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Networking merit of spatial-division and band-division multiplexing: a statistical assessment

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ABSTRACT We compare the networking merit of multiple bands – U-to-O band – by exploiting the installed cables (BDM) vs multiple parallel fibers (SDM). Despite the better transmission performance, SDM only enables 15% more traffic than BDM on the German network and the European network for cardinality up to 5.
Keywords: Transparent optical networks, multi-band transmission, SDM, physical layer aware networking.

1. INTRODUCTION

Spatial-division multiplexing (SDM) has been proposed to increase the traffic allocation keeping low blocking probability in transparent optical networks [1], [2], supposing the availability of dark fibers, or to install new fibers. In case of absence of available dark fibers, an alternative to SDM that does not need new cables is to exploit multiple bands on the deployed fibers, just updating the equipment in amplifiers' sites: the band-division multiplexing (BDM) [3], [4]. BDM aims at enlarging the exploited optical bandwidth up to the range between 1360 nm and 1675 nm by operating the low-loss U, L, C, S, E and O bands, for a total low-loss transmission bandwidth of ∼50 THz. In [3], [4], the point-to-point performance of a BDM line system has been investigated but no networking analyses have been derived. Also, results presented in [4] shows the importance of including stimulated Raman scattering (SRS) effects while evaluating the quality of transmission (QoT) if large bandwidths are used. The generalized Gaussian noise (GGN) model [5]–[7] has been proposed to include SRS in the NLI evaluation and it is used in the present paper to properly abstract the physical layer. 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], [8]–[12] and from the switching and networking point of view [13]–[17]. In this work, we compare the two multiplexing solutions relying on state-of-the-art transceiver technologies, so, we do not consider MMF and MCF implementations of SDM. Therefore, we consider BDM vs MPF as SDM solution. As fiber type, we consider the standard single-mode fiber (SSMF). SDM line systems clearly show a capacity per wavelength advantage with respect to BDM ones [4], that is paid by the need of new fibers. In this work, we estimate the enabled overall network capacity at given blocking probability for BDM and SDM solutions using the statistical network assessment process (SNAP) [4], [18] applied to the German network (Fig. 1a) and to the European network (Fig. 1b). We analyze only full BDM and full SDM upgrades to assess the fundamental limits and giving the bases for the case-by-case evaluation of optimal mixed BDM/SDM solutions.

We compare the progressive upgrade of a transparent optical network exploiting BDM or SDM solutions. The analysis targets to comparing the potentialities of the two solutions from the networking perspective being aware of the physical layer impairments. To this purpose, the SNAP uses an abstraction of the physical layer based on the unique quality-of-transmission (QoT) parameter that is the generalized SNR (GSNR) on lightpaths (LPs), that includes both the accumulation of the ASE noise and of the NLI disturbance in presence of SRS. So, the QoT estimator providing the network abstraction to SNAP for the NLI accumulation, computes the SRS profile and calculate the NLI generation using the GGN model [5]–[7]. For the BDM, we explore the progressive enlargement of the occupied bandwidth from the C-band only, up to the U, L, C, S, E and O bands. In case SDM is used, we progressively enlarge the number of parallel fibers used. By using SNAP, we progressively deploy LPs on the network at the maximum data rate enabled by the GSNR, according to a random traffic demand generation. We compare SDM to BDM for different multiplexing cardinalities (N_{M}), i.e., the multiplicative factor giving the total number of wavelengths (BDM) or the number of parallel fibers (SDM). We evaluate blocking probability vs total allocated traffic normalized with respect to the multiplexing cardinality, thus we estimate the advantage of SDM. As expected, the SDM solution gives more total capacity, but the advantage with respect to BDM solutions is roughly limited to 15% up to multiplexing cardinality of 5 that requires L+C+S bands for BDM. While, it goes up to 30% in case of cardinality of 7 and 12 needing the operation on the bad performing U, E and O bands.

