C+L+S-Band Optical Network Design Exploiting Amplifier Site Upgrade Strategies

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***Abstract*—It is possible to increase the available capacity of an optical network without any new fiber deployment, by exploiting transmission over the spectral bands beyond the C-band. Due to the characteristics of fiber and devices characteristics required to work with this wide-band transmission, as well as the physical effects raised by it, channels using spectral bands beyond C + L, e.g., in the S-band, can present comparatively poor quality of transmission (QoT), reducing the spectral efficiency. One way to deal with this problem is to install new amplification sites (ASs), decreasing the span length, improving the overall QoT and potentially allowing the use of more efficient modulation formats. In order to maintain the costs of a multi-band network upgrade reasonable, the spans which will receive a new AS need to be properly selected to maximize the overall delivered capacity without relying on an excessive number of new ASs. In this work, we investigate a C+L+S network design that takes advantage of the selective amplifier site upgrade. The results of the network simulation show that the proposed approach leads to a considerable increase in capacity while reducing the number of interfaces required for a fixed number of amplifiers and new ASs.**

***Index Terms*—Multi-band transmission, optical amplifiers, transmission modeling, optical network design**

I. Introduction

The steady increase of traffic in backbone optical networks due to factors such as 5G deployment [1] and fast growth of IP data [2], requires short- to mid-term solutions to cost-effectively increase network capacity. In this context, backbone networks can be upgraded to enable multi-band transmission (MBT), thus increasing the capacity [3], [4] while using the already deployed optical fiber infrastructure. MBT enlarges the usable transmission bandwidth, for example, by upgrading C-band (typically exploiting 4.8 THz) to already commercial C+L systems (which can exploit up to around 10 THz) or even beyond, up to the $\approx$ 50 THz available, from the L- to O-bands, when using the entire low-loss bandwidth of standard single-mode fibers (SSMF). Although MBT can avoid rolling out or leasing new fibers, MBT upgrades still require installing additional optical amplifiers for the new transmission bands. Specific filter/switch cards per band may also be needed at the reconfigurable optical add/drop multiplexers (ROADMs). The WDM channels which will be allocated in these newly-exploited bands may need to resort to lower order modulation formats than those used in the C- and L-bands, thus reducing the spectral efficiency. This is due to the worse fiber characteristics and expected lower performance of optical amplifiers, e.g., higher amplifier noise figures (NF), in these bands. Furthermore, stimulated Raman scattering (SRS) [5] can further degrade performance when widening the transmission spectrum. One way to improve the quality of transmission (QoT) in this scenario is to perform changes at optical line system (OLS) level, such as reducing the length of the spans via additional ASs. However, this approach increases (i) capital expenditure (CAPEX), due to requiring additional ASs and more amplifiers, and (ii) operational expenditure (OPEX), e.g., due to the increased power consumption and maintenance requirements associated with the operation of a larger number of amplifiers and sites. Therefore, a careful balance should be achieved between introducing new ASs to improve QoT and avoiding an excessive increase in CAPEX and OPEX from having to deploy and maintain too many new ASs. Several investigations have been carried out on the design of MBT networks. In [6], a network design strategy is presented for a geographically dependent, fiber-based capacity upgrade using C- and C+L-band systems, whereas in [7] a comparison between C+L-band systems and multi-fiber is reported, highlighting that MBT upgrades are beneficial even in case of low costs for fiber leases. Moreover, [8] also presented a cost-per-bit comparison as the network grows using C and C+L-band, showing that the multi-band solution has lower costs after the traffic to be delivered reaches a certain level. Recently, the next likely step in MBT, exploiting also the S-band, has started to be investigated [9]. Importantly, introducing the S-band is more complex, from a network design perspective, than adding the L-band, as a result of the higher fiber attenuation in this band, a larger impact of SRS over the full C+L+S-band transmission window and the potentially less efficient S-band optical amplifiers.

