Network Comparison of C+L-band Transparent versus C-band Translucent Upgrade

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***Abstract*—We investigate the designs for the capacity upgrade for transparent C- and C+L-band and translucent C-band only; and evaluate them in terms of capacity, energy consumption, cost, and link utilization ratio. Two different transceiver (TRX) implementations, namely Flex and Fix are used in transparent C- and C+L-band and translucent C-band network designs. We investigate networking performance enabled by different upgrade strategies on a reference topology by relying on an accurate optical transport model. We show that lighting the L-band by keeping a transparent approach leads to an increase in network capacity of more than two times. Conversely, applying translucent design to the C-band to improve the spectral efficiency by deploying regenerators results in only modest improvements of capacity. Also, C+L-band transparent design allows to reduce the number of transceivers per bit/sec and to consume almost 4 dB less energy than that required with the C-band translucent design.**

***Index Terms*—Optical fiber communication, multi-band, transmission modeling, optical amplification, network simulation**

I. Introduction

The network traffic is increasing over time, especially after the worldwide COVID-19 pandemic [1], and it becomes paramount to simultaneously increase the capacity of telecommunication networks and limit the overall energy consumption of networking equipment [2]. This trend highlights the need to use spectral- and power-efficient transceivers (TRXs) and to assess the cost-effectiveness of the available strategies to upgrade capacity. Nowadays, most operators use C-band only Wavelength-Division Multiplexing (WDM) optical transport systems with a spectral occupancy of around 4.8 THz. Two possible techniques to increase capacity via exploiting additional spectrum are: (a) spatial division multiplexing (SDM) [3] and (b) band division multiplexing (BDM) [4]. On one hand, The utilization of SDM depends on the availability of dark fibers, since rolling out new fibers requires large capital investments, particularly in core networks. On the other hand, BDM relies on the low-loss spectrum of the widely deployed ITU-T G.652.D optical fiber, which exceeds 50 THz [5]–[8], to exploit other single-mode bands in existing fibers. This capacity upgrade strategy, not only increases network capacity [5] but also holds the promise of attaining this with reduced capital expenditures (CAPEX) [9], [10], as it exploits the installed fiber cables. Also, deploying power-efficient TRXs in a network is increasingly important for network operators seeking to also reduce their operational expenditure (OPEX) in terms of footprint and power consumption. The scaling of Intel's integrated circuit CMOS node size has been shown to drop every two years [11]. Moreover, the availability of digital signal processing application-specific integrated circuit (DSP ASIC)s at the respective CMOS node size has been studied [12]–[14]. Accordingly, the CMOS power consumption depends on the node size, with an energy reduction of $\sim$30% in each process step [15]. In the last years, the Optical Internetworking Forum (OIF) defined an implementation agreement (IA) [16] to introduce coherent techniques in pluggable form factors . 400ZR [16] is a key IA that supports 400 Gbps with a symbol rate of 59.84 Gbaud and 16QAM modulation format, aiming at having a high-capacity, power-efficient and cost-effective coherent interface for data center interconnect (DCI) applications. Moreover, a recent multi-source agreement (MSA), OpenZR+ [17], is extending the usage of this type of coherent interfaces to longer reaches via trading-off capacity for reach.

In this work, we perform a statistical network assessment [18] over German (DT) network topology [6] in order to gain insight on key performance metrics, such as maximum capacity, transceiver count, and power consumption. Two main network upgrade strategies are considered. The first relies on using the C+L-band and employing a transparent design (i.e. without resorting to 3R regeneration devices), whereas the second one uses only the C-band but increases the spectral efficiency of deployed lightpaths (LP) (using additional transceivers at intermediate sites). The reference scenario consists of using only the C-band and enforcing a transparent design.

This paper is structured as follows: Section II describes the methodology implemented and utilized in this work to estimate the quality of transmission (QoT) of LPs and determine the regenerator assignment and describes the key characteristics of the TRXs implementations considered. In Section III different network designs are compared and their relative advantages and disadvantages are identified. Finally, the last section provides the conclusion and gives an outlook.

