Capacity and Energy Consumption Comparison in Translucent versus Transparent Multi-band Designs

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***Abstract*—A comparison of the capacity and energy consumption in translucent and transparent multi-band (from S- to U-band) optical network designs is reported. We show that enabling more bands in the transparent network design leads to higher capacity than exploring optical signal regeneration (translucent network design) in already deployed bands. Moreover, the results suggest that both the S- and U-band lead to similar capacity improvement in a transparent network design. However, we find out that deploying a C+L+S-band multi-band network is slightly more power-efficient than deploying the equivalent C+L+U-band scenario.**

***Index Terms*—Optical fiber communication, multi-band, transmission modeling, network simulation, energy consumption**

I. Introduction

Optical networks traffic demand is growing every year. Consequently, increasing the Wavelength Division Multiplexing (WDM) systems capacity, which nowadays usually exploit the C-band only (with a bandwidth of 4.8 THz [1]), is becoming increasingly more important. Multi-band transmission (MBT), which exploits the wide single-mode low-loss frequency range of already deployed fibers has been proposed with this objective [2]. Alternatively, a translucent network design (i.e., doing the regeneration of the optical signal in the intermediate nodes) can also be explored as a solution to cope with this traffic demand [3]. When exploring a translucent network design, the lightpaths (LPs) can be split into shorter LP segments that can support the transmission of higher spectral efficient signal formats and, consequently, increase the network capacity [4]. The deployment of elastic transceivers (TRX) is also important in modern optical networks, as it enables using different modulation formats based on the quality of transmission (QoT) of the LP. Although increasing the optical networks capacity is fundamental, we cannot neglect the impact of each approach on the total power consumption. To this end, the use of high capacity but also power-efficient TRXs is critical [5]. The 400ZR, a recent implementation agreement (IA) proposed by the Optical Internetworking Forum (OIF), addresses this issue by promoting a pluggable coherent TRX solution [6]. This TRX, which supports up to 400 Gb/s at a symbol rate of about 60 GBaud, mainly targets data center interconnections (DCI) up to a maximum distance of 120 km, providing a power- and cost-effective coherent interface. Additional analysis – focusing on the issue of power consumption, but considering different network topologies – can be found in [7].

In this work, the network capacity and power consumption – resulting from employing three different multi-band configurations, namely C+L-, C+L+S-, and C+L+U-band transmission – have been investigated. Particularly, the C+L-band transmission employing transparent and translucent network designs are compared to the transparent C+L+S- and C+L+U-band network designs.

II. Design Methodology

In this work, the optical performance of each LP is modeled based on two Gaussian disturbances: amplified spontaneous emission (ASE) noise and nonlinear interference (NLI), introduced by the optical amplifiers and fiber propagation, respectively. The generalized signal-to-noise ratio (GSNR) is calculated as the unique figure of merit for the QoT at the end of each fiber span [2]. The Generalized Gaussian Noise (GGN) model is used to evaluate the NLI effect, which includes both spectral and spatial variation of gain/loss and its interaction with the stimulated Raman scattering (SRS) effect [8]. The QoT of the LP is determined as in [9]: $\text{GSNR}_{i,\text{total}} = 1/\sum_{s\in L}(\text{GSNR}_{i,s})^{-1}$, where $\text{GSNR}_{i,s}$ is the GSNR of the i_{th} frequency on span s of the LP. Different optical amplifiers are considered for each transmission band. A noise figure (NF) of {4.3 dB, 4.7 dB, 6.5 dB, 6 dB} is assumed for the C-, L-, S-, and U-band optical amplifiers, respectively[1].

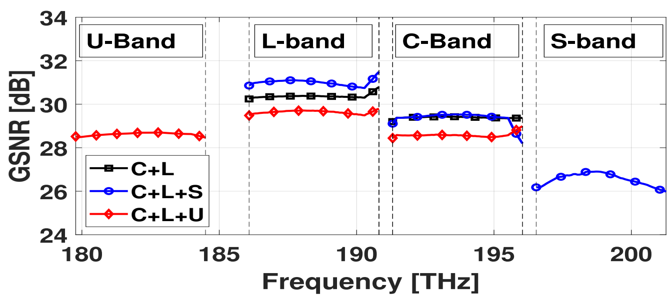


Fig. 1: GSNR profiles for a single SSMF span of 75 km in a C+L-, C+L+S-, and C+L+U-band transmission scenario.

Figure 1 shows the GSNR profile for a single 75 km long span of a standard single-mode fiber (SSMF) when using the C+L-, C+L+S-, and C+L+U-bands for data transmission. We assume the transmission of 64 channels on the ITU-T 75 GHz grid with symbol rate of $R_s = 64$ Gbaud in each band. Consequently, the C+L-, C+L+S-, and C+L+U-band multi-band scenarios consist in the transmission of a total of 128, 192 and 192 channels, respectively. The main results (average GSNR) extracted from this figure are highlighted

[1]The reported NF is mainly based on data from commercial/bench-top optical amplifiers. However, due to the lack of data for the U-band amplifier, the NF for this amplifier is assumed to be equal to 6 dB.