In this work, we propose a C+L+S-band network design strategy that assumes the scenario of an optical network initially exploiting C+L-band and evolving to also use the S-band and where the option of deploying additional optical amplifiers in the fiber links is viable. The C+L-band OLS abstraction with 80 km spans is shown on the right-hand side of Fig. 1. At the bottom of Fig. 1, two C+L+S-band upgrade options are presented: (1) adding a S-band optical amplifier

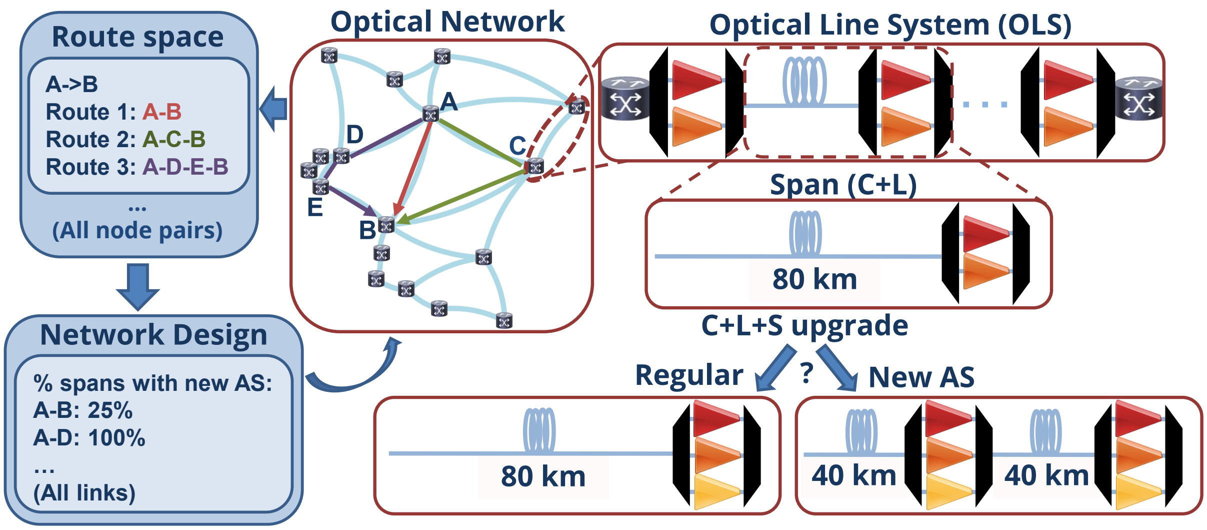

Fig. 1: Illustration of the OLS and network abstraction, namely of the network route space containing k routes for each pair of nodes, which is used by the network design algorithm to select the spans to upgrade when migrating to a C+L+S-band system. Bottom of the figure exemplifies these strategies: (1) Regular, which preserves the span length and (2) New AS, which splits the span in two.

(e.g., a Thulium-doped fiber amplifier - TDFA) after a regular 80 km span only, named "Regular", and (2) installing a new AS in the span, named "New AS", halving the span length. The left-hand side of Fig. 1 illustrates our design strategy, which is based on the computed route space, i.e., the set of k-routes for each network node pair. The paper is organized as follows: in section II we describe in detail the multi-band physical layer assumptions and the network design strategy proposed. Next, section III presents the results regarding costs, in terms of the total number of amplifiers and used interfaces, and the overall delivered traffic. Finally, section IV presents the conclusions of this work.