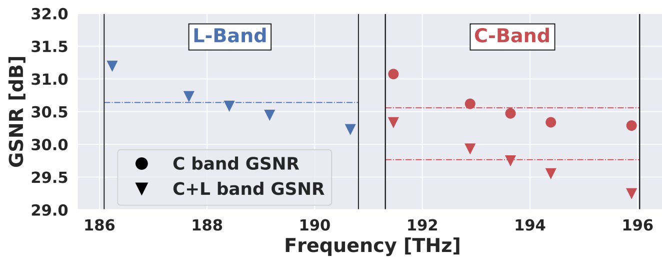


Fig. 1: GSNR profiles for a single 75 km span in C- and C+L-band transmission.

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 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 [6]. 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 [19]. The QoT of the LP is determined by [20]: $\text{GSNR}_{i,\text{total}} = 1/\sum_{s\in L}(\text{GSNR}_{i,s})^{-1}$, where $\text{GSNR}_{i,s}$ is the GSNR of the i_{th} frequency on span s of the LP.

Figure 1 shows the GSNR profile for a single span (75 km) of a standard single-mode fiber (SSMF) for the scenarios of using only the C-band and exploiting C+L-band. The average GSNR in the C-band only case is 30.55 dB, varying around 0.79 dB between the maximum and minimum values (ΔGSNR). However, enabling the L-band in the BDM case causes a decrease in the average GSNR of the C-band, which becomes 29.76 dB, whereas the average GSNR in the L-band is 30.64 dB. Moreover, the ΔGSNR is 1.08 dB and 0.97 dB in the C- and L-band, respectively. Therefore, a QoT degradation (in the C-band) of about 1 dB is obtained when lighting up the L-band to increase the amount of available spectrum. A total of 64 and 128 channels on the ITU-T 75 GHz grid with $R_s = 64$ GBaud have been considered for the C-band and C+L-band, respectively.

The DT topology considered in this work contains 17 nodes and 26 links. The average nodal degree is 3.1 and the average distance between two reconfigurable optical add/drop multiplexer (ROADM) nodes is 207 km [21]. For the purpose of routing traffic demands, 15 alternative shortest paths between source and destination are considered by the k-shortest path algorithm and a First-Fit (FF) wavelength assignment policy is enforced. The network is progressively loaded with traffic, where client traffic demands are assumed to be 100 Gbps (e.g., 100GbE, OTU4). The possibility of doing traffic grooming over existing LPs is always checked before the establishment of new LPs, i.e., verifying if any of the already deployed LPs has enough spare capacity to accommodate the new request (end-to-end).

Flexible (Flex) TRXs are deployed in the case of transparent network design for both the C-band only reference scenario and the C+L-band capacity upgrade scenario. According to Table I, the Flex TRX type supports three different modulation formats for various maximum reaches with different power consumption figures. When a new request arrives, based on the QoT of the LP as well as its length, the control plane selects the most efficient modulation format between the source and destination nodes [4]. An example of using this methodology is the selection of 8QAM (300 Gbps), or even a less efficient modulation format (<300 Gbps), depending on the estimated QoT of the path when the length of request between source and destination is above 600 km. It is worth mentioning that checking the length of potential LPs is used to verify that the accumulated chromatic dispersion is within the TRX specs.

Fixed (Fix) TRX is applied to the translucent network design, which supports only the 16QAM modulation format (400G). According to Table I, two types of Fix TRX are assumed to be available for deployment: one that is customized to minimize power consumption, 15 W, at the expense of short-reach, $L < 120$ km [16]; and another type that has a more relaxed power consumption budget, 20 W, in order to increase reach, with typical values in the range 120 km$<$ L $<$450 km [17].

