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Optimized Translucent S-band Transmission in Multi-Band Optical Networks

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Abstract *In multi-band optical networks using the C-, L-, and S-bands for data transmission, the latter provides the poorest Quality of Transmission (QoT). We have evaluated an optimized regenerator placement strategy focusing on the S-band, demonstrating the possibility of increasing the network capacity in a cost-effective manner.*

Introduction

Network traffic demands continue to grow and tackling this problem, as well as limiting the overall power consumption of telecommunication networks[1], requires the deployment of high capacity and power-efficient transceivers (TRXs). Network operators have exploited spatial division multiplexing (SDM) and band division multiplexing (BDM)[2] upgrades to increase the capacity of their Wavelength-Division Multiplexing (WDM) systems operating in the C-band only, with a total bandwidth of approximately 4.8 THz. BDM upgrades aim to utilize a wider region of the low-loss single-mode bands of optical fibers, namely of the widely-deployed ITU-T G.652.D fiber, which has a low-loss bandwidth exceeding 50 THz[3]–[6]. BDM may use already deployed optical fiber, which makes it a cost-effective way of increasing network capacity[3]. On the contrary, SDM requires the utilization of multiple fibers to increase network capacity. Additionally, the use of traffic grooming may be enforced, increasing the network capacity by maximizing the use of already deployed TRXs[7]. The network capacity may also be increased by doing a translucent optical network design, i.e., by regenerating the optical signal in intermediate nodes between the source and destination, therefore enabling the use of higher capacity modulation formats. Power optimization in translucent optical networks has been investigated by Kanj *et. al*, which extended the generalized multiprotocol label switching (GMPLS) to support optical regeneration[8]. In order to implement a greener solution, TRX power consumption investigations have been performed, for example in[9], where the authors showed that CMOS node size decreases every two years corresponding to the scale of Intel's integrated circuit. The Optical Internetworking Forum (OIF) is also seeking power efficient TRX solutions – The implementation agreement (IA) for the application of coherent techniques in a pluggable form[10] is a clear example of such a case. Additionally, one of the latest IAs defined the 400ZR, which is a power- and cost-effective coherent interface solution supporting 400 Gbps in a single channel.

Each optical fiber transmission band has a different QoT, with the S-band exhibiting the worst performance when compared to the C- and L-bands. In this work, we propose the use of optical signal regeneration in the S-band to reach similar optical performance in three considered transmission bands (C-, L- and S-bands). This approach impacts not only the deployed traffic, but also the cost and energy consumption of optical networks.

This paper is organized as follows. In section Methodology, the evaluation of the QoT for a single 70km fiber span and the TRX characteristics are discussed. Section Data and Network Analysis describes the details of regenerator assignment for two scenarios. The main results are presented and discussed in section Results. The main conclusions are outlined in section Conclusions.

Methodology

In this work, the QoT of a lightpath (LP) is calculated considering two Gaussian disturbances – the ASE noise and nonlinear interference (NLI), introduced by the amplifiers and optical fiber propagation, respectively. The generalized signal-to-noise ratio (GSNR)[4] approach is used to this end. Following a disaggregated abstraction of the physical layer[11],[12], the total LP GSNR is computed based on the GSNR at the end of each individual fiber span, which is calculated using the GNPy open source library[13]. For the C- and L-bands, commercial Erbium-doped fiber amplifiers (EDFAs)[14] are considered, whereas bench-

Tab. 1: TRX modelling variables.

TRX	Mod. format	Data rate [Gb/s]	CD tolerance [ps/nm]	P[W]	RGSNR [dB]
Flex	16QAM	400	20,000	20	21
	8QAM	300	40,000	18	18
	QPSK	200	50,000	16	14
	QPSK	100	100,000	13	11

top Thulium-doped fiber amplifiers (TDFAs)[15] are considered for the S-band. We assume that fiber losses are fully compensated at the end of each span. Fig. 1 shows the GSNR (for the C-, L-, and S-bands) after transmission along a single span of 70 km of ITU-T G.652D fiber. A 500 GHz guard band is imposed between the C-, L- and S-bands (black dashed lines in Fig. 1). We consider the transmission 64 channels (64Gbaud) in each band, with a 75 GHz frequency slot allocated to each channel. The LOGO approach[16] is used to estimate the optimum launch power per channel of -0.4, -0.2 and 0.6 dBm for the C-, L- and S-bands, respectively. In this case, the GSNR in the S-band is about 4 dB smaller than in the C- and L-bands.