II. Methodology and Network Design Strategy

A. Physical Layer Model

The QoT estimation with the OLS configurations considered is computed using the open-source GNPy library [10], which relies on the generalized signal-to-noise ratio (GSNR) as figure of merit. The GSNR calculation includes both the amplified spontaneous emission (ASE) and nonlinear interference (NLI) disturbances. The NLI is calculated using the generalized GN-model (GGN) [5], in order to properly model the interaction between the SRS and the NLI generation. All OLSs within the network consist of SSMF spans, each followed by an amplification site composed by a multi-band-demultiplexer (MB-Demux), in order to split the spectral bands, a set of amplifiers, each one responsible for a particular spectral band, and finally a MB-multiplexer (MB-Mux), responsible to combine all bands for fiber transmission, as shown in Fig 1. EDFAs with average NFs of 4.25 and 4.6 dB are assumed for the C- and L-band, respectively, whereas TDFAs with average NFs of 6.5 dB are used for the S-band [9]. Each band comprises a total of 64 channels over a 75 GHz WDM grid and each channel is operated with a symbol rate of 64 Gbaud. The total spectrum exploited for transmission is 9.6 THz and 14.4 THz when considering the C+L-band and C+L+S-band, respectively. A guard band of 500 GHz is enforced between consecutive bands. Channel input powers are defined by the tilt/offset strategy presented in [9] for three OLS types: (a) C-only case with average channel launch power of 0.0 dBm using span length of 80 km. (b) C+L MBT with an average channel launch power of 0.3 and 0.6 dBm for L- and C-band, respectively, for span lengths of 80 km, (c) C+L+S MBT with an average channel launch power of -0.7, -0.6 and 3.0 dBm for L-, C- and S-band, respectively, for span lengths of 80 km and, finally (d) C+L+S MBT with an average channel launch power of -2.9, -3.4 and -0.3 dBm for L-, C- and S-bands, respectively, for span lengths of 40 km. To achieve a more realistic modelling of the system, we further assume 0.25 dB connector loss, MB-Mux/Demux insertion losses of 2 and 1 dB, respectively, polarization dependent loss (PDL) of 0.5 dB/node traversed by the lightpath, filtering penalties as presented in [11], and splice losses of 0.01 dB/km. Finally, the control plane sets a 1 dB system margin to cope with other detrimental effects and the impact of aging before choosing the supported modulation format for each lightpath.

The GSNR profile for C-only, C+L and C+L+S Regular, after a single 80 km span, and for C+L+S New AS, after two 40 km spans, are presented in Fig. 2. Firstly, the C-only scenario presents an average GSNR of 29.0. In the C+L-band scenario, an average GSNR of 28.1 and 27.0 dB is estimated for the L- and C-band, respectively, whereas in the C+L+S-band scenario the average GSNR is 29.2, 27.0 and 23.8 dB for the L-, C- and S-band, respectively, when considering 80 km

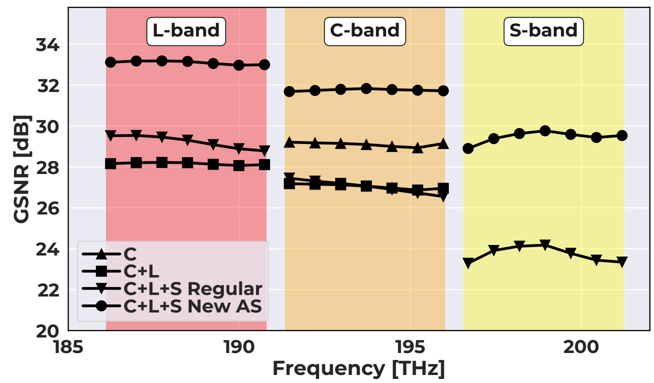

Fig. 2: GSNR profile for C+L and C+L+S Regular, for single span, and for C+L+S New AS, for two spans, scenarios.

fiber spans. If we compare the C+L and C+L+S Regular cases, we can see a small improvement in L-band GSNR average. This comes from the fact that, as we add the S-band channels, they generate a higher power transfer due to the SRS, causing this band to require less gain and consequently producing less ASE noise. Moreover, as the input power in L-band is reduced, if compared with the C+L system, to compensate for the SRS effect, we are able to maintain the NLI levels, thus generating an increase in GSNR. If we decrease the span length to 40 km, the estimated average GSNR after two spans is 33.1, 31.7 and 29.5 dB for the L-, C- and S-band, respectively.