In the translucent network design scenario, regenerators (assumed to be realized as a pair of back-to-back TRXs) are deployed as required at intermediate nodes to achieve the QoT needed to set up the end-to-end connection. Both the QoT and maximum supporting length of the TRX, as well as the availability of ROADMs at intermediate nodes, are the conditions underpinning the placement of regenerators. This type of network design enables to improve spectral efficiency, consequently increasing the available network capacity, by ensuring all LPs operate at 16QAM (400G). However, in order to achieve this goal it also requires more TRXs. Once a request arrives, the control plane computes the QoT and length of new LPs that may be set up to accommodate the request. During the LP assessment between source and destination nodes, if the control plane estimates that the GSNR is equal or higher than the required GSNR (RGSNR) [21] for 16QAM modulation format and the total length is equal to or smaller than the maximum reach, defined in Table I, the algorithm does not allocate a regenerator. Otherwise, one or more regenerators will be assigned at intermediate nodes, such that the number of regenerators is minimized. By ensuring that the minimum number of regenerators is always deployed, it is guaranteed that this design strategy does not lead to unnecessary increases in cost and power consumption. It is also worth mentioning that in the current implementation it is assumed that regenerators are not placed for the purpose of wavelength conversion and that, for simplicity, it is assumed that the wavelength continuity constraint is still enforced end-to-end. In the next section, three scenarios (transparent network design using C- and C+L-band transmission and translucent network design using C-band only) are compared in order to show the advantages and disadvantages of each capacity upgrade

TABLE I: TRXs modelling assumptions.

TRX	mod. form.	Data rate [Gb/s]	Typical reach [km]	P[W]
Flex	16QAM	400	L<120	15
	16QAM	400	120<L<450	20
	8QAM	300	450<L<1500	18
	QPSK	200	1500<L<2500	16
	QPSK	100	2500<L	13
Fix	16QAM	400	L<120	15
	16QAM	400	120<L<450	20

strategy.

III. Results and Discussion

In this section, translucent (C-band only) and transparent (C+L-band) capacity upgrade scenarios are investigated in terms of capacity, energy consumption and cost in the DT network and assuming 100 Gbps traffic requests. The transparent C-band case is utilized as the baseline scenario to execute the comparison. Since we consider that Flex TRXs are only used for transparent network design and Fix TRXs are only used for translucent network design, for simplicity in the remaining of this section the terms Flex TRX and Fix TRX are used to denote not only the transceiver type but also the network design scenario. The capacity and the average energy consumption of all above-mentioned network designs, transparent and translucent, are depicted in Fig. 2.

