Impact of Network Physical Topology on Planning Multiband Optical Networks Aware of Physical Layer Impairments

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ABSTRACT

A multiband planning tool is developed in this work to solve the routing, modulation format and spectrum assignment problem and is used to discuss the influence of the network physical topology on several parameters considering four optical network topologies, different target bit error rates (BERs) and transmission capacities.

We conclude that, in non-regenerated optical links, the length of the network links has a direct impact on the percentage of blocked demands leading to a higher assignment of lower modulation formats. This effect is particularly pronounced when considering lower BERs, higher information bit rates and full mesh logical topologies.

Keywords: Flexible grid, multiband transmission, optical networks, physical layer impairments, RMSA.

1. INTRODUCTION

The need for more capacity in the optical transport network, due to, for example, the growth of cloud-based and 5G applications demands, nowadays, new transport solutions [1]. The implementation of spatial division multiplexing techniques in the optical domain [2] is seen as a long term solution, whereas the exploitation of the unused bands on the widely deployed G.652.D fibers, called multiband (MB) solution, is seen as a near term solution [2].

Efficient use of the capacity increase provided by MB solutions, in comparison to C-band only systems, e.g. [2], requires well-designed planning tools to optimize transport capacity and achieve cost-effectiveness. This optimization typically involves a two-step procedure, known as routing, modulation format, and spectrum assignment (RMSA) problem. Some authors, [2], [3] have already developed, both heuristic and integer linear programming tools for solving this RMSA problem.

In this work, a C+L MB heuristic planning tool is designed for solving RMSA problems. This tool is used in four network topologies (COST 239, NSFNET, UBN and CONUS 30) considering three different bit rates, 100, 200 and 400 Gbps. A detailed analysis of the RMSA results is performed, in particular the percentage of blocked demands, the number of frequency slots (FSs) used and the usage of the different types of modulation formats are discussed. Moreover, we discuss the influence of the network physical topology on the various parameters analyzed, like the number of paths that utilize the most used link, an analysis that has not been done in [2] and [3], that consider only a single network, the German network in [2] and the British network in [3].

This work is organized as follows. Section 2 presents the MB planning tool used to solve the RMSA problem aware of physical layer impairments (PLIs). Section 3 shows the RMSA results for several networks, and discusses them, considering requests with different bit rates. In section 4, the conclusions of this work are drawn.

2. MULTIBAND NETWORK PLANNING TOOL

The C+L MB network simulator was developed in Matlab and has two main steps in order to solve the RMSA problem, first routing and modulation format assignment and, then, spectrum assignment. The simulator inputs are the network physical topology, the traffic matrix, the number of candidate paths, the available bands, the total number of FSs per band, the bit error rate (BER) and the information bit rate.

The first step consists in computing the list of the k-th candidate paths for each demand (or request). These paths are computed with the Yen's k-shortest path algorithm. After, the optical signal-to-noise ratio (OSNR) of each candidate path is calculated as in [4] considering the amplified spontaneous emission noise along the path and the nonlinear interference (NLI) noise with modulation format correction formulation [5]. The following simplifications are assumed in the OSNR calculation: 1) the NLI noise at the end of a link is calculated considering that all FSs are being used in the C+L band; 2) the NLI noise accumulates incoherently [5], which means that the NLI noise is calculated at the end of each link independently of the NLI noises calculated for the other links of a given path; 3) the channel launch power is optimized for the longest candidate path in the network [3] for each modulation format and is used in all channels across the network that use that specific modulation format; 4) the NLI noise and corresponding OSNR are calculated for the center channel, since there is no a priori knowledge of how the spectrum will be assigned. Then, it is checked, starting from the highest to the lowest modulation format (64-Quadrature-amplitude modulation (QAM), 16-QAM and Quaternary phase-shift keying (QPSK)), if the required OSNR (ROSNR) is achieved. If none of the modulation formats meets the ROSNR, the corresponding candidate path is not used. Moreover, if no candidate paths for the demand satisfy the ROSNR, that demand is blocked. After calculating the OSNR for all demands and candidate paths and assigning the modulation format, the paths are sorted based on the OSNR in descending order, for each demand.