B. Network assessment

The network assessment is performed using the Statistical Network Assessment Process (SNAP) framework [12], which is based on Monte-Carlo simulations. A total of 1500 iterations of progressive traffic loading analysis with a threshold blocking probability (BP) of 5% is executed for two traffic patterns: uniform and population-based [9]. The connection requests are 400 Gbps, which are routed over a single or multiple channels, depending on the GSNR of the lightpath. The reference Italian network topology is considered, shown in Fig. 3 and consisting of 21 ROADM nodes and 36 links, with the latter composed of spans of 80 or 40 km long. Furthermore, the k-shortest path, with $k = 5$, and the first-fit (FF) spectrum assignment algorithms are used for routing and wavelength assignment (RWA).

C. C+L+S Network Design Algorithm

The proposed network design method is based on the network route space (RS), as illustrated in Fig. 1 and presented in Alg. 1. From our previous analysis, we found that focusing on the distribution of new AS only among the shortest paths (route space of $k = 1$) is more beneficial, even if during the allocation process we have $k = 5$ possibilities for each pair of nodes. Moreover, the algorithm requires the percentage of spans in the network in which the length is halved. In this work, we set percentages of 10, 20, 40, and 60 % of the total number of spans to receive a new AS. Firstly, we initialize the sets of number of new AS per link (A) and link usage (U) between

Algorithm 1 Network design for new AS distribution

Input: $RS_{k=1}$: network route space only for the shortest path ($k = 1$); L: list of network links; p: percentage of spans to receive a new AS;
Output: A: List of new AS per link.

1: $t \leftarrow 0$
2: $A, U \leftarrow \emptyset$
3: **for all** link l in L **do**
4:     $A_l, U_l \leftarrow 0$
5:     $S_l \leftarrow$ number of spans of link l
6:     $t \leftarrow t + S_l$
7: **end for**
8: $n = t \cdot p$ {total number of new AS to distribute}
9: $t \leftarrow 0$
10: **for all** route r in $RS_{k=1}$ **do**
11:     **for all** link l in r **do**
12:         $U_l \leftarrow U_l + 1$
13:         $t \leftarrow t + 1$
14:     **end for**
15: **end for**
16: **for all** link l in L **do**
17:     $A_l \leftarrow round(U_l/t \cdot n)$ {normalization times total number of new AS}
18:     **if** $A_l > S_l$ **then**
19:         $A_l \leftarrow S_l$
20:     **end if**
21: **end for**
22: $s \leftarrow 0$ {Spare ASs}
23: **if** $\sum_{l \in L} A_l < n$ **then**
24:     $s \leftarrow n - \sum_{l \in L} A_l$
25: **end if**
26: **while** $s > 0$ **do**
27:     $l \leftarrow$ link with higher usage U_l in which $A_l < S_l$
28:     **if** $(S_l - A_l) \leq s$ **then**
29:         $s \leftarrow s - (S_l - A_l)$
30:         $A_l \leftarrow S_l$
31:     **else**
32:         $A_l \leftarrow A_l + s$
33:         $s \leftarrow 0$
34:     **end if**
35: **end while**

lines 3 and 7, counting also the total number of spans (t) in the network. With the total number of network spans, we can compute the total number of ASs (n) which will be distributed among the links, as shown in line 8. Between lines 10 and 15 we count the number of times each link, as well as the total number of links (t), is used by the route space. The loop between lines 16 and 21 sets the amount of new AS per link, multiplying the normalized usage set U/t times n and then checking if this number is higher than the total number of spans in each link (line 18). As some links present a high degree of importance, the result of this multiplication can generate some links to receive more ASs than the number of