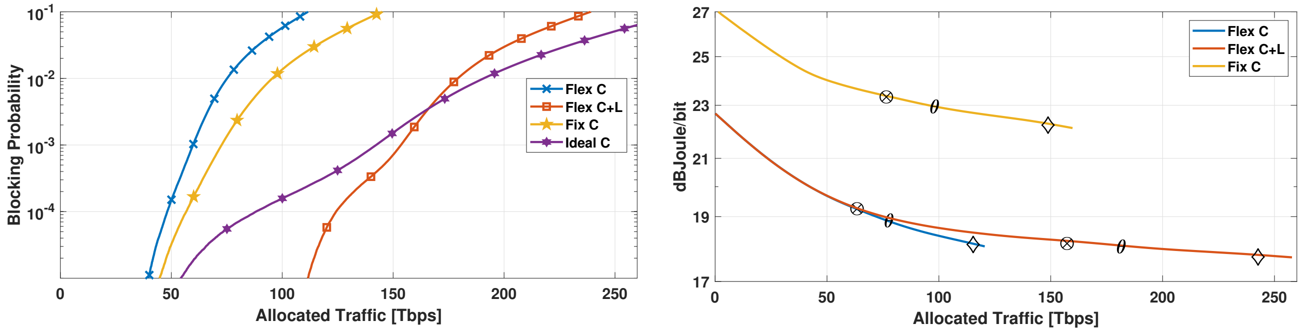
A. Network Capacity

Fig. 2a shows the total allocated traffic versus blocking probability (BP) for a BP range between 10^{-5} and 10^{-1}. In addition to the cases of transparent C (Flex C), transparent C+L (Flex C+L), and translucent C (Fix C), Fig. 2a also presents the result obtained when using a transparent network design with ideal elastic transceivers (Shannon limit), in which case the maximum possible LP bit-rate is assumed according to the available GSNR. The results obtained with ideal TRXs enable to show the (theoretic) upper bound on the capacity of the DT network with traffic grooming of 100G. It is observable (in the C-band) that from very low BP, e.g. near 10^{-5}, to higher BP values translucent network design allows to reduce BP by less than an order of magnitude when compared to transparent network design. The difference between both schemes in the traffic load for the same blocking probability tends to increase as BP increases. This is due to the fact that at lower BP, new LPs are being created between node pairs that do not have LPs created between them yet and, hence, these new LPs start with low utilization. As more traffic load is offered to the network, existing LPs start to reach higher levels of utilization, enabling to set up fewer new LPs. The advantage of the translucent design becomes more significant due to the fact that all LPs established have 400G capacity and, consequently, on average, each LP supports more traffic load than in the transparent scenario (where some LPs may provide 300G, 200G or 100G). Nevertheless, the extent of capacity increase obtained by moving to a translucent design is significantly smaller than that of exploiting the C+L-band (which doubles the number of wavelengths). In fact, Fig. 2a shows that lighting up the L-band while preserving a transparent design allows to (i) reduce the BP for a given offered traffic load by several orders of magnitude; and (ii) increase the delivered capacity for a target BP by a factor of slightly more than two times. For instance, the total allocated traffic at BP of 10^{-5} is 40, 45, 55 Tbps for Flex, Fix, and Ideal network designs using C-band only. Enabling the L-band, the total allocated traffic at this BP increases to 112 Tbps by using Flex TRX with C+L-band, even taking into account the additional performance impact of SRS. At higher traffic loads (and BP), Flex TRX with C+L-band is still clearly a more effective strategy to increase capacity than using only the C-band and adopting a more aggressive LP provisioning scheme at the expense of deploying additional regenerators. Noteworthy, it is the case of ideal TRXs that benefit the most from operating in this region. This is due to the fact that the average LP capacity (and spectral efficiency) is significantly higher than that made available by the generation of TRXs considered and, as a result, it is possible to support more traffic load over the existing LPs.

B. Network Energy Consumption

Fig. 2b shows the power consumption normalized to the transported traffic as a function of the traffic load offered to the DT network. BP values of 0.1%, 1%, and 10% are indicated with $\otimes$, θ, $\diamondsuit$, respectively. The first observation is that the translucent network design using C-band leads to higher energy consumption than that obtained with transparent network designs. Particularly, the average additional consumed energy is approximately 4 dB joule per bit at the same traffic load. The higher energy consumption of the translucent network design is a consequence of having to deploy regenerators (i.e. more TRX devices) to increase capacity via using more spectral efficient LPs. On the other hand, Fig. 2b also shows that when exploiting an additional spectrum band, i.e., using C+L-band instead of C-band only, it is possible to double the capacity of the network without a significant increase of the network average energy consumption. As can be seen, both transparent scenarios (C only and C+L) result in almost the same energy consumption until reaching reach the maximum allocated traffic for C-only. The slight difference, occurring between around 75 and 120 Tbps, can be explained by the fact that with transparent C-band, blocking becomes significant (e.g., see Fig. 2a) and finding spectrum resources to set up new LPs requires using longer, and thus less spectral efficient, routing paths.

It is worth mentioning that the energy consumption values being shown are only due to TRXs and do not account for the power consumption contribution of amplifiers, active filters, controller cards, fans, etc. Enabling the L-band demands using C+L-band amplifiers, which have a higher power consumption than C-band only amplifiers. Nevertheless, the energy consumption of the set of TRXs being used is much higher than that of the optical amplifiers and, therefore, the results are



(a) (b)

Fig. 2: (a) Blocking probability and (b) energy consumption – dB joule per bit – versus total allocated traffic for DT topology with fixed and flex TRXs in the translucent and transparent network design.

not expected to change substantially if the contribution of the above-mentioned devices was also modeled.