TABLE I: Average GSNR [dB].

	U-band	L-band	C-band	S-band
C+L	-	30.4	29.4	-
C+L+S	-	31.0	29.4	26.5
C+L+U	28.6	29.6	28.6	-

TABLE II: TRX modelling.

Mod. Form.	Data rate [Gb/s]	P [W]	RGSNR [dB]
16QAM	400	20	21
8QAM	300	18	18
QPSK	200	16	14

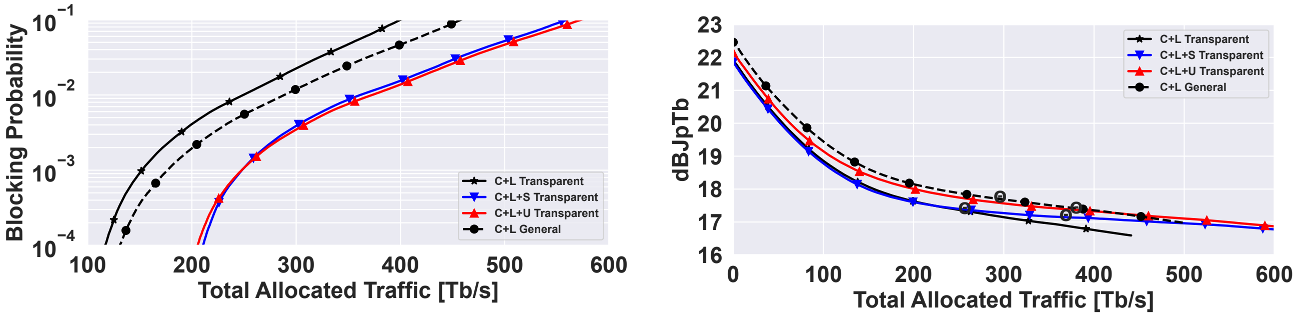
in Table I According to Table I, average GSNRs of 29.4 and 30.4 dB for the C- and L-bands, respectively, can be reached in C+L-band transmission scenario. In the C+L+S-band transmission scenario, the average GSNR in the C-band remains mostly unchanged, but it is improved to 31 dB in the L-band. However, the average GSNR in the S-band is of only 26.5 dB. On the other hand, if the U-band is deployed instead of the S-band, the GSNR in both C- and L-band decreases in comparison to the C+L+S-band scenario, reaching 28.6 and 29.6 dB only in the C- and L-bands, respectively. The average GSNR in the U-band is 28.6 dB. The more realistic USNET optical meshed network topology, comprising 24 nodes and 43 links, is considered in the remaining of this work [10]. In this case, the statistical network assessment process (SNAP) [11] has been used for network evaluation, where the k-shortest paths algorithm with $k_{max} = 5$ shortest paths between source and destination has been considered. Moreover, First-Fit (FF) wavelength assignment policy is enforced. When using the SNAP, the network is progressively loaded with 100 Gb/s traffic requests, which are uniformly generated among all node pairs of the network. SNAP starts by checking the already allocated LPs (same end-to-end nodes) to find possible spare capacity. If none is available, a new LP is established. In this case, the SNAP establishes the highest capacity LP that fulfills the QoT of the requested LP. The selection of capacity of the new LP is done accordingly to the TRX modelling depicted in Table II. The considered TRX supports three different modulation formats, namely 16QAM, 8QAM, and QPSK with data rates of 400, 300, and 200 Gb/s, which are characterized by different power consumption and required GSNR (RGSNR). As an example, if the QoT of the new LP to be set is higher than 21 dB, the SNAP process selects the most efficient modulation format (16QAM). However, if the QoT is smaller than 21 dB but still higher than 18 dB, the 8QAM modulation format is selected instead. In the transparent network design, signal regeneration is not allowed in the intermediate nodes. On the other hand, in case of a translucent network design, the assignment of a pair of back-to-back TRXs is allowed, if necessary, at intermediate node(s). This corresponds to dividing a long transparent LP into shorter sub-LPs with higher QoT and, consequently, higher spectral efficiency. The QoT, as well as the availability of ROADMs at intermediate nodes, are the conditions underpinning the placement of regenerators in the translucent network design. In the General translucent strategy (General), the SNAP controller sets extra pairs of TRXs on the intermediate nodes so that the highest possible bit-rate is enabled in the end-to-end LP, i.e., 400 Gb/s (16QAM). Nevertheless, the SNAP controller avoids assigning unnecessary regenerators, using the minimum number of required regenerators to achieve the maximum LP capacity.

III. Results and Discussion

In this section, the impact of exploiting C+L and beyond transmission bands on the capacity and consumed energy in a transparent network design is compared with employing a translucent network design but exploiting C+L-band only for data transmission. The allocated traffic and the average energy consumption, in jpb, for the above-mentioned network designs (transparent and translucent) are shown in Fig. 2.

