Optimal Spectral Usage and Energy Efficient S-to-U Multiband Optical Networking

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Abstract: We investigated and showed that using the U-band instead of the complete S-band is a more effective solution for increasing capacity while still reducing energy consumption and cost in transparent and translucent network designs.

OCIS codes: 060.0060, 060.4256.

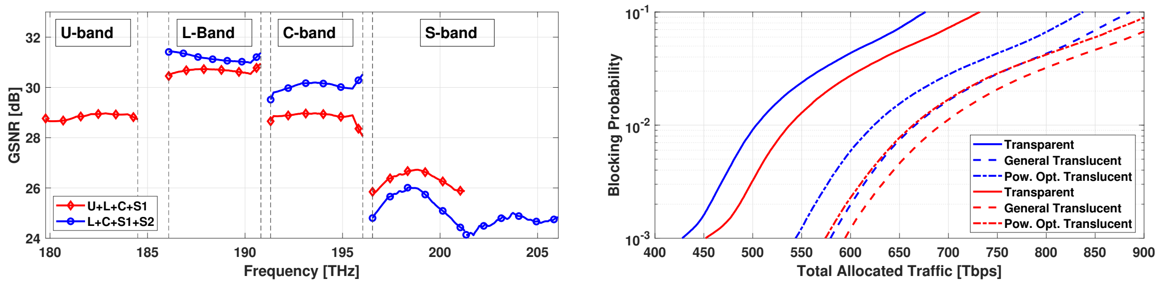
1. Introduction

The data traffic demanded from optical networks keeps increasing every year. In this context, multiband transmission [1,2] which consists in transmitting data over a wider optical fiber spectral bandwidth, is a promising solution to increase network capacity since it reuses the already deployed fiber infrastructure. The deployment of elastic transceivers (TRX) is also important to cope with the requested capacity since it enables using different data rates and modulation formats depending on the quality of transmission (QoT) of the lightpath (LP). The usage of these devices can be further improved via traffic grooming [3]. Simultaneously, minimizing the overall power consumption is increasingly an economic imperative for network operators, as well as a societal objective, further motivating the use of high capacity as well as power-efficient TRXs [4]. The Optical Internetworking Forum (OIF) 400ZR implementation agreement (IA)[1] represents a milestone in pluggable coherent transceivers [5]. Initially targeting data center interconnect (DCI) applications, this TRX is a power-efficient and cost-effective coherent interface that supports 400 Gbps at a symbol rate of about 60 GBaud. A detailed investigation on the expected network-wide power consumption making use of this TRX type and different channel provisioning strategies has been reported in [6]. In this work, we evaluate six scenarios, combining two wideband configurations, namely ULCS1 and LCS2, with three resource allocation strategies, one transparent (end-to-end connections) and two translucent (signal regeneration in middle nodes). The results are shown in terms of network capacity, energy consumption, and cost for all of these scenarios.

2. QoT abstraction and regenerator placement

When coherent TRXs are considered, the performance of a LP can be modeled based on two Gaussian disturbances: amplifier spontaneous emission (ASE) noise and nonlinear interference (NLI), introduced by optical amplifiers and fiber propagation, respectively. The QoT at the end of each fiber span can be estimated by the generalized signal-to-noise ratio (GSNR) [1]. The NLI evaluation can resort to the generalized Gaussian noise (GGN) model, including both spectral and spatial variation of gain/loss and its interaction with the stimulated Raman scattering (SRS) effect [7]. Following a disaggregated approach [8], the QoT of an LP depends only on the GSNR of each span. In the remaining of this work, the physical layer abstraction is carried out assuming a fully-loaded spectrum, a WDM grid with 75 GHz frequency slots, optical channels operated with a symbol-rate of 64 GBaud, and fiber spans of 75 km. In Fig. 1(a) the GSNR profiles are presented for the two wideband configurations used in this work: (i) ULCS1, with 64 channels in each band (U-, L-, C- and S-) using only half of the S-band capacity; (ii) LCS2, without the U-band but exploring the full S-band capacity, dividing it into two sub-bands and using one amplifier for each. In both configurations, the number of wavelengths for each band is considered equal to 64 (the only exception being S-band with 128 channels in LCS2) for a total of 256. The launch power profile strategy is performed following the same approach as [9]. The average GSNR per band for the ULCS1 configuration is 28.83, 30.67, 28.84, and 26.32 dB for the U-, L-, C- and S1-bands, respectively. For the LCS2 configuration, the average GSNR is 31.18, 30.06, 25.37, and 24.64 for L-, C-, S1- and S2-bands, respectively. After the detailed characterization of the physical layer, the network analyzes is performed via the statistical network assessment process (SNAP) [10] in the USNET topology. The *k*-shortest

[1] 400ZR IA defines only 400G transmission with 16QAM $<$ 120km. OpenZR+ and OpenROADM multi-source agreements aim at extending the use of the technology to longer reaches.



