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(Article begins on next page)

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Network Performance Assessment with Uniform and Non-Uniform Nodes Distribution in C+L Upgrades vs. Fiber Doubling SDM Solutions

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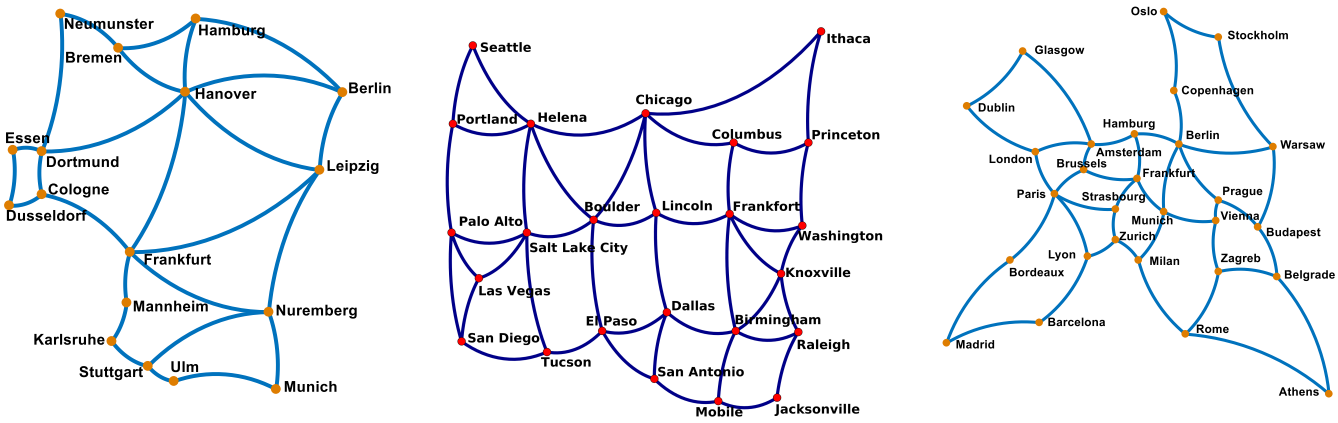
***Abstract*—Both spatial-division multiplexing (SDM) and band-division multiplexing (BDM) have been proposed to increase the traffic allocation in transparent optical networks. If available, SDM may take advantage of the already deployed dark fibers, otherwise BDM is a viable and cost-efficient solution by exploiting multiple bands on the deployed fibers just upgrading the required equipment. We assess the network capacity upgrades enabled by C+L BDM and fiber doubling SDM solutions as realistic upgrade scenario from a C-band only case, using the statistical network assessment process (SNAP). SNAP has been applied to the German, the US-NET and the COST networks by generating any-to-any traffic according to both an uniform or population-based joint probability density function. We show that both SDM and BDM upgrades double the network capacity, making the performances of the two solutions comparable.**