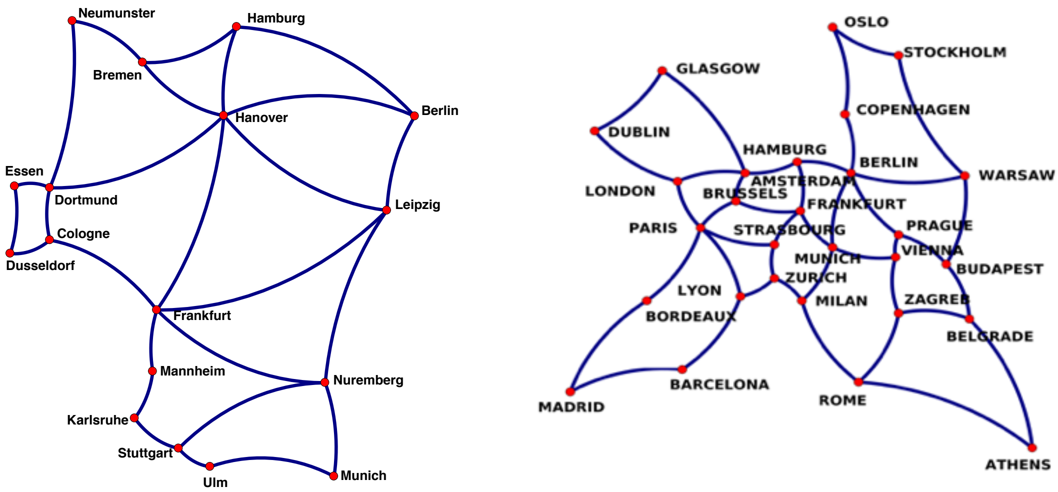
N_{M}		1	3	5	7	12
BDM	N_λ	80	240	400	560	960
	N_{SDM}	1	1	1	1	1
SDM	N_λ	80	80	80	80	80
	N_{SDM}	1	3	5	7	12

(a) Multiplexing cardinality for BDM and SDM.

N_λ	U	L	C	S	E	0
80	-	-	80	-	-	-
240	-	137	80	23	-	-
400	-	137	80	183	-	-
560	108	137	80	183	52	-
960	108	137	80	183	296	156

(b) BDM bandwidth occupation.

TABLE I: Parameters of each simulated scenario.



(a) German network. (b) European network.

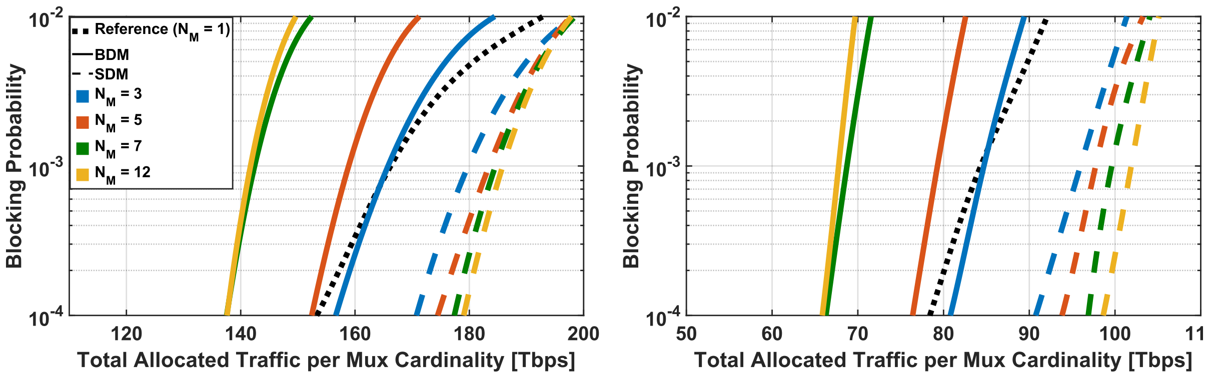
Figure 1: The networks under analysis.