In the second step, the path list just built is used by the spectrum assignment algorithm to assign the FSs using the First-Fit (FF) algorithm. It starts with the candidate path with the highest OSNR, and, if necessary, tries different candidate paths in OSNR descending order. As we are considering a flexible grid scenario, the FSs assigned to each demand must be contiguous, and must be the same in every link of a specific optical path [2]. The number of FSs allocated for each demand depends on the symbol rate and on the modulation format used in the candidate path [2]. Therefore, depending on the modulation format, the FF algorithm tries to assign the corresponding FSs. If those FSs cannot be assigned in the whole C+L band, then another candidate path from the list is chosen. If the FSs are not assigned to any of the candidate paths of a specific demand, then the demand is blocked.

3. RESULTS AND DISCUSSION

In this section, we are going to use the MB planning tool presented in section 2 in several network topologies scenarios - COST 239, NSFNET, UBN and CONUS 30 [6] - considering a static traffic matrix and a full mesh logical topology. In particular, we solve the RMSA problem for each one of the network topologies studied considering three BERs (4×10^{-2}, 10^{-2} and 10^{-3}) for 100, 200, and 400 Gbps requests. A detailed analysis for the 100 Gbps requests case is given in subsection 3.1, whereas in subsection 3.2, the 200 and 400 Gbps scenarios are considered.

Table 1 presents some physical (number of nodes, number of links, average node degree, average link length) and logical (number of demand requests for full mesh topology) parameters of the network topologies considered. As can be observed in Table 1, the network with more nodes is the CONUS 30, and therefore, this is the network that has more traffic demands, while the network with the longest links in average is the NSFNET network. The network that presents nodes with a higher average degree is the COST 239, which is the smallest size network. Table 2 presents the ROSNR for the three BERs and for three modulation formats considered in this study - QPSK, 16-QAM and 64-QAM [2]. Table 3 shows the system and network parameters considered.

Table 1: Physical and logical features of the network topologies.

Network	#Demands	#Nodes	#Links	Average node degree	Average link length [km]
COST 239	55	11	26	4.73	463
NSFNET	91	14	21	3	1081
UBN	276	24	43	3.58	996
CONUS 30	435	30	36	2.40	696

Table 2: ROSNR for the different BERs.

BER	ROSNR [dB]		
	64-QAM	16-QAM	QPSK
4×10^{-2}	18.9	13.3	7.1
10^{-2}	21.9	16.1	9.5
10^{-3}	24.8	18.6	12

Table 3: System parameters used in the RMSA problem.

Parameters	Values
Number of candidate paths k	5
Total number of FSs in the C+L band	862
Frequency slot width	12.5 GHz
Amplifier maximum gain G_{max}	25 dB
Fiber attenuation coefficient α	0.25 dB/km
Fiber effective area A_{eff}	80 μm^2
Dispersion $D_{\lambda 0}$	17 ps/nm/km
Dispersion slope S_0	67 fs/nm^2/km
Reference wavelength λ_0	1550 nm
Raman gain slope C_r	0.028 1/W/km/THz
Nonlinear refractive index $\overline{n_2}$	2.6×10^{-20} m^2/W
Coherent factor ε	0

Table 4: System parameters used to calculate the OSNR for 100 Gbps.

Parameters	64-QAM	16-QAM	QPSK
Channel Spacing	25 GHz	37.5 GHz	50 GHz
#FSs allocated	2	3	4

3.1 100 Gbps requests scenario

In this subsection, the 100 Gbps requests scenario is analyzed. Table 4 shows the channel spacing and the required number of FSs that depend on the chosen modulation format, calculated as in [2], including one FS used as a guard-band. The solution for the RMSA problem considering 100 Gbps requests is given in Table 5 for the four network topologies. In particular, Table 5 shows the number of blocked demands, the number of allocated FSs, the highest and lowest OSNR values, the path with the longest distance served, the number of unused links and the usage of the different modulation formats in the whole network. Furthermore, it has been also assessed that the results presented in Table 5 do not depend much on the requests ordering strategy.