Table 1 presents the TRX characteristics, supporting three different dual-polarization modulation formats considered in our work; 16QAM, 8QAM, and QPSK (bit rate, maximum allowed chromatic dispersion (CD), consumed power and required GSNR (RGSNR)). We assume the same RGSNR in back-to-back operation (B2B) for each modulation format as indicated in[17].

Data and Network Analysis

We focus upon optimization of a translucent approach in the S-band targeting at: a) attaining similar capacity in S-band as in the C-band, which we refer to as S-band with limitations and b) achieving the maximum capacity in S-band, which we refer to as S-band without limitations. Both network designs are compared with the fully transparent reference approach, denoted in the figures as transparent CLS.

A transparent design is always assumed for the C- and L-bands. As an example of the implementation of the proposed approaches, let's assume that 8QAM and QPSK modulation formats are supported by a LP in the C- and S-bands, respectively. In this case, regenerators are assigned in the S-band to improve the overall QoT. In the S-band with limitations scenario, the minimum number of optical regenerators required to enable 8QAM transmission are deployed in the intermediate nodes. Conversely, in the S-band without limitations scenario, the minimum number of regenerators required to enable 16QAM transmission (the most efficient modulation format used by the TRX) are deployed. Concerning the regenerator assignment, if the maximum LP capacity is different in the C- and S-bands, the algorithm evaluates all possible regenerator placement options with respect to the GSNR and the CD threshold (see Table 1) of each LP. Then, based on the scenario, the best option is selected. This regenerator assignment algorithm considers the least possible number of regenerators thus preventing unnecessary increase of cost and power consumption.

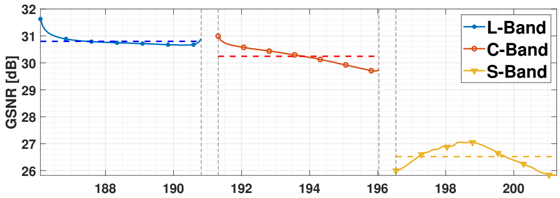


Fig. 1: GSNR profile for a single span of 70 km for L-, C-, and S-bands.

The statistical network assessment process (SNAP)[18] is used to analyze the blocking probability vs. allocated traffic for the USNET network topology[19] by progressively loading the network with 100 Gbps connection requests.

Results

Fig. 2 shows the total allocated traffic for different blocking probabilities (BP) forthe three investigated scenarios: the transparent CLS reference scenario, S-band with limitations and S-band without limitations. Firstly, it is clear that the fully transparent network design (solid blue) leads to the highest blocking probability. As an example, a BP of 1 % is reached at a network capacity of approximately 200 Tbps. In the S-band with limitations scenario (red dashed line), there is a small capacity increase of almost 5 Tbps for the same BP. Finally, for the S-band without limitations scenario (dashed black curve) the total capacity is increased by about 15 Tbps for the same BP.

