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

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Abstract *For multi-band optical networks that encompass the C-, L-, and S-bands, the latter provides the poorest Quality of Transmission (QoT). We have evaluated optimization of the S-band in a multi-band optical network scenario, demonstrating the possibility of increasing overall 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.

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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-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 to attain the same levels of the C- and L- bands for two scenarios: a) Attaining the same level as the C-band for the S-band, (S-band with limitations) and b) Finding the maximum achievable capacity of this band (S-band without limitations). Moreover, both network designs are compared with the fully transparent reference network, denoted in the figures as transparent CLS.

In all scenarios we considered transparent design for the C- and L-bands, however for the first scenario the capacity of the LPs in each frequency were calculated and then compared with the same frequency order on the C-band. If 8QAM and QPSK modulation formats were supported for a LP in the C- and S-bands, respectively, regenerators were assigned to the S-band with limitations scenario in the intermediate nodes to increase the minimum required QoT to allow 8QAM transmission. Conversely, in the S-band without limitations scenario, regenerators were assigned in the intermediate nodes to increase the minimum required QoT to allow 16QAM transmission – the most efficient modulation format used by the TRX. Concerning regenerator assignment, if the LP capacity is different between the C- and S-bands, the algorithm acquires all possible regenerator places with respect to the GSNR and the CD threshold (see Table 1) of each LP. Then, based on the scenario, the best choice with proper modulation formats is selected. This regenerator assignment algorithm considers the least possible number of regenerators preventing an increase in cost and power consumption.

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) for all three investigated scenarios: the transparent CLS reference scenario, S-band with limitations and S-band without limitation. Firstly, it is visible that the BP is greatest for the fully transparent network scenario (solid blue), for example having a capacity of approximately 200 Tbps for a BP of 1 %. Considering next the S-band with limitation scenario (red dashed line), there was a small capacity increase of slightly under 5Tbps for the same BP. Finally, the S-band without lim-

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

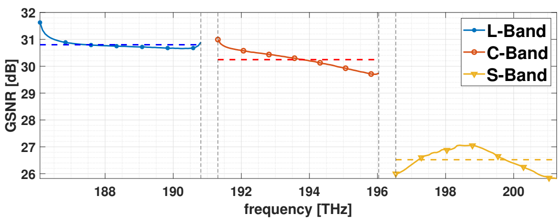


Fig. 1: GSNR profile for a single span of 70 km for L-, C-, and S-bands.

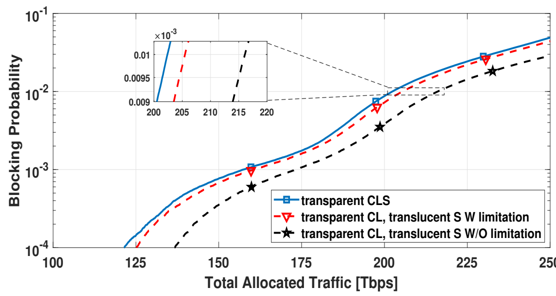
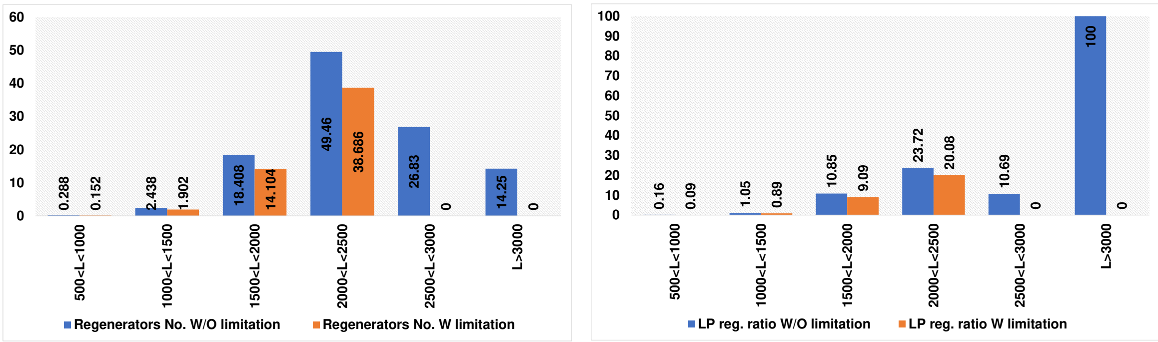


Fig. 2: Blocking probability versus total allocated traffic for the USNET topology.



(a)

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

itation scenario (dashed black curve) shows that performing signal regeneration leads to a total capacity increase of approximately 15 Tbps.

To analyze these results in detail we also present Fig. 3. 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 this network is approximately 54, along with maximum of 38 2000-2500 km lightpath route length. However, when considering the S-band without limitations, the number of regenerators is approximately 111, with a maximum of approximately 50 corresponding to distances in the 2000-2500 km range. Additionally, in this scenario regenerators are used for lengths of more than 2500 km, which is due to the increase of LP capacity not being limited.

The ratio between the number of LPs with and without regenerators is also shown for both network designs in Fig.3b. This figure demonstrates that when designing a translucent S-band with limitations, the increase of LP length requires using regenerators in more LPs. Lightpaths being assigned regenerators for route lengths in 1000-1500, 1500-2000, and 2000-2500 km, which are 0.9%, 9%, and 20% of total LPs per range, are a clear example of this. Moreover, in this scenario LPs with longer reaches do not require assignment of regenerators. On the other hand, for the S-band without limitations case, we expect that the ratio of LP using regenerators increases proportionally to LP route length; we find that this is the case, except for LPs within 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, for numerous node pairs, the first option for assignment is a route within this range, meaning that the majority of LPs are assigned within the C and L bands. This greatly reduces the number of S-band samples within this range, correspondingly reducing the number of LP which may be assigned regenerators out of all LPs.

In Table. 2 we provide the values of 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 in question, we show that placing regenerators within the S-band with limitations can provide a small capacity increase, 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 optimize the behavior of the S-band. We showed that deploying regeneration for S-band lightpaths is a cost-effective way to increase network capacity without significantly increasing the overall energy consumption and cost.

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