As observed in Table 5, the COST 239 network is the only network that successfully serves all demands for the three BERs scenarios, i.e., the blocked demands percentage is zero. In this network, as the BER decreases, slightly more FSs are allocated, since lower BERs demand higher ROSNRs (Table 2), resulting on the assignment of lower modulation formats that require more FSs. So, in this network, more energy-efficient and cheaper transponders (with lower BERs) can be used [1], while still serving all demands and maintaining the quality-of-service. For the other three networks, the number of FSs allocated decreases for lower BERs, since the number of blocked demands increases, being the QPSK format predominant in the successful demands. In the CONUS 30 and UBN

Table 5: RMSA solution for the COST 239, NSFNET, UBN, and CONUS 30 topologies for 100 Gbps requests.

Network	BER	#Blocked demands	#FSs allocated	Highest OSNR	Lowest OSNR	Longest path served	Higher #paths assigned to link	Higher #FSs allocated to link	#Unused links	#Paths using 64-QAM format	#Paths using 16-QAM format	#Paths using QPSK format
COST 239	4×10^{-2}	0 (0%)	50 (5.8%)	24.0 dB (64-QAM)	14.1 dB (16-QAM)	1452 km	18 (32.7%)	50 (5.8%)	4	20 (36.4%)	35 (63.6%)	0 (0%)
	10^{-2}	0 (0%)	62 (7.2%)	24.0 dB (64-QAM)	12.4 dB (QPSK)	1452 km	18 (32.7%)	62 (7.2%)	4	10 (10.9%)	32 (58.2%)	17 (30.9%)
	10^{-3}	0 (0%)	70 (8.1%)	23.6 dB (16-QAM)	12.4 dB (QPSK)	1452 km	18 (32.7%)	68 (7.9%)	4	0 (0%)	20 (36.4%)	35 (63.6%)
NSFNET	4×10^{-2}	2 (2.2%)	114 (13.2%)	22.8 dB (64-QAM)	7.2 dB (QPSK)	4467 km	30 (33.0%)	113 (13.1%)	-	4 (4.5 %)	28 (31.5 %)	57 (64 %)
	10^{-2}	32 (35.2%)	71 (8.2%)	22.8 dB (64-QAM)	9.6 dB (QPSK)	2885 km	18 (19.8%)	71 (8.2%)	1	1 (1.7 %)	12 (20.3 %)	46 (78 %)
	10^{-3}	62 (68.1%)	28 (3.2%)	22.6 dB (16-QAM)	12.3 dB (QPSK)	1545 km	6 (6.6%)	15 (1.7%)	6	0 (0%)	4 (13.8 %)	25 (86.2 %)
UBN	4×10^{-2}	66 (23.9%)	133 (15.4%)	22.6 dB (64-QAM)	7.1 dB (QPSK)	4150 km	33 (12.0%)	131 (15.2%)	3	2 (1 %)	46 (21.9 %)	162 (77.1 %)
	10^{-2}	168 (60.9%)	44 (5.1%)	22.6 dB (64-QAM)	9.5 dB (QPSK)	2300 km	10 (3.6%)	39 (4.5%)	3	1 (0.9 %)	9 (8.3 %)	98 (90.7 %)
	10^{-3}	232 (84.1%)	16 (1.9%)	22.5 dB (16-QAM)	12.0 dB (QPSK)	1300 km	4 (1.4%)	15 (1.7%)	5	0 (0%)	2 (4.5 %)	42 (95.5 %)
CONUS 30	4×10^{-2}	91 (20.9%)	350 (40.6%)	27.9 dB (64-QAM)	7.6 dB (QPSK)	4850 km	75 (17.2%)	289 (33.5%)	-	19 (5.5 %)	73 (21.2 %)	252 (73.3 %)
	10^{-2}	249 (57.2%)	156 (18.1%)	27.9 dB (64-QAM)	9.5 dB (QPSK)	2835 km	35 (8.0%)	132 (15.3%)	-	7 (3.8 %)	35 (18.8 %)	144 (77.4 %)
	10^{-3}	350 (80.5%)	73 (8.5%)	27.9 dB (64-QAM)	12.0 dB (QPSK)	1602 km	19 (4.4%)	71 (8.23%)	3	2 (2.4 %)	17 (20 %)	66 (77.6 %)

networks, more than half of the demands are blocked for BER=10^{-2} or lower. The UBN has the higher number of blocked demands, with a maximum of blocked demands of 84% for the lowest BER. Also, it is observed in Table 5, that none of the networks use more than 40% of the MB spectrum, despite the existence of blocked demands for NSFNET, UBN and CONUS 30 topologies. The reason for blocking the demands is the insufficient OSNR, and not the unavailability of FSs. The maximum spectrum allocated is for the CONUS 30 network with 40.6%, corresponding to 350 FSs of the 862 available in the C+L MB. This network is the only one that assigns FSs in the L-band using only 5 FSs in this band.

