(Article begins on next page)

Networking Performance of Power Optimized C+L+S Multiband Transmission

Bruno Correia
Politecnico di Torino
Turin, Italy
bruno.dearaujo@polito.it

Rasoul Sadeghi
Politecnico di Torino
Turin, Italy
rasoul.sadeghi@polito.it

Emanuele Virgillito
Politecnico di Torino
Turin, Italy
emanuele.virgillito@polito.it

Antonio Napoli
Infinera
Munich, Germany
Anapoli@infinera.com

Nelson Costa
Infinera
Portugal
Ncosta@infinera.com

João Pedro
Infinera
Portugal
jpedro@infinera.com

Vittorio Curri
Politecnico di Torino
Turin, Italy
vittorio.curri@polito.it

***Abstract*—Both spatial-division multiplexing (SDM) and band-division multiplexing (BDM) emerge as possible solutions to increase the optical network capacity to support the traffic demand which has been rising over time. In this work, two different ROADM (Re-configurable Optical Add Drop Multiplexer) switching techniques, namely SDM-InS (Independent switching) and SDM-CCC (Core Continue Constant) are investigated and the resulting network capacity is compared with the BDM approach. In the BDM case, both L- and S-bands have been used in addition to C-band to increase the network capacity. The launch power is optimized to control the QoT (Quality of Transmission) summarized by the generalized SNR (GSNR) per channel. Due to: stimulated Raman scattering, frequency variation of loss, frequency variation of dispersion coefficient and noise figures, an optimum power tilt and offset are calculated for each band. We show that the total network capacity increased by $\sim 2\times$ and $\sim 3\times$, when using the L-band and L+S-bands in addition to the C-band, respectively, in both a reference German and a reference US network. Additionally, it was also shown that using additional bands, the increase in network capacity is close to the result of using additional optical fibers in the SDM case.**

***Index Terms*—Multi-band, transmission modeling, high-capacity optical systems**

I. Introduction

The imminent deployment of 5G and high-capacity access optical networks will stress the telecommunication infrastructures [1]. To deal with this high demand, several possible solutions have been proposed to extend the wavelength-division multiplexing (WDM) capacity of optical networks, which now mainly works in a 4.8 THz spectrum window in the C-band. The main proposals are based on: (a) spatial-division multiplexing (SDM), a solution that can be implemented using multi-core/-mode fibers (MMC/MMF) or lighting up new ones, possible dark, fibers (Multiple parallel fibers – MPF); (b) band-division multiplexing (BDM), which aims to exploit the available low-loss optical spectrum of 53.5 THz over the widely deployed ITU G.652.D optical fiber [2]. With SDM, if dark fibers are not available, the only option consists in the deployment of additional fibers. This leads to a multiplication of the network elements, potentially entailing prohibitive capital expenditure (CAPEX). Using the BDM approach, we can exploit the major part of the unused spectrum in already deployed fibers, potentially reducing the CAPEX required to enhance the network's capacity, especially in areas where using or deploying new fibers leads to prohibitive costs or it is not possible because of local regulations [2].

Solutions using SDM technology were extensively investigated and compared from a physical layer performance perspective [3]–[6]. Additionally, the switching techniques using SDM technology were also analyzed [7]–[10]. Regarding BDM, C+L-band transmission systems are already commercially available [11], several works, especially recently, addressed the BDM approach aiming to investigate the viability of using others spectral bands. Transmission using the five ITU bands (O, E, S, C, and L) with multiple modulation formats achieved 106.77 Tb/s within 23.5 THz [12]. In [13], the transmission over up to 6 bands (O- to U-band) in multiple scenarios of increasing spectral usage were investigated, achieving a capacity increase of up to $8\times$ when compared with C-band only when using the 48 THz. An extensive discussion about the potential and challenges of BDM over O- to L-band on ITU-T G.652.D fiber has been presented in [2], addressing the generalized signal-to-noise ratio (GSNR) [14] as QoT metric, which includes both linear and nonlinear fiber propagation effects, to assess optical performance. This work considers the Stimulated Raman Scattering (SRS) impact in the nonlinear interference (NLI) by using the generalized Gaussian noise (GGN) model [15] to estimate the NLI (nonlinear interference) component in the GSNR, together with realistic amplifier noise figure for the ASE noise assessment. With this objective, the GNPy tool [16] is used to abstract the physical layer and obtain a quite accurate performance estimate.

In order to increase the transmission QoT, particularly in wideband networks, the launch power optimization is crucial.

This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement 814276 and by the Telecom Infra Project.