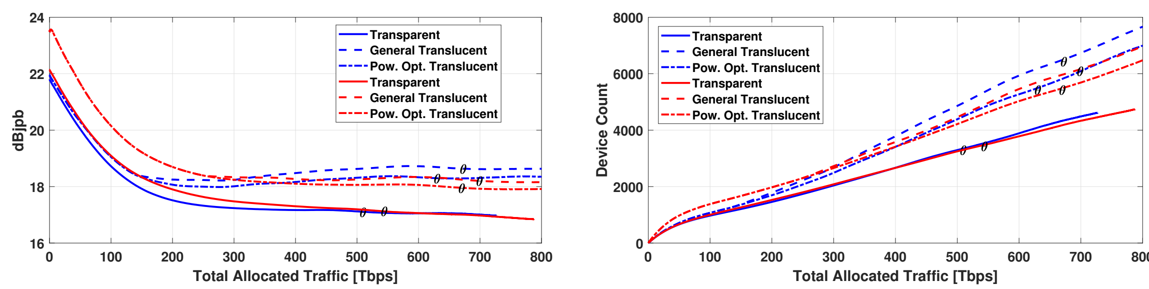
(a) (b)

Fig. 1: (a) Frequency versus GSNR for the LCS2 and ULCS1 scenarios, and (b) total allocated traffic versus blocking probability for the USNET topology (LCS2: Blue and ULCS1: Red).

path algorithm is used to compute up to $k_{max} = 5$ candidate routing paths for each node pair and wavelength assignment enforces the first-fit algorithm. A progressive traffic load analysis is performed, where each new request consists of a 100 Gbps traffic demand. Additionally, before the establishment of a new LP, traffic grooming is first attempted, by checking the availability of idle capacity in existing lightpaths. When establishing a new LP is necessary that the optical controller selects the proper modulation format based on the estimated QoT and the TRX required GSNR (RGSNR) [11]. Three different channel provisioning scenarios are considered: transparent, translucent, and power-optimized translucent. In the transparent network scenario, a new LP is always established end-to-end, resorting to the highest order modulation format that is feasible without intermediate regeneration and guaranteeing the wavelength continuity constraint among all links in the path. In the translucent scenarios, this constraint is removed in the nodes where the regeneration is performed (realized as a pair of back-to-back TRXs). In the first translucent strategy, designated as General Translucent, the controller activates an extra pair of TRXs on intermediate nodes when this is strictly required to maintain the maximum bit rate for that LP, which is 400 Gbps (16QAM) in this work. Finally, in the second translucent strategy, designated as Pow. Opt. (Power Optimization), the controller finds all possible combinations between source and destination nodes of modulation format and the minimum number of regenerators needed. It then selects the most efficient modulation format and regenerator placement such that the total power consumption of the required TRXs is minimized. This results in a solution that, on average, can be more power-efficient than the general translucent, while being at the same time more spectrally efficient than the one obtained with the transparent strategy. Importantly, in both translucent strategies, the controller avoids deploying unnecessary regenerators to attain the target data rate, consequently preventing further increases in cost, as shown in Sec. 3.

3. Network simulation results and discussion

Network analysis has been executed considering the LCS2 and ULCS1 band configurations, keeping the same total number of channels and amplifiers. In Fig. 1(b) the total allocated traffic for different blocking probability (BP)s has been shown. It is observable that due to its lower overall QoT, LCS2 (blue color) results in higher BP when compared to ULCS1 (red color) in both the transparent and general translucent scenarios. For instance, in the transparent network design, the utilization of the ULCS1 band configuration enables it to support approximately 6% more capacity, when compared to LCS2. Moreover, moving from the transparent to the translucent network design leads to an increase of capacity of between 24% to 37% in the Pow. Opt. and general translucent network designs, respectively. From the energy consumption viewpoint, which is investigated as the energy consumed to



(a) (b)