The highest OSNR presented in Table 5 is always obtained for the same demand, independently of the BER, whereas the lowest OSNR can be reached with different demands. Moreover, the highest OSNR is obtained in all four networks in the direct path that uses the shortest link. On the other hand, the lowest OSNR is obtained in one of the longest paths, that has not been blocked due to not fulfilling the ROSNR. In the three larger networks, the path reach is similar for all BERs, the maximum distance with BER=4×10^{-2} is $\sim$4000 km, for BER=10^{-2} is $\sim$2500 km, and $\sim$1500 km for BER=10^{-3}. This maximum reach limits the number of hops in networks with longer links, like in the UBN where the average link length is 996 km (Table 1). This means that, in this network, for BER=4×10^{-2}, where the maximum average range is 4000 km, the source and end nodes can have at most four links between them for a demand to be served, without resorting to the more expensive regeneration solution [4].

We have tried a more realistic traffic demand scenario for the UBN, considering that only demands within a maximum reach achievable without regeneration, of 4000 km for BER=4×10^{-2}, 2300 km for BER=10^{-2} and 1300 km when BER=10^{-3} are potentially served. In this scenario, the blocked demand percentage is 1.97% (of a total of 203 demands) for BER=4×10^{-2} and for the other two BERs there are no blocked demands, for a total of 108 (BER=10^{-2}) and 44 (BER=10^{-3}) demands. These percentages are in agreement with the 1% blocked demands reference [3]. For the CONUS 30 and NSFNET networks, it was also checked that the blocked demand percentage is below the 1% reference scenario considering this more realistic traffic scenario.

From Table 5, it is observed that, in general, the number of paths utilized in the most used link is higher for higher BERs, since other paths with lower OSNRs tend to be blocked when the BER is lower. The link with the most paths assigned, in general, is also the one with the most FSs allocated. Generally, the number of unused links increases for lower BERs, since the unused links are some of the longest in the network, experience higher OSNR degradation and do not meet the ROSNR. In networks with higher average node degree, like the COST 239 and UBN networks, some links are never used, since these links lead to a severe PLIs performance degradation, but as these nodes are more interconnected, the demands can be routed using a different link. In contrast, the CONUS 30 network, since it has the lowest average node degree, only has unused links for the lowest BER.

Finally, in Table 5, it can be observed that the QPSK is the most used format, except for the COST 239 network for BER=4×10^{-2} and BER=10^{-2}, where the 16-QAM is the most used modulation format. The only scenario where the QPSK format is not assigned in the COST 239 network occurs when BER=4×10^{-2}, which is also the scenario where the 64-QAM format is assigned more often (36.4% of the assigned optical paths). This happens since this network has an average shorter link length that induces less PLI degradation and also due to the higher average node degree. The CONUS 30 network is the only network where the 64-QAM format is assigned when the BER=10^{-3}. In this case, the two paths with 64-QAM are unamplified direct links.

3.2 Higher than 100 Gbps requests scenario

In this subsection, the RMSA tool is used for studying the 200 and 400 Gbps requests scenarios. The channel spacing (and the FSs allocated) for the 200 Gbps for 64-QAM is 37.5 GHz (3 FSs), for 16-QAM is 50 GHz (4 FSs) and for QPSK is 87.5 GHz (7 FSs). For 400 Gbps, the channel spacing (and the FSs allocated) for 64-QAM is 62.5 GHz (5 FSs), for 16-QAM is 87.5 GHz (7 FSs) and for QPSK is 150 GHz (12 FSs).