C. Network Transceiver Count

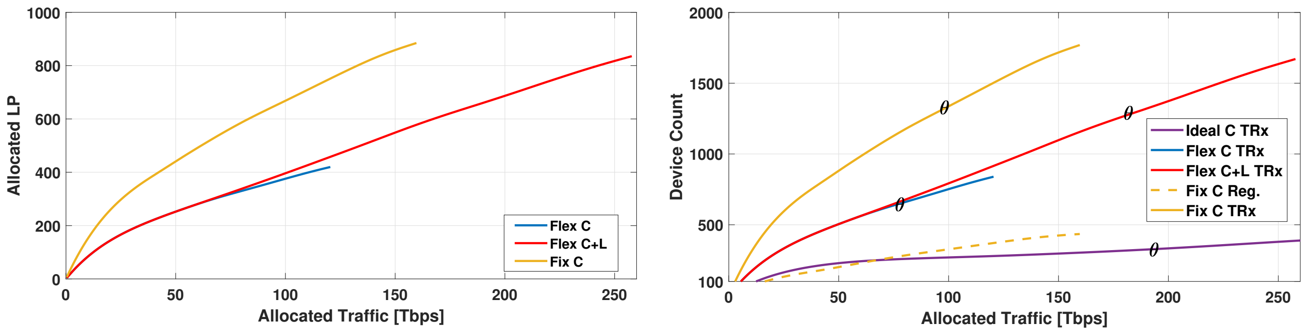
Fig. 3 provides additional insight on the results of the network dimensioning, supporting some of the observations made in previous sub-sections and giving device count figures that can be used with a cost model (which is outside the scope of this work) to determine the cost-effectiveness of each capacity upgrade strategy. Fig. 3a shows the number of allocated LPs as a function of the traffic load, whereas Fig. 3b presents the total number of TRXs used for translucent C-band only, transparent Ideal, and transparent C- and C+L-band.

From the viewpoint of cost and LP allocation in different network designs, Fig. 3a clearly shows that the translucent design strategy requires to allocate significantly more LPs than the transparent design strategies. This is the pre-condition to increase spectral efficiency and, consequently, capacity when using only the C-band (see Fig. 2a). The number of TRXs required grows in the same proportion as the number of allocated LPs. Therefore, it is also evident that the translucent network design requires more TRXs, which leads to higher energy consumption (see Fig. 2b). Fig. 3b also includes the number of regenerators that have to be deployed with this capacity upgrade strategy. For instance, in order to support 100 Tbps traffic load, the translucent network design requires deploying 1338 TRXs, against the 792 TRXs that are needed when using a transparent network design with C+L-band. The number of allocated LPs and the number of TRXs is very similar when using the transparent network design with C- and C+L-band, the only difference being that the latter enables to support more LPs/TRXs in view of the additional spectrum made available. The fact that the figures are so close, supports that the performance difference between exploiting only the C-band and exploiting C+L-band (as discussed in Section II) has a negligible impact on the networking results. To this end, transparent network design with C+L-band enables to increase to roughly double capacity while keeping similar cost and energy consumption (associated to transceiver devices) per bit transported. In contrast, the utilization of a translucent network design in the C-band significantly increases cost and energy usage and can only provide a moderate increase of capacity.

D. Summary

Table II summarizes the key findings of the comparison performed in this work, showing the total traffic supported for BP = 1%, the total energy consumed, and the TRX count. To facilitate the comparison, these results are normalized to the reference scenario (transparent network design with C-band). In other words, the total allocated traffic, total energy, and normalized TRX count values in the transparent network (C-band) in the BP of 1%, which are 75 Tbps, 18.91 dBj/b, and 637, respectively, considered as a reference values to do the normalizing.