***Index Terms*—Telecommunication traffic, blocking performance, wavelength assignment**

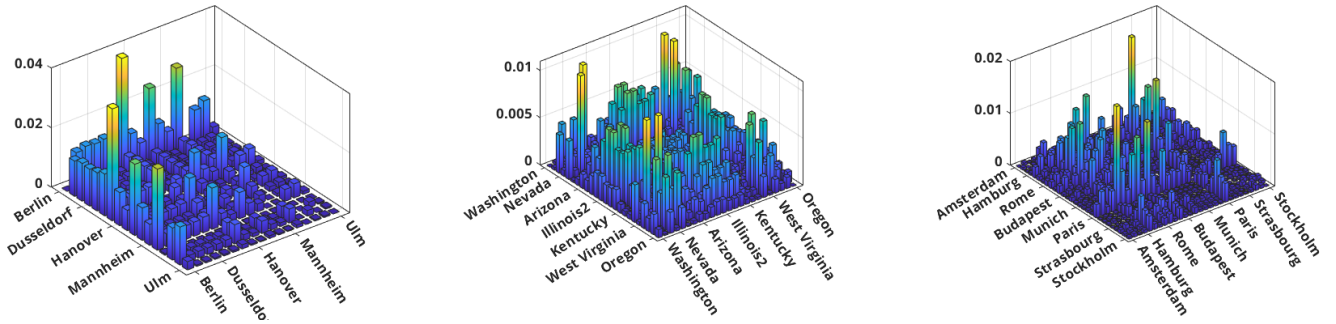
I. Introduction

Spatial-division multiplexing (SDM) has been proposed to increase the traffic allocation keeping low the blocking probability (BP) in transparent optical networks [1], [2], supposing the availability of dark fibers, or the possibility to deploy new ones. Instead, when no dark fibers are available, an alternative to SDM – that does not require new fiber deployment – is to exploit the large spectrum by transmitting over multiple bands on the same deployed fibers just by upgrading the required equipment, e.g., amplifiers, filters, etc. We name this approach as band-division multiplexing (BDM) [3], [4]. This solution allows to further exploit the capacity of existing fibers on optical networks maximizing returns on capital expenditure (CAPEX). BDM aims at enlarging the exploited optical bandwidth up to the range between 1360 nm and 1675 nm by operating the low-loss bands. In [5], [6], the point-to-point performance of a BDM line system has been investigated but no networking analyses have been carried out. Also, results presented in [6] shows the importance of including stimulated Raman scattering (SRS) effects while evaluating the quality of transmission (QoT) if wide bandwidths are used. The generalized Gaussian noise (GGN) model [3] has been proposed to include SRS in the nonlinear interference (NLI) evaluation and it is used in the present paper to properly abstract the physical layer. In [7], a power optimization strategy – based on GGN – has been proposed. In [8], [9] Mitra et al. investigated on the effect of channel launch power on fill margin in C + L bands and its effects in elastic optical networks. The family of SDM technologies includes several solutions: multimode fibers (MMF), multicore fibers (MCF) and multiple parallel fiber (MPF) systems. Those technologies have been extensively studied and compared from the physical layer perspective [2], [10]–[14] and from the switching and networking point of view [15]–[19]. In this work, we compare the networking traffic improvements and penalties arising from the two multiplexing solutions relying on state-of-the-art transceiver technologies, so, we do not consider MMF and MCF implementations of SDM, focusing only on MPF. SDM line systems clearly show a capacity per wavelength advantage with respect to BDM ones [6], which is cancelled by the need for new fibers. Finally, in [20] it has been estimated the network capacity combined with the physical optimization approach shown in [7] applied to the German and the US-NET topologies. In this paper we propose an assessment of the network capacity upgrades enabled by C+L BDM and fiber doubling MPF-SDM solutions as realistic upgrade scenario of a reference C-band only case, using the statistical network assessment process (SNAP) [21]–[23] which is a Monte Carlo-based algorithm delivering statistical network performance metrics such as the blocking probability vs the allocated traffic. In particular, we consider the SDM implementation with two different switching constraints: SDM with independent switching (InS) and SDM with core continuity constraint (CCC) [17], where the latter represents a less complex solution with respect to reconfigurale optical add-drop multiplexer (ROADM) architecture. SNAP has been applied to the German, the US-NET and the European Cost network topologies depicted in Figs. 1a, 1b and 1c, respectively. We do such analysis by generating any-to-any traffic according to both an uniform joint probability density function (PDF) and population based joint PDF [24] in order to understand whether this affect the benefit given by the two multiplexing strategies. Close attention was paid to the physical layer, where optical launch power of both single- and multi-band transmission has been optimized by taking into account SRS effects. The physical layer impairment is



(a) (b) (c)

Fig. 1: Analyzed networks: (a) German, (b) US-NET and (c) COST topologies.



(a) (b) (c)

Fig. 2: Population-based joint-PDF of the source-destination nodes for (a) German, (b) US-NET and (c) COST topologies.

completely taken into account by evaluating the generalized signal-to-noise-ratio (GSNR) as a unique figure of merit of optical transmission performance, both considering ASE noise and NLI generation interplay with SRS [25]. Its evaluation has been carried out by mean of the GNPy supported by the Telecom Infra Project [26]. We show that, although MPF-SDM always delivers the largest capacity when upgrading from a single-band, single-fiber scenario, BDM still offers a cost-effective upgrade when no dark fibers are available. Results demonstrate that, even if a different traffic distribution impacts the absolute value of the allocated traffic, we demonstrate that the upgrade hierarchy still holds when considering a population-based PDF in place of a simpler uniform model. Thus, in most of the cases, both SDM and BDM upgrades double the network capacity. Hence, the techno-economical analysis will decide which solution to pursue.

In this section we have introduced the problem. In section II we will report more in detail the methodology used to perform our investigations. Some more details on the physical layer optimization and on the generation Light Paths (LP) allocation request will be provided. In section III the obtained results will be commented by observing the delivered network performance in terms of BP from a dynamic point-of-view – as the network is loaded by LPs – and then focusing on the gains and losses at a target BP. Finally, in IV the overall conclusions are drawn.