Fig. 2: (a) Energy consumption and (b) Device count versus total allocated traffic. Indicator θ determines the BP of 1% (LCS2: Blue and ULCS1: Red).

transfer a bit in Fig. 2(a). As can be seen, when starting to load a network the energy consumption is high, which is a consequence of having new LPs that are not fully loaded [12]. However, as load increases, LPs will tend to be full and energy consumption decreases. According to Fig. 2(a), the transparent network scenario with ULCS1 supports more traffic load than the same scenario with LCS2, while energy consumption is comparable, i.e., 17.1 dBjpb at a BP of 1% (marked with θ). In the ULCS1 band configuration with both translucent strategies, the energy consumption is high, flattening at around 300 Tbps. From this load value onward, energy consumption drops about 1 dBjpb below that of the LCS2 band configuration and reaches around 18 dBjpb. The number of used point-to-point TRXs for each scenario is depicted in Fig. 2(b). Each regenerator is assumed to be realized as two TRXs. This figure shows that the transparent cases for both ULCS1 and LCS2 require almost the same amount of TRXs for a target capacity. As an example, for 500 Tbps, 3270 TRXs are required in the transparent network design. However, for a fairer comparison one needs to consider the same BP value. For instance, for a BP of 1%, the number of used TRXs at Pow. Opt. scenarios are close to 5500 but the capacity supported is 667 and 625 Tbps, for the ULCS1 and LCS2, respectively. In other words, for the same number of TRXs an extra 40 Tbps of capacity is supported when using ULCS1 instead of LCS2 band configuration.

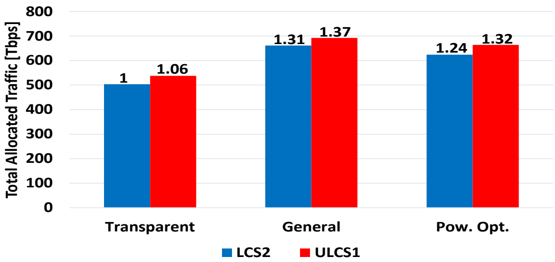


Fig. 3: Multiplicative factor at the BP=1% (with respect to the transparent LCS2).

Table 1: Multiplicative factor for 600 Tbps traffic load (with respect to the transparent LCS2).

Traffic = 600 Tbps		Transparent	General	Pow. Opt.
LCS2	Total Energy	1	1.09	1.07
	Device Count	1	1.52	1.35
ULCS1	Total Energy	1	1.07	1.05
	Device Count	0.99	1.40	1.29

The multiplicative factor of the capacity results at a BP=1% is presented in Fig. 3, in which the transparent network design for the LCS2 configuration is considered as a reference. It can be observed that the capacity of the network in the transparent design increased $\times$1.06 times when using the U band instead of the full S-band. Additionally, this value increased $\times$1.37 and $\times$1.32 times in the translucent design with different approaches namely general and Pow. Opt., respectively. Furthermore, Table 1 shows the multiplicative factor for both the energy consumption and TRX count considering a traffic load of 600 Tbps and assuming the transparent LCS2 case as a reference. Based on this, the energy consumption and the number of used TRXs are almost the same for the transparent network design in both ULCS1 and LCS2. Noteworthy, the energy consumption is slightly lower with the Pow. Opt. translucent strategy. The higher energy consumption observed with the LCS2 case is a result of this configuration making use of more TRXs than those required with ULCS1. For instance, the number of TRXs required by the General translucent network design is 1.52$\times$ more than with the transparent design in the LCS2 case. However, this value drops to 1.40$\times$ in the ULCS1 band configuration. Additionally, the minimum number of TRXs used in the Pow. Opt. translucent network design in the ULCS1 case is 1.29$\times$ that with transparent network design. Overall, Pow. Opt. translucent network design provides a trade-off by decreasing power consumption at the expense of a slight decrease in network capacity.

4. Conclusions

The impact of optimal usage of multiple bands is investigated in this work, showing that using the U-band instead of the second half of the S-band leads to a capacity increase and savings, in both energy consumption and costs. Moreover, we show the results for transparent and translucent networks, with two modulation format and regenerator assignment policies. We demonstrate that a translucent policy focusing on consuming less power can lead to a high increase in allocated traffic (around 24 and 26 % compared to the transparent cases) while decreasing both power consumption and used interfaces (compared to the other regenerator assignment policy).

Acknowledgment

This work was partially funded by the EU H2020 within the ETN WON, grant agreement 814276 and by the Telecom Infra Project.

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