffic load, better dynamic performance is generally obtained. Therefore, network operators should leverage on monitoring data from their networks and employ traffic prediction techniques to get a good estimate of the traffic matrix. Moreover, again, for the case of nonuniform traffic scenarios, MaxPaths usually yields better (or at least equal) results than MostUsed.

This work opens several future research lines. We have shown that there is trade-off between the congestion and the number of precomputed paths that benefit from the upgrade, which makes that in some occasions MostUsed leads to better results than MaxPaths. Therefore, it would be worth exploring whether the combination of both metrics in a single objective function brings advantages compared to the individual use of the MaxPaths and MostUsed methods. However, a much more relevant extension would be the development of techno-economic models for multiband ROADMs and transceivers, and the incorporation of these models to the methods proposed in this paper, so that the cost of upgrading not only EDFAs but also ROADMs and transceivers is considered.

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