II. Methodology

The network performance assessment has been performed in two main steps. First, we have conducted the physical layer performance evaluation and optimization. Then, the output of this phase has been used to perform statistical network analyses with physical layer awareness using SNAP. In order to statistically analyze each network, physical layer impairment awareness plays a key role. The physical layer is, in fact, characterized by the use of the GSNR as a unique figure of merit for the QoT. In order to realistically model the physical layer, we have assumed that links are made of 75 km long of standard single mode fiber (SSMF) spans whose loss is recovered using only lumped amplification. We also assume that C and L band are amplified by two separate EDFA types. The GGN model, as available in GNPy [27], has been used to estimate the non-linear interference in presence of SRS, which cannot be neglected especially when extending the C-band

to C+L bands. The GGN model has been proved to provide reliable QoT results in the presence of SRS, as shown in [3], [7]. 96 and 192 channels on the ITU-T 50 GHz grid at symbol rate R_s = 32 GBaud have been considered on C-Band/SDM and C+L cases, respectively. The guard-band between C and L bands is assumed to be equal to 500 GHz. The launch power has been optimized in order to maximize and equalize the GSNR applying an offset and a tilt to the channel powers in C and L bands. The optimum tilt and offset for single C-band transmission and C+L bands transmission have been evaluated with a brute force approach as shown in [20]. Starting from flat channel launch power of -2.1 dBm in C-Band and -1.99 dBm in L band, which were obtained by the classic Locally Optimized Globally Optimized (LOGO) strategy [28], the optimum tilt and offset have been derived. For C-Band the only choice was -0.4 dB/THz tilt with no offset, while for the C+L we found 1 dB offset, -0.3 dB/THz tilt for C-Band and 1 dB offset, 0.1 dB/THz tilt for L-Band with no offset. With these profiles, C-band delivers an average GSNR of 30.6 dB per span in the single band scenario, while in the C+L case the QoT is 29.8 dB and 29.6 dB of average GSNR on C and L band, respectively. Hence, the 0.8 dB degradation upgrading the network from C to C+L band accounts for the further NLI and SRS effect added by lighting up the L-band. The obtained GSNR values are then used inside SNAP to assess the network performance of the topologies of Fig.1. The SNAP algorithm is a Monte Carlo based algorithm which progressively loads the network with randomly generated connection requests. These allocation requests are issued up to the saturation condition of the network. For each LP allocated, the supported rate is calculated according to the Shannon capacity and the overall traffic in the network is computed. The Monte Carlo process is iterated N_{MC} times, which is here equal to 75000. The routing space has been computed according to the k_{max} = 15 and the wavelength is assigned according to the best-SNR principle. At the end of the process we obtain a statistical characterization of the dynamic network performance, such as the blocking probability as the network is loaded, i.e., vs. the total allocated traffic. As previously mentioned, the source-destination pair of each request is randomly extracted according to a given joint PDF. In this work we have tested two types of joint PDFs. In the simplest case the PDF is assumed uniform, i.e, each source-destination pair has the same probability of being extracted. In this case, this probability between a generic pair is equal to $1/n(n-1)$, where n is the number of nodes of the topology. In the other case, the source-destination nodes probability is assumed non-uniform but determined according to the population associated with each physical site. Here, the assumption is that couples of nodes associated with more populated generate more traffic, in analogy to the gravity models [24]. Hence, in this case the probability value is determined by the product of the nodes' associated population and normalized to the total population of all network nodes. Then, although we are aware that more realistic traffic distribution models are available in literature, we use the two considered joint probability models in order to assess their impact on the evaluation of the capacity improvement offered by the BDM and SDM strategies, with the aim of deciding the most convenient upgrade.