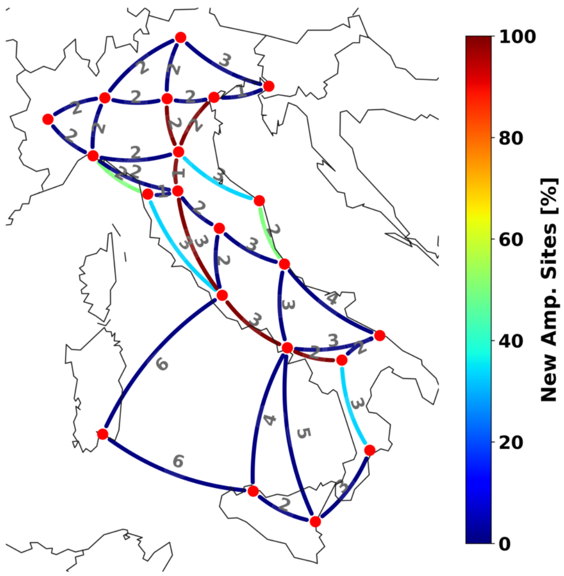

Fig. 3: Italian network topology with the number of spans per link and new AS distribution when 20% of the spans are upgraded.

spans. If that occurs, the proposed algorithm sets all spans in this link to receive a new AS. Moreover, in line 23 is evaluated if the total number of new AS (A) to be installed is less than the total number defined in n, computing the number of spare new ASs (s). Finally, the spare new AS that were not allocated are distributed among links with higher utilization that have not reached the maximum number of upgrades(between lines 26 and 35). The proposed algorithm prioritizes the link with higher usage among the shortest paths, focusing on links that are more likely to be used during the connection allocation process in the network. Moreover, this allocation policy is traffic independent, meaning that even if the traffic pattern changes during network operation, the distribution of new ASs may still be close to optimal. Fig. 3 illustrates the outcome of this strategy, highlighting the percentage of the link spans that receive a new AS when 20% of the total spans of the Italian network are upgraded, corresponding to a total of 18 new ASs. From the plot, we can see that 6 links split 100% of its spans, using a total of 13 new ASs. The other 5 new ASs are deployed among 5 links, using one per link. Moreover, 25 links of this topology did not receive any new amplification sites, relying on the original 80 km span length. The distribution presented in Fig. 3 highlights the distinct importance based on the route space of each link in the network, especially when there is only a small number of new ASs. This distribution prioritizes the deployment of new ASs in links seen as more critical, that is, which are likely to be more used than others. As a result, it can lead to enhancing the spectral efficiency of a larger number of provisioned optical channels, increasing the overall network capacity.

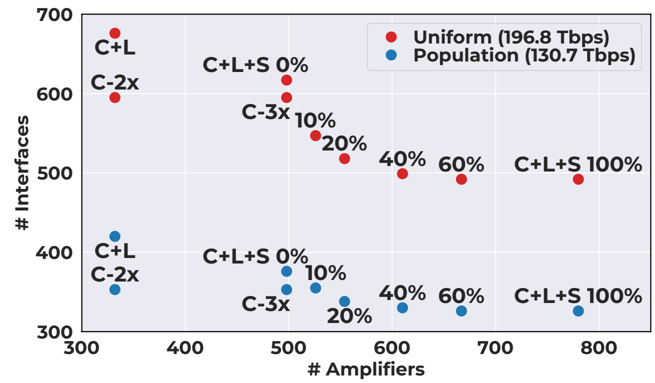

Fig. 4: Cost in terms of the number of used interfaces and total amplifiers for all scenarios tested.