Several power optimization strategies based on the GGN model being proposed in [17], [18], where the effect of launch power in C- and L-bands and its effects in elastic optical networks are investigated. A 40 km transmission demonstration optimizing the launch power for C-, L- and S-bands, comprising a total bandwidth of 13.6-THz was presented in [19]. Additional power optimization methods were used in [20]–[22] to analyze the network capacity when implementing SDM and BDM upgrades. The network capacity considering different multiplexing approaches, namely BDM and SDM-CCC/InS are compared in [9]. In [21], [22], L-band has been considered besides C-band and the resulting network capacity was compared with SDM-CCC/InS approaches when considering the use of two fibers. Finally, the statistic network assessment process (SNAP) was used to analyze the network capacity in [23], [24].

The remainder of this paper is organized as follows: The methodology of our work is described in detail in section II, which presents the power optimization method and the network assessment approach. Then, the analysis of the best QoT for the BDM case and the network assessment are presented in section III. Finally, section IV presents the conclusions.

II. Methodology

The potential of BDM is evaluated considering three different transmission scenarios: i) use of C-band only (reference scenario, where the transmission of 96 channels in a single optical fiber per link is assumed); ii) use of C+L-bands with 96 channels transmitted in each band; and iii) C+L+S-band transmission still assuming the transmission of 96 channels per band. Two different network topologies are considered in our work: the US-NET and German reference networks, shown in Figs. 1(a) and 1(b), respectively. In the SDM case, two ROADM (Re-configurable Optical Add Drop Multiplexer) switching techniques are evaluated. The two switching techniques are the core continuity constraint (CCC) and the independent switching (InS), with the first option being the less complex approach [22]. Moreover, to make a fairer comparison with BDM scenarios, the number of fibers in all links is increased to two or three, depending on the number of bands considered in the corresponding BDM case. The network analyses are performed for a single traffic joint probability density function (JPDF) with uniform distribution among the network nodes.

Both amplified spontaneous emission (ASE) noise and NLI disturbance generated by the nonlinear fiber propagation are considered when estimating the QoT of the links. The ASE power is calculated using:

$$P_{\text{ASE}}\left(f\right) = hf\text{NF}(f)G(f)B_{\text{ref}} \quad (1)$$

where h is the Planck's constant, f is the channel frequency, *NF* and *G* are the noise figure and amplifier gain, respectively (which are frequency dependent), and B_{ref} is the reference bandwidth. The NF profile of the optical amplifier for the S-band used in this work, which is not yet commercially available, is shown in Fig. 2 [25], with average of 6.50 dB.

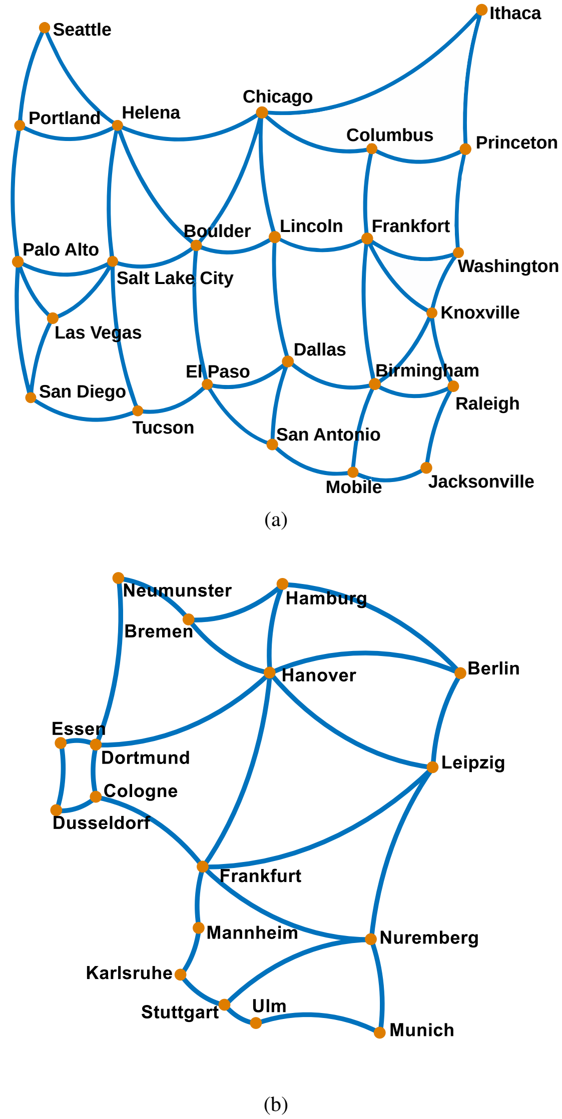


Fig. 1: Reference networks: (a) US-NET and (b) German.