III. Results

The optimized GSNR profiles for C-band only and C+L bands transmission have been used on SNAP on the three topologies of Fig.1 The German topology has 17 nodes, 26 edges, and the average distance between two ROADM nodes is 207 km for an overall covered area with a diameter of 600 km and an average node degree of 3.1. Instead, the US-NET topology has 24 nodes and 44 edges and the average distance between ROADM nodes is 308 km for a covered area with a diameter of 4000 km and an average node degree of 3.6. Finally, the European COST network has 28 nodes and 41 edges, with an average node degree 2.93. The average link length is 637 km over a covered area with a diameter of 2000 km. Fig.3 shows the BP as a function of the total allocated traffic for both uniform (upper row) and population-based non-uniform source-destination nodes joint PDF (lower row). Let us first consider the uniform PDF case. Despite its longer link lengths, thus yielding poorer QoT, the US-NET topology always delivers the largest traffic thank to its better flexibility enabled by the higher average node degree. COST network instead, delivers performance similar to the German network, despite being considerably larger, because of the longer average link length. From an upgrade perspective, regardless of the topology and nodes' joint PDF, both the BDM and SDM solutions always deliver more than the double of the single band network capacity. The best performance is always provided by the SDM upgrade with InS. This solution, in fact, enables the most of the network flexibility due to the absence of strict constraints from the ROADM switching point of view preserving QoT of the LPs at the same time. However, in most of the cases, the SDM solution with CCC delivers almost the same performance allowing significant savings in terms of ROADM complexity by sacrificing network flexibility. The BDM solution, instead, behaves always worse than SDM but still delivering a significant upgrade. The penalty with respect to SDM solutions is due to the QoT degradation caused by the SRS interaction between C and L bands and the poorer network flexibility implied by the wavelength routing constraints. This gap, however, can be still acceptable, especially when considering that this could often be the lowest-cost upgrade and the only one when no new fibers are available. Let us now focus on the effects of the source-destination nodes joint PDF: while for the US-NET and COST topologies the implementation of the population-based PDF leads to less throughput, it is instead increased for the German topology. This can be justified by the fact that the German topology well matches the nodes distribution. In addition, the COST network shows a significant gap in delivered traffic between the SDM with InS and CCC when going to the non-uniform nodes PDF model, being InS most effective strategy by far. This can be explained by looking at the population-based PDF of Fig.2c. Using the population-based model results in a

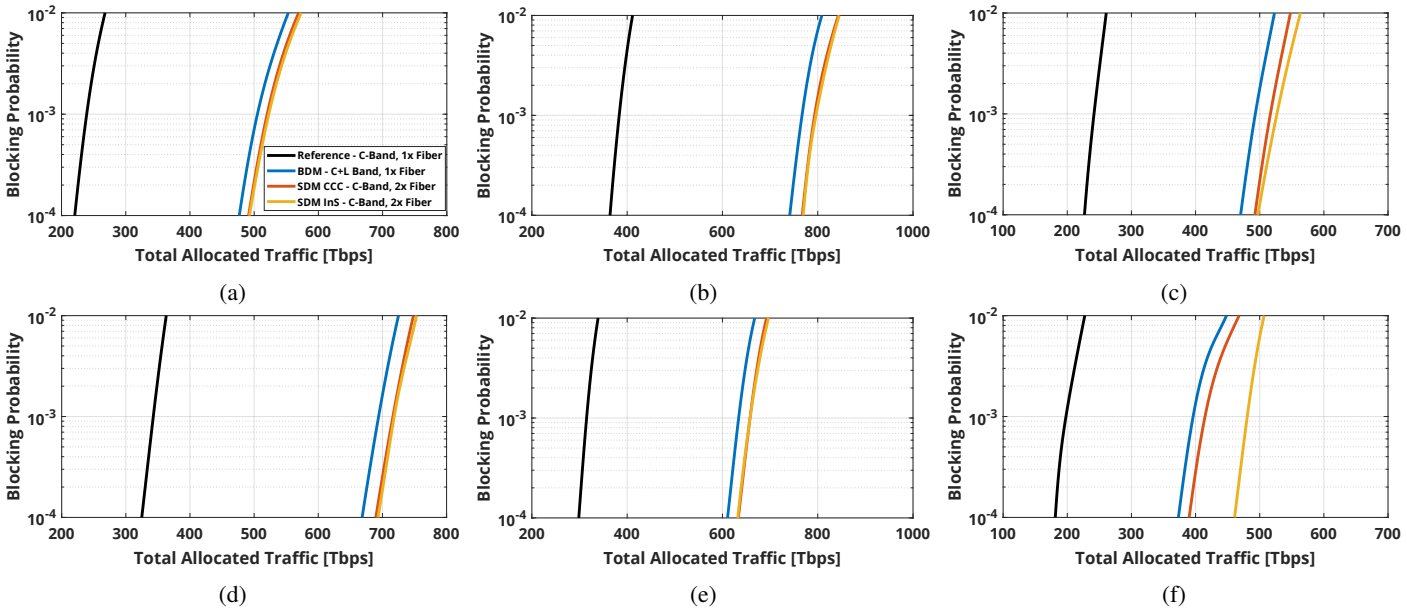


Fig. 3: Blocking probability vs. total allocated traffic for (a,d) German, (b,e) US-NET and (c,f) COST topologies. Upper row: uniform connection requests joint PDF. Lower row: population-based non-uniform connection requests joint PDF.