III. Simulation Results

The first set of results, depicted in Fig. 4, shows the number of interfaces and amplifiers required for the C-only with 2 fibers per link (C-2x), C+L, C-only with 3 fibers (C-3x) and C+L+S MBT scenarios with 0% (all Regular), 10%, 20%, 40%, 60% and 100% (all New AS) of network spans receiving an additional AS. The total traffic load considered for the uniform (196.8 Tbps) and population-based (130.7 Tbps) patterns correspond to the traffic that can be delivered with the C+L-band scenario for a target BP $= 10^{-2}$. The uniform scenario requires using 676 and 595 interfaces for C+L and C-2x, respectively, both using 332 optical amplifiers (166 per fiber for C-2x and 166 per band for C+L). When considering the C+L+S 0% scenario, a total of 617 interfaces and 498 amplifiers (still 166 per band) is required. Obviously, the number of used interfaces for the C-3x is the same as the C-2x, as this system only replicates the single-band C-only system. For the C+L+S 10% case, it is used 547 interfaces and 526 amplifiers in total. A total of 518 interfaces and 554 amplifiers are required in this case when 18 spans (20%) are upgraded with a new AS. The first two C+L+S cases already show that with 10% and 20% is already possible to achieve or decrease the number of used interfaces, compared with the multi-fiber (C-2x and C-3x), C+L and C+L+S 0%, albeit at the expense of deploying 194 and 222 additional amplifiers and 9 and 18 new ASs for 10% and 20%, respectively. When upgrading 40 and 60% of the network spans, a total of 499 and 492 interfaces, and 610 and 667 amplifiers, respectively, are required. Importantly, we have observed that upgrading 60% of the network spans already leads to similar savings in the number of interfaces to those achieved when all spans are upgraded (i.e., 100%), since the latter requires also 492 interfaces but demands 112 additional amplifiers and 38 new ASs. The number of interfaces required for the population-based scenario are: 420, 353, 353, 376, 355, 338, 330, 326 and 326 for C+L, C-2x, C-3x, C+L+S 0%, 10%, 20%, 40%, 60%, and 100%, respectively. The number of amplifiers is the same as in the uniform case. Additionally, upgrading 20% of the spans already leads to most of the interface savings when considering this traffic pattern.

The first set of results, considering a fixed traffic load, provides insight into the trade-off between the number of amplifiers (and new ASs) and the number of interfaces, where the latter benefits from the improved QoT that arises from increasing the former. It is useful to estimate the expected cost of the different configurations and namely to determine the minimum number of new amplifiers/ASs that already enable achieving most of the benefits associated with an improvement of QoT across key network links. The second set of results, shown in Fig. 5, assesses the overall delivered traffic as a function of the BP for the uniform and population-based cases. If not specified in another way, all the percentages of traffic increases presented in the next paragraphs are related to the reference case used in this work, the C+L MBT scenario. Moreover, all the delivered traffic values described for BP $= 10^{-2}$ are presented in Table I for easier comparison. As shown in Fig. 5(a), for uniform traffic with a target BP $= 10^{-2}$, C+L MBT delivers 196.8 Tbps, C-2x delivers 236.8 Tbps, C+L+S 0% supports 306.5 Tbps (56% increase) and 356.5 Tbps for the C-3x scenario (81% increase). In the C+L+S 100% case, the traffic increases to 487.9 Tbps (148% increase when compared to the C+L scenario). If the C+L+S 0% scenario is used as reference, the deployment of the new ASs in all network spans (C+L+S 100%) results in a traffic increase of 59%. Moreover, using the proposed deployment strategies, it is possible to increase the network capacity by 20, 28, 38 and 55% when restricting the upgrade to 10, 20, 40 and 60% of the total number of spans, respectively. When evaluating the network capacity, and similarly to the interface count analysis, we find that similar capacity is achieved when upgrading all AS or just the 60% most promising ones. It can also be noticed that for this case using adding a new AS in only 10% of the network spans is possible to overcome the delivered traffic of the C-only system with 3 fibers. The results for the population-based traffic pattern are presented in Fig. 5(b), again for BP $= 10^{-2}$. In this case, the C+L MBT scenario delivers 103.7 Tbps, the C-2x delivers 174.6 Tbps, C-3x delivers 264.2 Tbps, whereas the C+L+S 0% and 100% enable 209.9 and 291.1 Tbps, respectively. Comparing C+L+S 0% and 100%, the traffic load increases by $\approx$ 39%. If the C+L+S 0% is used as reference, we find that our allocation strategy allows increasing the total traffic delivered by 9, 16, 24 and 32%, when the AS upgrade is restricted to 10, 20, 40 and 60% of the network spans, respectively. If we consider the difference obtained from the C+L+S 0% to the C+L+S 100% scenarios as the maximum capacity enhancement possible, we already achieve 62 and 83% of this maximum improvement by enforcing a selective upgrade of 40 and 60% of the potential upgrades. For the population based traffic, the 40% case presents the same performance as the C-only system with 3 fibers. This highlights the importance of choosing the best links where to deploy new ASs to simultaneously maximize network capacity while avoiding unnecessarily increasing CAPEX and OPEX.