For other spectral bands, the NF average is around 4.25 and 4.68 dB for C and L, respectively. A complete fiber loss compensation by the optical amplifiers is assumed [21], [22].

With the increase of the used spectrum, the SRS impact on optical performance cannot be neglected. We take this effect into account when estimating the NLI contribution, which is given by:

$$P_{\text{NLI}} = G_{\text{NLI}}(f)B_{\text{ref}} \quad (2)$$

where $G_{\text{NLI}}(f)$ is the NLI power spectral density, which takes into account the self- and cross-channel interference, but neglects the multichannel interference [26]. The QoT metric, GSNR, is calculated from both P_{ASE} and P_{NLI}, using:

$$\text{GSNR}_i = \frac{P_{S,i}}{P_{\text{ASE}}\left(f_i\right) + P_{\text{NLI},i}\left(f_i\right)} \quad (3)$$

for the ith channel with central frequency f_i, where $P_{S,i}$ is the signal launch power.

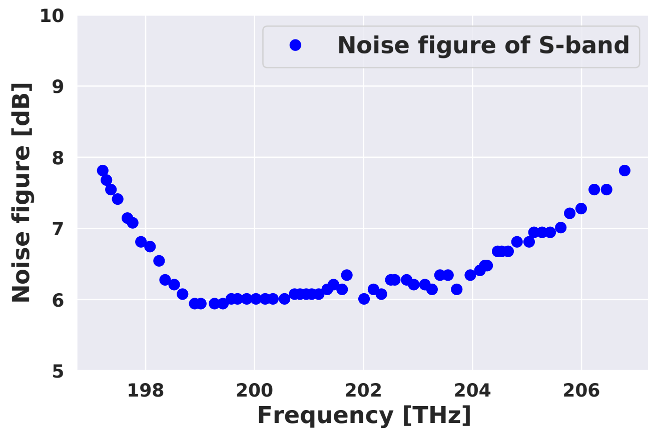


Fig. 2: Noise figure of optical amplifier for S-band [25].

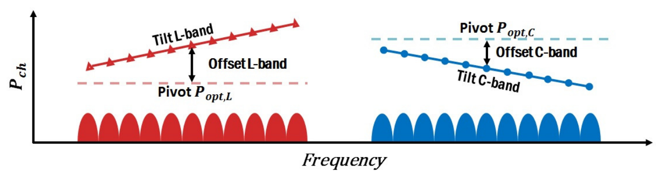


Fig. 3: Illustration of tilt and offset strategy for C+L-band transmission scenario.

The launch power optimization plays a key role in maximizing the GSNR and, consequently, the QoT, especially when using BDM to increase a network capacity [21], [22]. In this work, the tilt and offset strategy is used to optimize the launch power. This is a practical engineering strategy that enables maximizing the QoT uniformity over the used spectrum [20]. Fig. 3 presents an illustration on how this strategy is implemented. In this example, in the case of the L-band (channels in red), we begin with a flat power spectrum and apply a positive offset that will add-up to the defined flat value. In the case of the C-band (blue channels), a negative offset is applied. Then, a tilt is applied to each band, which will define the slope of the launch power. A positive and a negative tilt for the L- and C-bands, respectively, are set in this example.

In this work, all link spans of the reference networks are assumed to be composed of uniform 75 km long ITU-T G.652D standard single mode fibers (SSMF), in which the loss is recovered using lumped amplification, are assumed. The C- and L-bands are amplified using separate commercially available EDFAs, and the S-band is amplified using a TDFA benchtop amplifier [25]. A total of 96 channels are transmitted per band on the ITU-T 50 GHz grid considering a symbol rate of 32 Gbaud for all scenarios and a guard band of 500 GHz between adjacent bands.

For the C+L+S-band transmission scenario, we start by determining the optimized flat launch power [27] of each band in each fiber span using the LOGO approach, leading to an estimate of -2.1, -1.99, and -1.43 dBm for C-, L- and S-bands, respectively. Afterwards, a set of potential optimum launch power tilts and offsets is selected for each band. Offsets ranging from 0 and up to 3 dB for C- and S-bands and from -1.0 and up to 2.0 dB for L-band with a step size of 1.0 dB and power tilts ranging from -1.0 and up to 1.0 dB/THz with a step size of 0.5 dB/THz for the 3 bands are considered. Thus, a total of 8000 possibilities are considered when assessing the optimized power and tilt offsets. This optimization is carried out via a brute force approach [22], in which all combinations of tilt and power offsets are computed and the one that leads to the best profile, i.e., the one that maximizes the GSNR while still leading to approximately the same QoT for all channels, is selected. In order to speed up the simulation, only the NLI contribution of 5 channels in each band (sufficiently spaced to cover most of the band) is calculated while the remaining ones are determined by interpolation, following the same procedure of [21].