In Fig. 1, the blocked demands percentage for three BERs, three bit rates (100, 200 and 400 Gbps) and four network topologies (COST 239, NSFNET, UBN and CONUS 30) is represented. As shown in Fig. 1, the percentage of blocked demands increases for higher information bit rates and lower BERs. The highest percentage increase (14.3%) of blocked demands occurs for the NSFNET network, when BER=4×10^{-2}, and we replace the 100 Gbps requests by 200 Gbps requests. As the maximum reach is $\sim$3000 km for the 200 Gbps requests (1000 km less than with 100 Gbps requests), the distance between nodes is limited. So, paths with longer distances are blocked. From the four topologies analyzed, the UBN has the highest percentage of blocked demands - 92% for BER=10^{-3} and 400 Gbps requests- since the maximum reach served in this network is 959 km, which is shorter than the average link length (996 km, see Table 1). This is also the scenario where the COST 239 network exhibits a non-zero blocked demand percentage (9.1%), due to the shorter path reach.

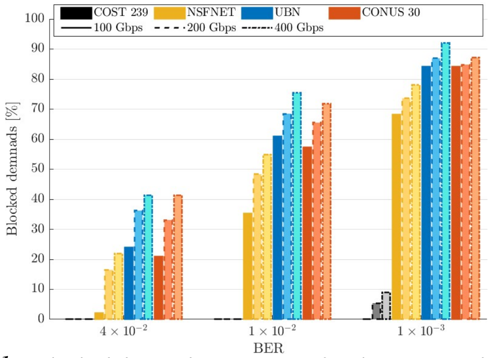

Fig. 1: Blocked demands percentage for three BERs, three bit rate request scenarios and four network topologies.

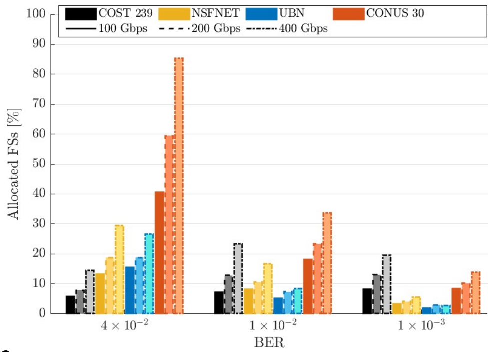

Fig. 2: Allocated FSs percentage for three BERs, three bit rate request scenarios and four network topologies.

In Fig. 2, the allocated FSs percentage for three BERs, considering three bit rate request scenarios (100, 200 and 400 Gbps) and four network topologies (COST 239, NSFNET, UBN and CONUS 30) is represented. From Fig. 2, it can be observed that the higher the information bit rate, more percentage of FSs is allocated as the BER increases, even though more demands are blocked than in the 100 Gbps requests (Fig. 1), since these information bit rates require more allocated FSs. Only for the COST 239 network, the percentage of FSs allocated increases from BER=4×10^{-2} to BER=10^{-3} and then decreases from BER=10^{-2} to 10^{-3}, since, for this last scenario, the percentage of demands served is no longer 100%, as observed in Fig. 1. Likewise, for 100 Gbps, the CONUS 30 topology continues to be the only network that assigns spectrum in the L-band. For BER=4×10^{-2} and 400 Gbps requests, 85% of the available MB spectrum is assigned, which corresponds to 735 FSs of the 862 available.

4. CONCLUSIONS

In this work, we studied the influence of the network physical topology on the planning of MB C+L optical networks. For that, we have developed a RMSA tool to explore several network parameters. The RMSA tool has been applied to four optical networks, considering different target BERs and bit rates.

For 100 Gbps, in networks with more nodes and longer links, as the BER lowers, the number of blocked demands increases, resulting in fewer allocated FSs and lower order modulation formats. The UBN, which is the network studied with more links, for the BER=10^{-3}, has a higher percentage of blocked demands and the QPSK modulation format is assigned to 95.5% of paths. In contrast, the COST 239 network, with shorter links and fewer nodes, can potentially use more cost-effective and energy-efficient transponders, as it can serve all demands for the same BER using QPSK modulation format in 63.6% of the paths. Higher bit rates lead to an increased blocked demands percentage, with a 14.3% maximum increase for the NSFNET which is the network with longer links.

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