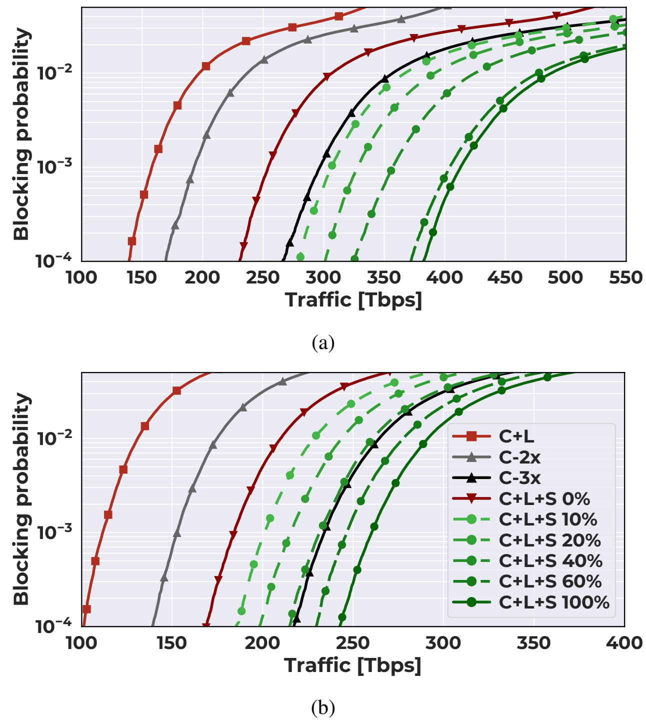

Fig. 5: Delivered traffic versus blocking probability for all scenarios tested with (a) uniform and (b) population based traffic patterns.

IV. Conclusion

In this work, we proposed a C+L+S MBT network design strategy to determine which spans receive a new amplifier site and which do not, based on a reference case of a network currently relying on C+L-band transmission systems. We present network performance results, in terms of overall delivered traffic versus blocking probability, and cost in terms of number of used optical interfaces and total number of optical amplifiers deployed. We have shown that by applying our approach to an Italian reference topology and upgrading only 60% of the spans, almost the same total network capacity can be achieved as when upgrading all spans. Furthermore, by upgrading only 10% of the spans and using the same number,

TABLE I: Overall delivered traffic for all scenarios with BP $= 10^{-2}$.

Upgrade	Uniform	Population
	Traffic [Tbps]	
C+L	196.8	130.7
C-2x	236.8	174.6
C-3x	356.8	264.2
C+L+S 0%	306.5	209.9
C+L+S 10%	366.7	228.1
C+L+S 20%	391.3	243.6
C+L+S 40%	424.9	260.6
C+L+S 60%	477.2	277.6
C+L+S 100%	487.9	291.1

or less, of optical line interfaces as in the corresponding C-only multi-fiber and C+L MBT scenario, much higher network capacity can be achieved (for the same delivered traffic).

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