2. Analysis

We investigate on the SDM solution by varying the SDM cardinality (N_{SDM}), i.e., the count of parallel fibers. For BDM, we consider the U, L, C, S, E and O bands, so, the maximum multi-band (MB) bandwidth is of 48 THz. We suppose flex-rate transceiver operating root-raised cosine shaped PM-MQAM signals in the 50 GHz WDM grid. The symbol rate is set to 32 GBaud and the FEC and protocol overhead to 18%. The count of the available WDM slots per band, and the amplifier's noise figure is 6 dB, 6 dB, 5.5 dB, 7 dB, 6 dB and 7 dB for the U, L, C, S, E and O bands respectively. We suppose transceiver being fully flexible in rate, so enabling the deployment of the maximum rate according to the LP GSNR. Fiber propagation parameters are obtained from G.652 fiber standard. The QoT parameter for every line system giving abstraction of the physical layer needed by the SNAP analyses – the GSNR per wavelength – is computed considering the amplified spontaneous emission (ASE) of the optical amplifiers, and the non-linear interference (NLI) due to fiber propagation. The NLI has been evaluated considering the presence of SRS by using the GGN [5]–[7]. The transmitted power has been evaluated according to a per-band locally-optimized-globally-optimized (LOGO) strategy [19] assuming the worst-case of full spectral load and GSNR degradation. We perform our analysis on the German network (Fig. 1a) and on the European network (Fig. 1b) by using SNAP with progressive traffic loading [18]. Traffic connectivity requests are randomly generated assuming any-to-any connections with uniform distribution. The GSNR over routes is calculated by using the open source GNPy [20], [21]. The routes are computed according to a k-th shortest path algorithm. We compute k=15 paths per source-destination pair. Wavelengths and cores are assigned on a best GSNR basis, i.e., the available wavelength providing the highest GSNR among the fibers has been used. For SDM technology we assume core continuity [16] within the ROADM to have a fair comparison in terms of switching matrix complexity at the ROADM node vs N_{M} for the two technologies. Tab. Ia shows the number of wavelengths (N_λ) and the SDM cardinality (N_{SDM}), i.e., the number fibers, used for each technology varying N_{M}: for BDM the number of fibers used is always 1 and N_λ is equal to N_{M} times 80 channels, while, for SDM, N_λ is fixed to 80 channels and N_{SDM} is equal to the multiplexing cardinality. Hence, for SDM, N_λ is set to 80 wavelengths on the C-band, and N_{SDM} changes between 1 and 12. For the BDM solutions, N_{SDM}=1 and N_λ progressively increases from 80, up to 960 according to the bandwidth occupation reported in Tab. Ib. The case N_{SDM}=1, N_λ=80 is the reference scenario both for BDM and SDM. For each case, we generate 7,500 realizations of progressive traffic load and we allocate them according to the routing, space and wavelength assignment algorithm. To do this, we use SNAP with progressive traffic loading [17]. Then, we evaluate the overall allocated traffic in the network, and we normalize it with respect to N_λ and N_{SDM}, to have a fair ranking among the different scenarios. As a networking performance metric of each scenario we present the blocking probability (BP) vs. the normalized total allocated traffic. We also evaluate the multiplexing gain of each upgrade as the ratio between the total allocated traffic using that technology and total allocated traffic for the reference scenario at the same BP.

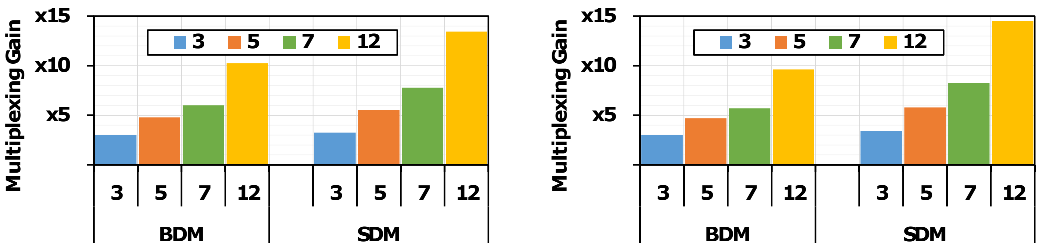
3. Results

Figs. 2 show the BP vs total allocated traffic normalized with respect to the multiplexing cardinality of the reference single-fiber single-band scenario (black dotted line), BDM (solid lines) and SDM (dashed lines) for the German network (Figs . 2a) and for the European network (Figs. 2b). For each technology, the analyzed multiplexing cardinalities are: 3 (blue curves), 5 (red curves), 7 (green curves) and 12 (yellow curve). The SDM



(a) German network. (b) European network.