Networking analyses have been done by using the statistical network assessment process (SNAP) [24] on the US-NET and German reference network topologies. The US-NET topology in Fig. 1(a) consists of 24 optical nodes and 43 edges with average node degree of 3.6 and 308 km of average distance between nodes. The German topology in Fig. 1(b) is composed by 17 optical nodes and 26 edges with average node degree of 3.1 and 207 km of average distance between nodes. The SNAP is a Monte-Carlo framework that progressively loads the network with randomly generated requests between nodes and progressively increases the traffic in the network under test until reaching the threshold blocking. A uniform traffic pattern generation is considered. Therefore, all nodes have the same probability to be the traffic source/destination. Consequently, the probability of selecting a node as a source or destination is where n is the number of nodes in a network. The number of Monte-Carlo runs in the SNAP for each considered scenario is $N_{\text{MC}} = 75000$. The K-shortest path algorithm has been implemented for routing and wavelength assignment (RWA). K_{MAX} has been set to 15 in both reference networks and wavelength assignment follows the first fit (FF) with best GSNR principle. A statistical characterization of the network performance when progressively loaded is obtained with the SNAP. As a result, the blocking probability versus total allocated traffic requests is available. Additionally, the supported rate in each lightpath (LP) is calculated according to the Shannon capacity and the overall capacity of each network is computed.

III. Results

A. Power Optimization

Fig. 4 shows the GSNR resulting from the 8000 combinations of launch power offset and tilts tested to optimize the launch power. The average GSNR is plotted versus the flatness of the GSNR (average GSNR variation over all considered bands). The 7 best non-dominant solutions are highlight in the inset of Fig. 4. We decided to select as optimum the solution that maximizes the GSNR due to the small difference in flatness between these 7 solutions. The optimum launch

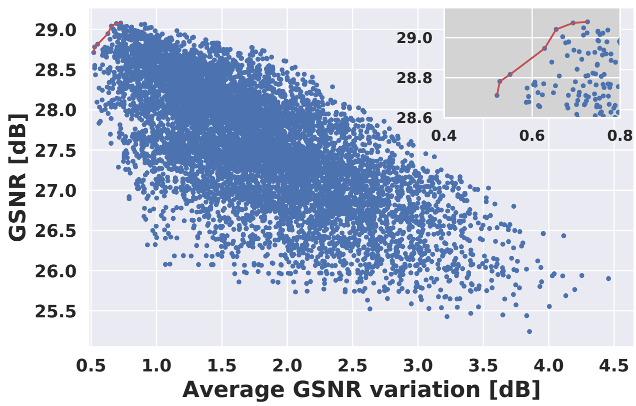


Fig. 4: Average GSNR vs. average GSNR variation for all combinations of tilts and offsets for C+L+S-band scenario.

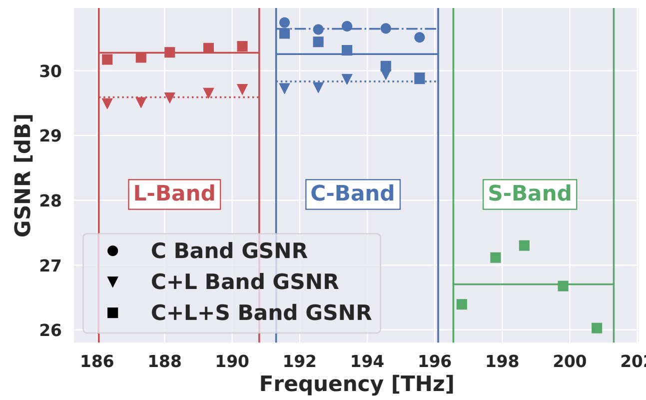


Fig. 5: GSNR vs. frequency for the channels evaluated in each band and average GSNR for each optimization scenario.

power setup (offset and tilt) calculated for the C+S+L-band transmission case is shown in Table I. The optimum power profiles for C- and C+L-band transmission were already presented in [21] and are indicated also in Table I.

TABLE I: Optimum launch power tilt and offset per band for the C-, C+L- and C+L+S-band transmission cases.