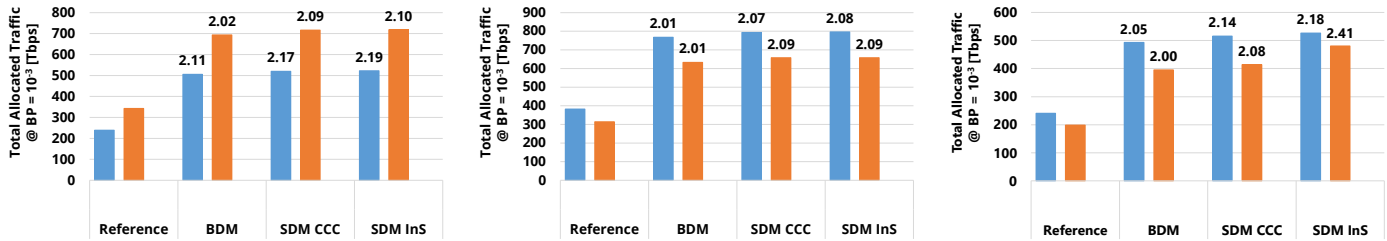


Fig. 4: Total Allocated Traffic at BP = 10^{-3} [Tbps] for reference case and upgrade solutions with uniform connection requests joint PDF (blue), population-based non-uniform connection requests joint PDF (orange) for (a) German, (b) US-NET and (c) COST topologies. Labels on top of the upgrade solutions bars are the corresponding traffic multiplicative factors with respect to reference case.

very unbalanced topology where the most probable nodes are all located in the southwest area of the network (Barcelona, Madrid, Paris, London), so that the links in that area will be highly congested. In such a situation, the additional network flexibility enabled by InS is strongly beneficial for the overall network capacity. In order to provide few quantitative results, Fig.4 reports the total allocated traffic on the networks at a target BP of 10^{-3}. Blue bars refer to the uniform nodes joint PDF, orange bars to the population-based joint PDF. On top of the upgrades bars, the traffic multiplicative factor is reported, which is calculated as the ratio between the upgrade solution average traffic and the single-band, single-fiber reference case average traffic (with the same nodes PDF model). In any case, the traffic is at least doubled with any upgrade solution with respect to the reference case. The additional upgrade gain, for German topology with uniform nodes joint PDF is 11% for BDM and 17% and 19% for SDM with CCC and InS, respectively. Going to population-based nodes PDF decreases the gain to 2% for BDM and 9% and 10% for SDM with CCC and InS respectively. Hence, even if the absolute traffic for the German topology is increased with non-uniform PDF for German (from 239 Tbps to 342.8 Tbps for reference single-band case), the increased network flexibility introduced by the upgrades becomes less effective with such unbalanced nodes joint distribution. Still, SDM gains are larger than BDM because of the improved network flexibility with no QoT degradation. As for the US-NET and COST, instead, the absolute traffic decreases with non-uniform nodes PDF. However, US-NET gains for the two node distributions are much similar. For BDM, SDM-CCC, SDM-InS respectively, the gains are 1%, 7% and 8% with uniform PDF and 1%, 9% and 9% with non-uniform PDF. This may be justified with the larger node degree of the US-NET topology which can support the unbalanced traffic. Finally, regarding the COST network,

for BDM, SDM-CCC, SDM-InS respectively, the upgrade gains are 5%, 14% and 18% with uniform PDF and 0%, 8% and 41% with non-uniform PDF. Here, the network flexibility introduced by the SDM solution is always highly beneficial with respect to the BDM, providing larger gains, especially in the non-uniform node PDF case, where InS delivers a 41% gain which can counteract the strongly unbalanced nodes PDF.

IV. Conclusion

We have shown that, in all the analyzed cases, both the BDM and SDM solutions at least double the network capacity. Further upgrade gains can be delivered depending on the upgrade solution and the nodes distribution model and topology properties. In general, the SDM-InS enables the largest capacity when upgrading from single-band, single-fiber. SDM-CCC provides similar results with a small loss but a huge complexity reduction in ROADM architecture, except for the COST, non-uniform case, where the maximum switching flexibility of the SDM-InS provides a further gain of 41% with respect to the 8% of the SDM-CCC case.
BDM still delivers a cost-effective upgrade when no dark fibers are available and SDM is not a viable solution. In addition, results demonstrate that, even employing a population-based PDF in place of a simpler uniform model, the same upgrade advantage hierarchy holds. Hence, the techno-economical analysis will decide which solution to pursue among BDM and SDM. However, at the same time, results have shown that a different node probability distribution model can significantly impact the allocated traffic, hence this aspect should be carefully modelled when assessing network performance.

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