Figure 3 provides more details on the poten-

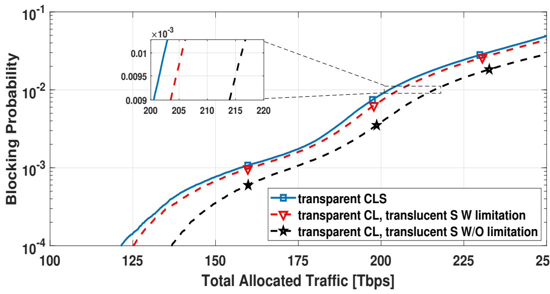
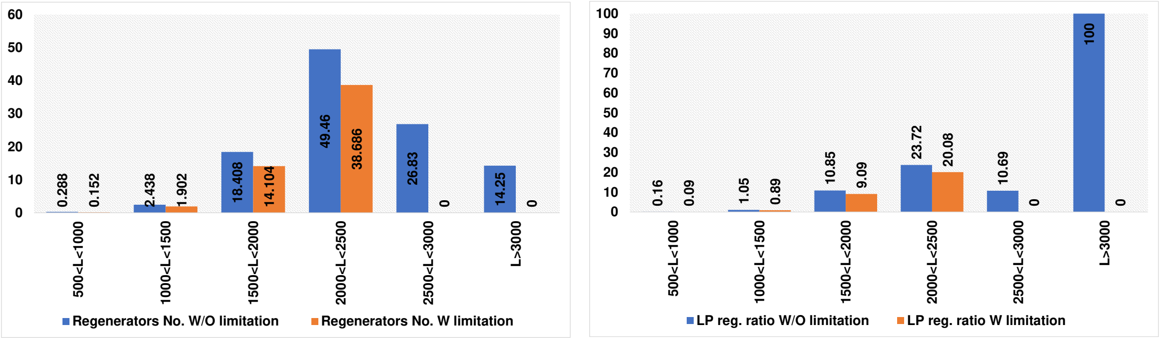


Fig. 2: Blocking probability versus total allocated traffic for the USNET topology.



(a)

Fig. 3: The (a) regenerators quantity, and (b) LP regenerator assignment ratio, for a range of different route lengths within the USNET topology.

tial of the proposed approach. Fig. 3a shows the number of regenerators used in both S-band scenarios for different lightpath route distances. Considering first the S-band with limitations scenario, the total average number of regenerators used in the network is approximately 54, with about 38 lightpath routes in the range of 2000-2500 km. However, in the S-band without limitations scenario, the number of regenerators is approximately 111, with a maximum of approximately 50 corresponding to distances in the 2000-2500 km range. In this scenario, additional regenerators are used for LP longer than 2500 km to enable 16QAM modulation format.

The ratio between the number of LPs with and without regenerators is also shown for both network designs in Fig.3b. This figure shows that, when designing a translucent S-band with limitations, as the LP length increases, so does the number of required regenerators until only QPSK is suported in C-band. In this case, and assuming this modulation format is also supported in S-band, no optical regenerators are required. Lightpaths being assigned regenerators for route lengths in 1000-1500, 1500-2000, and 2000-2500 km ranges, which are 0.9%, 9%, and 20% of total LPs, are a clear example of this. On the other hand, for the S-band without limitations case, we expect that the ratio of LP using regenerators increases proportionally to the LP route length; we find that this is the case, except for LPs in the 2500-3000km range, where the ratio of assigned regenerators drops to approximately 10 %. The reason for this drop is that, in this topological configuration and for several node pairs, the first option for traffic assignment is a route within this range, meaning that the majority of LPs are still assigned frequencies within the C- and L-bands. This condition greatly reduces the number of S-band samples within this range, correspondingly reducing the number of LP which may be assigned regenerators.

In Table. 2 we provide the total capacity, energy consumption and TRX number (normalized with respect to the transparent reference scenario), along with the average number of LPs requiring regenerators. These results show that, for both scenarios, the average energy consumption only marginally increases, along with a progressive but small increase in the number of required TRXs. Overall, we remark that, if there are strict power consumption limitations within the network, placing regenerators within the S-band with limitations can provide some capacity enhancement, which can be increased beyond the C+L reference level, if these limitations are not imposed.

Tab. 2: Multiplicative factor of capacity, energy consumption, TRX point-to-point number, and number of LPs assigned regenerators for the three scenarios under investigation.

	Capacity	Energy Consumption	TRX	Avg. # LPs with regenerators
Transparent CLS	1	1	1	0
Transparent CL, S band W limitation	1.01	1.00	1.04	54.84
Transparent CL, S band W/O limitation	1.06	1.01	1.10	111.67

Conclusions

We proposed two network design strategies to increase the capacity of the S-band. We showed that deploying regeneration for lightpaths in the S-band is a cost-effective way to increase network capacity without significantly increasing the overall energy consumption and cost.

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