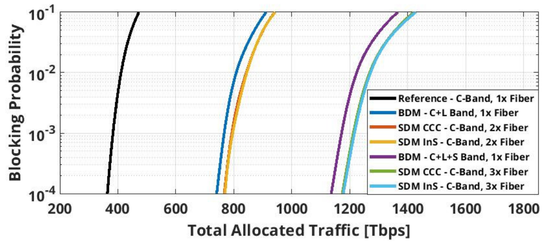
	Tilts [dB/THz]			Offsets [dB]		
	L	C	S	L	C	S
C	-	-0.4	-	-	0.0	-
C+L	0.1	-0.3	-	1.0	1.0	-
C+L+S	1.0	0.5	0.5	0.0	0.0	1.0

Fig. 5 presents the GSNR computed for the selected 5 channels in each band for each transmission scenario. The obtained average GSNR, shown in lines in Fig. 5, for each optimization scenario are 30.6 dB for C-band transmission only, 29.8 and 29.6 dB in C- and L- band, respectively, in the C+L-band transmission case and 30.2, 30.3 and 26.7 dB in C-, L- and S-band, respectively, for C+L+S-band transmission case. Comparing with the reference case, the average GSNR in C-band for the C+L-band scenario presents a degradation of 0.8 dB in QoT due the NLI and SRS effects resulting from using the L-band also. For the C+L+S case, it can be seen that the C-band GSNR only decreases by 0.4 dB with respect to the reference case. This improvement with respect to the C+L-band case can be explained by the SRS, which leads to a pumping effect from higher to lower frequencies, i.e., from the S-band into the C-band.

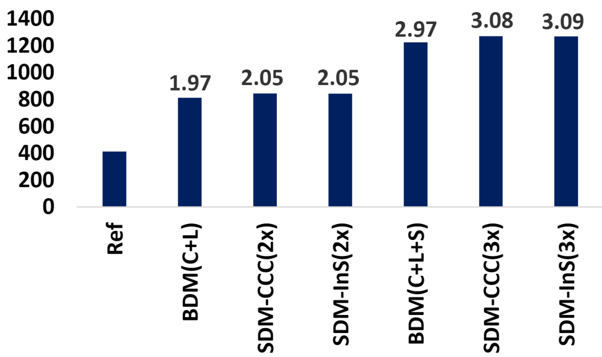
B. Network analysis with allocated traffic

Fig. 6(a) shows the blocking probability (BP) vs. total allocated traffic for the US network. C-band only transmission with a single optical fiber is used as reference scenario. In this case, the allocated traffic at BP $= 1\%$ is about 412 Tbps. In case of BDM upgrade, with only the C-and L-band enabled, the allocated traffic is approximately doubled with respect to the reference scenario. Although the behavior of the SDM-InS/CCC is comparable, they lead to a slightly higher capacity in comparison with the BDM upgrade resulting from the lower QoT in BDM, of about 1 dB, in average. In the case of the German topology, illustrated in Fig. 7(a), the BDM upgrade with C+L bands more than double the reference allocated traffic at BP $= 1\%$, which is of about 268 Tbps, with SDM still slightly outperforming BDM. Further increasing the number of used bands, in the BDM case, or using additional dark fibers, in the SDM case, maintains the same behavior in both reference networks. By using also S-band, the BDM solution increases the US network capacity by 2.97 times with respect to the reference case, while the capacity in German topology more than triple. However, the gap between BDM and SDM increases due to the higher QoT degradation in the BDM case of 1.5 dB, in average. Nevertheless, due to the potentially lower-cost of BDM or the non-availability of dark fibers in a network, this gap in performance between BDM and SDM is very acceptable, highlighting the potential of BDM for networks capacity upgrade. Interestingly, the German network has smaller capacity than the US one, despite the shorter average link length and, consequently, higher QoT. This effect is a consequence of the network structure itself, namely the higher degree of flexibility of US network resulting from the higher average nodal degree.

In order to provide a better view of the differences in network capacity, a multiplicative factor histogram is plotted for each scenario in Figs 6(b) and 7(b), for a target BP of 1%. These figures show that network capacity in German and US networks increased 2.06 and 1.97 times for BDM-C+L and 3.2 and 2.97 times for BDM-C+L+S upgrade for German and US networks, respectively. Moreover, the multiplicative factors are 2.12 and 2.14 for SDM-CCC and SDM-InS, respectively, when using 2 fibers and 3.27 and 3.29 for SDM-CCC and SDM-InS, respectively, when using 3 fibers, in the case of the German reference network, whereas, in the case of the US reference network, the SDM approach lead an increase of 2.05 for both SDM-CCC and SDM-InS, when using 2 fibers and to 3.08 and 3.09 for SDM-CCC and SDM-InS, respectively, when using 3 fibers.