Fig. 2a depicts the statistical total allocated traffic versus blocking probability (BP). The analysis of Fig. 2a shows that, when employing a transparent network design and the C+L-band only is used for data transmission (black solid line), we can allocate a total traffic load of about 249 Tb/s at the BP of 1%. If, instead, a translucent network design is employed, the total allocated traffic in the same C+L-band transmission scenario increases to about 288 Tb/s at the same BP. This result highlights that the USNET capacity can be increased by about 16% when deploying optical regenerators in a C+L band transmission scenario. It is worth mentioning that, even though signal regeneration is performed, the wavelength continuity is preserved, i.e., wavelength conversion is not allowed in this work. Enabling the S- or U-band results in significant capacity increase with respect to using the C+L-band only for data transmission, even when comparing the transparent to the translucent network design. For instance, the allocated traffic in the transparent network design exploiting the S-band (C+L+S-band) is equal to 361 Tb/s at the BP of 1%. If, instead, the U-band is used (C+L+U-band), the network capacity further increases to about 373 Tb/s at the same BP.

The energy consumption for the different network configurations is depicted in Fig. 2b. Please Note that, The energy consumption is shown in dB Joule per Terabit (dBjpTb) versus the progressively allocated traffic, i.e., the average consumed energy per Tera bit is evaluated by dividing the total consumed power by the amount of allocated traffic. To facilitate the comparison, only the TRXs energy consumption is depicted in this analysis. However, it is clear that enabling more bands requires a higher fixed energy consumption resulting from the need of enabling a higher number of optical amplifiers. Although the introduction of more amplifiers causes to increase the average energy consumption, the power consumption of the network is usually dominated by the TRXs and not by the amplifiers. The analysis of Fig. 2b shows that the energy consumption per transmitted bit is higher when there is a small load in the network, as would be expected. Indeed, each new connection request is likely to require a new LP, as only few connection are deployed. Gradually, the average energy consumption decreases, as spare capacity can be found in already allocated LPs. For instance, the initial energy consumption for all scenarios is about 22 dBJpTb. However, and due to the traffic grooming, the average energy consumption decreases to about



(a) (b)

Fig. 2: (a) Blocking probability and (b) energy consumption – Joule per Terabit [dB] – versus total allocated traffic for USNET topology for translucent (C+L-band) and transparent (C+L-, C+L+S-, C+L+U-band) network designs.

TABLE III: Values and multiplicative factors (inside parentheses) of allocated traffic and energy consumption at the BP=1%.

Scenario	Capacity [Tb/s]	Energy Consumption [dBJpTb]
Transparent C+L	249.42 (1)	17.37 (1)
Transparent C+L+S	361.52 (1.45)	17.15 (0.98)
Transparent C+L+U	372.97 (1.5)	17.38 (1)
Translucent C+L	288.65 (1.15)	17.72 (1.02)

17 dBJpTb when the network becomes heavily loaded. It is clear that a transparent network design leads to smaller average energy consumption in comparison to the translucent network design, mainly due to requiring a smaller number of TRXs. As an example, the energy consumption in the C+L-band scenario is 17.4 dBJpTb for the transparent network design whereas it increases to 17.7 dBJpTb in the corresponding translucent design (at the BP of 1%). Although exploiting the U-band (C+L+U-band) in the transparent network design leads to a higher delivered capacity, the average energy consumption remains the same as in C+L-band transparent case (17.4 dBJpTb) for the same BP of 1%. On the contrary, enabling the S-band in the transparent case (C+L+S-band) leads to a slightly smaller energy consumption, 17.1 dBJpTb, which is a consequence of the higher average GSNR in the C- and L-bands. To ease the comparison of the different configurations, the allocated traffic and energy consumption and their respective multiplicative factors at the BP of 1% are shown in Table III. The analysis of Table III shows that employing signal regeneration in the C+L-band transmission scenario increases the network capacity by 15% but also leads to an increase of the average energy consumption of 2% at the BP of 1%. On the other hand, enabling the S- or U-band, in addition to the C- and L-bands, in a transparent network design leads to an increase in the network capacity of, at least, 45% without requiring an increase of the average energy consumption.

IV. Conclusion

The network capacity and energy consumption in transparent and translucent network designs, combined with multi-band transmission, have been analyzed. We showed that enabling more transmission bands in a transparent network design is a more effective way to increase the network capacity than exploiting signal regeneration in the existing transmission bands. Indeed, while exploiting signal regeneration in a C+L transmission system enabled increasing the network capacity by 15% only, enabling an additional transmission band allows boosting the total network capacity by, at least, 45%. Moreover, we have shown also that, while using signal regeneration leads to an increase of the cost per transmit, enabling data transmission in additional transmission bands allows keeping the cost per transmitted bit almost constant.

Acknowledgment

This work was partially funded by the EU H2020 within the ETN WON, grant agreement 814276, by the Telecom Infra Project. Antonio Napoli would like to thank the EU's Horizon 2020 research and innovation program B5G-OPEN Project, grant agreement 101016663, for the support of his research.

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