Figure 2: BP vs. normalized allocated traffic per multiplexing cardinality (N_{M}) varying N_{M} (3 blue, 5 orange, 7 green and 12 yellow) and multiplexing solutions: BDM (solid line) and SDM (dashed) for German network (a) and European network (b. Also reference scenario ($N_{\text{M}} = 1$) is reported (black-dotted curve).



(a) German network. (b) European network.

Figure 3: Multiplexing gain for SDM and BDM for different multiplexing cardinalities (3 blue, 5 orange, 7 green and 12 yellow) at BPs values for the German network (a) and European network (b) at BP=10^{-3}.

solutions shows a general increase of the normalized allocated traffic with respect to the reference scenario by enlarging N_{M}. This happens because, a larger SDM cardinality enables more network flexibility when the line systems are far from the saturation, i.e., at low BPs, since the number of allocated LPs increases with the SDM cardinality. Instead, as the network gets loaded, i.e., at larger BPs, the network flexibility reduces and the SDM curves get closer one to each other and to the reference curve. For both the networks, in BDM, the increase of N_{M} improves the network flexibility as well as N_{SDM} does, but the LPs' GSNR degrades because the NLI generation gets larger and larger, therefore, also LPs' capacity is reduced. The net effect is, in general, a decrease of the network BP vs normalized traffic with increasing multiplexing cardinality. The only exception is when using $N_{\lambda} = 3$ (240 wavelengths) at low BPs, since, in this case, the higher network flexibility overcomes the QoT decrease. It should also be noted that BDM, using 560 and 960 wavelengths at low BP, delivers almost the same performance. This happens because wavelengths with larger GSNR are used first and low performing wavelengths are scarcely occupied, while, increasing the network load, also bands with poor QoT start being employed. The German network is able to allocate more traffic than the European because the second one has longer path with lower QoT. Furthermore the European network is not as well connected as the German network, especially in between Portugal and UK, between Spain and Italy and between UK and the scandinavian countries.

Fig. 3 shows the multiplexing gain for each case, i.e. the ratio between the total traffic of that case and the traffic at the reference case at target BPs of 10^{-3} for thte German network (Fig. 3a) and the European network (Fig. 3b). For both the networks, the multiplexing gain of BDM decreases as the multiplexing cardinality grows of a quantity smaller than the multiplexing cardinality. This because the growth of the bandwidth decreases the QoT of the LPs. Focusing on SDM, the gain is larger than the multiplexing cardinality, because of the larger network flexibility of SDM. In the European network, the gap between SDM and BDM is a little larger then in the German network, because the GSNR penalty due to the bandwidth enlargement is higher and because the European network gains more from SDM flexibility. In both the networks, for $N_{\text{M}} \leq 5$ the multiplexing gain is almost equal for SDM and BDM, while the gap between SDM and BDM start being relevant for larger values of N_{M}.

4. Conclusion

We compared the networking merit of SDM solutions, implemented as MPF on the C-band, to BDM, with the purpose to enable a proper cost-to-benefit evaluation of the SDM upgrades, in case of absence of dark fibers.

The two multiplexing technologies show opposite trends at the enlarging of both N_{M} and the target blocking probability. BDM, in fact, delivers a less effective improvement by enlarging N_{M} and BP. On the contrary, SDM gets better gains at lower BP values and larger N_{M}. As a general trend, SDM performs better than BDM because of the better QoT of SDM line systems, but the advantage with respect to BDM solutions is roughly limited to 15% up to multiplexing cardinality of 5 that requires U+L+C+S+E bands for BDM. While, it goes up to 30% in case of cardinality of 7 and 12 needing the operations on the bad performing O band.So, BDM appears as a feasible solution for multiplexing implementation up to a cardinality of 5, and in general avoiding the exploiting of the bad performing O-band. This analysis, integrated with techno-economic studies, can be used to plan upgrade strategies, trading-off costs and benefits. Mixed BDM/SDM solutions will be considered in further investigations.

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