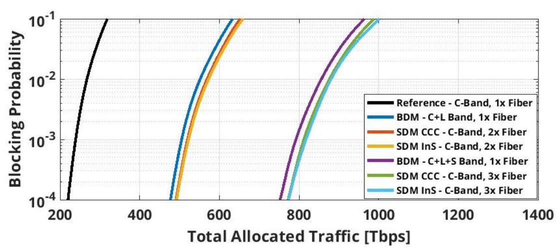


(a)

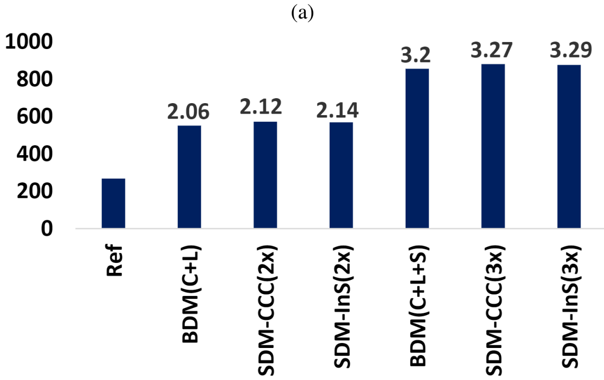


(b)

Fig. 6: Reference networks: (a) US-NET and (b) German.



(a)



(b)

Fig. 7: Reference networks: (a) US-NET and (b) German.

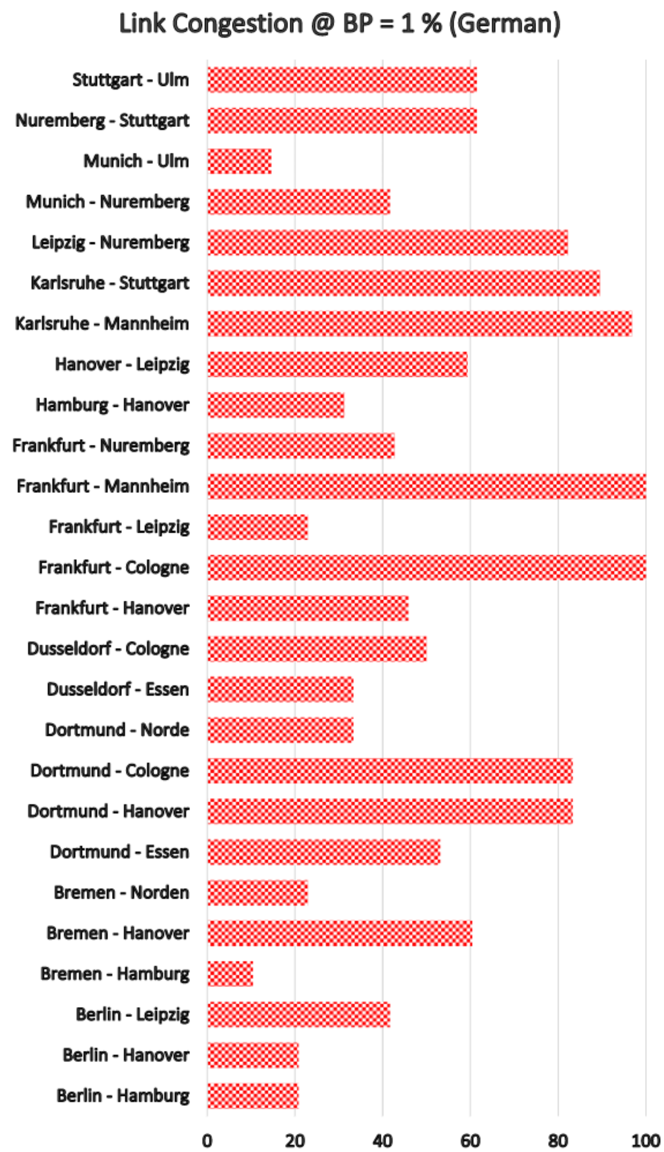


Fig. 8: Links congestion at BP = 1% for German network.

As a final result, the network links congestion for the reference C-band with BP of 1% is shown in Fig. 8 for German reference network. The analysis of Fig. 8 shows that 7 out of 26 links present more than 80% of occupancy while 9 links show less than 40% of usage. This example of unbalance between links usage results in an inefficient use of network capacity. BDM can offer scalability in this case by providing an easy pay-as-you-grow approach. Another possibility of BDM application to increase the network usage is the reservation of spectral bands with lower QoT, like S-band, for connections inside regional networks, while more robust bands in terms of QoT are left for long distance connection requests.

IV. Conclusion

In this work, we target the launch power optimization and network capacity assessment, in terms of offered traffic, for BDM using C+L- and C+L+S-band transmission scenarios, comparing its results with the corresponding SDM case. For the C+L-band case, BDM almost doubles the capacity of the US network for a target BP of 1% while in the C+L+S-band case, the capacity is almost tripled. In the case of a German reference network, BDM more than doubles and triples the reference capacity for C+L- and C+L+S-band transmission, respectively. Although the SDM approach delivered more traffic than BDM in all investigated cases, it is possible to minimize this difference with a careful choice of launch power, making BDM a plausible solution to upgrade WDM optical networks capacity, specially when no spare fibers are available or the CAPEX required to deploy new ones is prohibitive.

References

[1] A. Napoli *et al.*, "Towards multiband optical systems," in *Advanced Photonics 2018 (Networks)*, vol. Part F106-, p. NeTu3E.1, OSA, 2018.

[2] A. Ferrari, A. Napoli, J. K. Fischer, N. M. S. d. Costa, A. D'Amico, J. Pedro, W. Forysiak, E. Pincemin, A. Lord, A. Stavdas, J. P. Fernndez-Palacios Gimnez, G. Roelkens, N. Calabretta, S. Abrate, B. Sommerkorn-Krombholz, and V. Curri, "Assessment on the achievable throughput of multi-band itu-t g.652.d fiber transmission systems," *Journal of Lightwave Technology*, pp. 1–1, 2020.

[3] R.-J. Essiambre and R. W. Tkach, "Capacity trends and limits of optical communication networks," *Proceedings of the IEEE*, vol. 100, no. 5, pp. 1035–1055, 2012.

[4] R. Ryf, J. C. Alvarado, B. Huang, J. Antonio-Lopez, S. H. Chang, N. K. Fontaine, H. Chen, R.-J. Essiambre, E. Burrows, R. Amezcua-Correa, *et al.*, "Long-distance transmission over coupled-core multicore fiber," in *ECOC 2016-Post Deadline Paper; 42nd European Conference on Optical Communication*, pp. 1–3, VDE, 2016.

[5] C. Antonelli, M. Shtaif, and A. Mecozzi, "Modeling of nonlinear propagation in space-division multiplexed fiber-optic transmission," *Journal of Lightwave Technology*, vol. 34, no. 1, pp. 36–54, 2015.

[6] T. Hayashi, T. Sasaki, and E. Sasaoka, "Multi-core fibers for high capacity transmission," in *OFC/NFOEC*, pp. 1–3, IEEE, 2012.

[7] F. Pederzolli, D. Siracusa, B. Shariati, J. M. Rivas-Moscoso, E. Salvadori, and I. Tomkos, "Improving performance of spatially joint-switched space division multiplexing optical networks via spatial group sharing," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 9, no. 3, pp. B1–B11, 2017.

[8] P. S. Khodashenas, J. M. Rivas-Moscoso, D. Siracusa, F. Pederzolli, B. Shariati, D. Klonidis, E. Salvadori, and I. Tomkos, "Comparison of spectral and spatial super-channel allocation schemes for SDM networks," *Journal of Lightwave Technology*, vol. 34, no. 11, pp. 2710–2716, 2016.

[9] A. Ferrari, M. Cantono, and V. Curri, "A networking comparison between multicore fiber and fiber ribbon in WDM-SDM optical networks," in *2018 European Conference on Optical Communication (ECOC)*, pp. 1–3, IEEE, 2018.

[10] R. Rumipamba-Zambrano, F.-J. Moreno-Muro, P. Pavón-Marino, J. Perelló, S. Spadaro, and J. Solé-Pareta, "Assessment of flex-grid/MCF optical networks with ROADM limited core switching capability," in *2017 International Conference on Optical Network Design and Modeling (ONDM)*, pp. 1–6, IEEE, 2017.

[11] V. Lopez, B. Zhu, D. Moniz, N. Costa, J. Pedro, X. Xu, A. Kumpera, L. Dardis, J. Rahn, and S. Sanders, "Optimized design and challenges for c&l band optical line systems," *Journal of Lightwave Technology*, vol. 38, no. 5, pp. 1080–1091, 2020.

[12] S. Okamoto, K. Horikoshi, F. Hamaoka, K. Minoguchi, and A. Hirano, "5-band (O , E , S , C , and L) WDM Transmission with Wavelength Adaptive Modulation Format Allocation," in *European Conference on Optical Communication (ECOC) 2018*, pp. 20–22, 2016.

[13] A. Ferrari, A. Napoli, J. K. Fischer, N. Costa, J. Pedro, N. Sambo, E. Pincemin, B. Sommerkohrn-Krombholz, and V. Curri, "Upgrade capacity scenarios enabled by multi-band optical systems," *International Conference on Transparent Optical Networks*, vol. 2019-July, pp. 3–6, 2019.

[14] M. Cantono, D. Pilori, A. Ferrari, and V. Curri, "Introducing the Generalized GN-model for Nonlinear Interference Generation including space/frequency variations of loss/gain," *Journal of Lightwave Technology*, vol. 36, pp. 3131–3141, oct 2017.

[15] M. Cantono, D. Pilori, A. Ferrari, C. Catanese, J. Thouras, J.-L. Augé, and V. Curri, "On the interplay of nonlinear interference generation with stimulated Raman scattering for QoT estimation," *Journal of Lightwave Technology*, vol. 36, no. 15, pp. 3131–3141, 2018.

[16] A. Ferrari, M. Filer, K. Balasubramanian, Y. Yin, E. Le Rouzic, J. Kundrát, G. Grammel, G. Galimberti, and V. Curri, "GNPy: an open source application for physical layer aware open optical networks," *Journal of Optical Communications and Networking*, vol. 12, p. C31, jun 2020.

[17] A. Mitra, D. Semrau, N. Gahlawat, A. Srivastava, P. Bayvel, and A. Lord, "Effect of channel launch power on fill margin in C+L band elastic optical networks," *Journal of Lightwave Technology*, vol. 38, no. 5, pp. 1032–1040, 2019.

[18] A. Mitra, D. Semrau, N. Gahlawat, A. Srivastava, P. Bayvel, and A. Lord, "Effect of reduced link margins on C+L band elastic optical networks," *Journal of Optical Communications and Networking*, vol. 11, no. 10, pp. C86–C93, 2019.

[19] F. Hamaoka, M. Nakamura, S. Okamoto, K. Minoguchi, T. Sasai, A. Matsushita, E. Yamazaki, and Y. Kisaka, "Ultra-Wideband WDM Transmission in S -, C -, and L -Bands Using Signal Power Optimization Scheme," *Journal of Lightwave Technology*, vol. 37, pp. 1764–1771, apr 2019.

[20] A. Ferrari, D. Pilori, E. Virgillito, and V. Curri, "Power Control Strategies in C+L Optical Line Systems," *2019 Optical Fiber Communications Conference and Exhibition, OFC 2019 - Proceedings*, pp. 10–12, 2019.

[21] E. Virgillito, R. Sadeghi, A. Ferrari, G. Borraccini, A. Napoli, and V. Curri, "Network performance assessment of c+l upgrades vs. fiber doubling sdm solutions," in *Optical Fiber Communication Conference (OFC) 2020*, p. M2G.4, Optical Society of America, 2020.

[22] E. Virgillito, R. Sadeghi, A. Ferrari, A. Napoli, B. Correia, and V. Curri, "Network performance assessment with uniformand non-uniform nodes distribution in c+l upgrades vs. fiber doubling sdm solutions," in *International Conference on Optical Network Design and Modelling (ONDM) 2020*, 2020.

[23] M. Cantono, R. Gaudino, and V. Curri, "Potentialities and criticalities of flexible-rate transponders in DWDM networks: A statistical approach," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 8, no. 7, pp. A76–A85, 2016.

[24] V. Curri, M. Cantono, and R. Gaudino, "Elastic All-Optical Networks: A New Paradigm Enabled by the Physical Layer. How to Optimize Network Performances?," *Journal of Lightwave Technology*, vol. 35, pp. 1211–1221, mar 2017.

[25] "AMP-FL8221-SB-16 Amplifier Datasheet from FiberLabs Inc.."

[26] A. Carena, G. Bosco, V. Curri, Y. Jiang, P. Poggiolini, and F. Forghieri, "Egn model of non-linear fiber propagation," *Opt. Express*, vol. 22, pp. 16335–16362, Jun 2014.

[27] V. Curri, A. Carena, A. Arduino, G. Bosco, P. Poggiolini, A. Nespola, and F. Forghieri, "Design strategies and merit of system parameters for uniform uncompensated links supporting nyquist-wdm transmission," *Journal of Lightwave Technology*, vol. 33, no. 18, pp. 3921–3932, 2015.