Additionally, the average capacity fill ratio, indicating the fraction of used capacity averaged over all LPs, and the average LP length are presented in this table. In order to derive capacity fill ratio, the capacity of each link with respect to the QoT and modulation format in the proposed wavelength for the used links has been obtained, and then the fraction value for each link calculated bt considering the allocated traffic versus the proposed capacity by each link As can be seen, the translucent network design with the C-band provides a capacity increase of the only 27%, when compared to the reference scenario. Conversely, exploiting the C+L-band using a transparent network design increases the capacity 2.3 times. Moreover, this increase can be executed while scaling the number of TRXs in approximately the same proportion, whereas the translucent network design approach requires around 66% more TRXs. A direct consequence of this is that the translucent network design is also clearly less energy-efficient, increasing this metric by around 21%. The average capacity fill ratio and the average LP length support the above-mentioned observations. Particularly, it becomes clear that as a consequence of using higher capacity and more spectral efficient LPs in the translucent network design (i.e., only 400G), on average the LPs established are shorter (with an average of 280 km instead of 515 km), providing the opportunity to better groom traffic demands, as can be observed by the higher average capacity fill ratio (69% versus



(a) (b)

Fig. 3: (a) allocated LP and (b) the number of used point to point TRX and regenerator number versus total allocated traffic for DT topology in transparent and translucent network design. Each regenerator considered as two TRX.

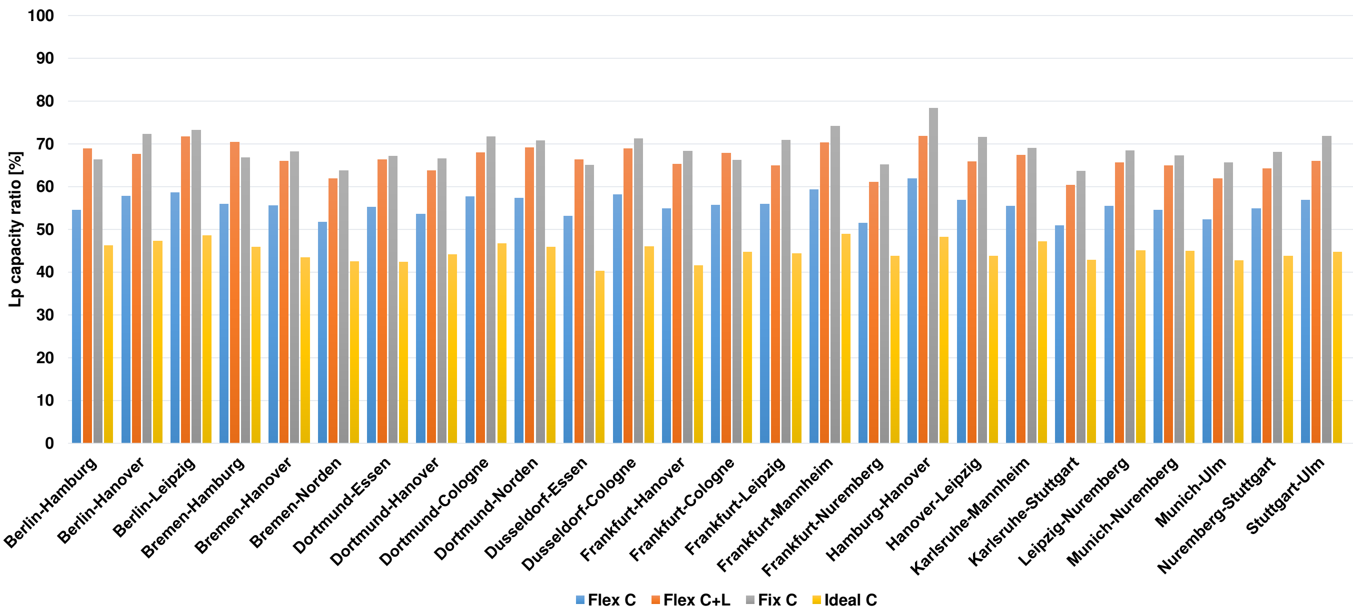


Fig. 4: Links capacity fill ratio for different network designs at BP of 1%.

56%). On the other hand, lighting the L-band and keeping a transparent network design leads to a similar average LP length, while providing an increase of the average capacity fill ratio. This grow is the key reason why capacity is increased by $\times 2.3$, albeit only twice the spectrum is made available and there is a minor decrease of performance in the C-band. Noteworthy, duplicating the number of channels facilitates finding an available wavelength end-to-end (i.e., relaxes the impact of the spectrum continuity constraint). A breakdown of the average capacity fill ratio per individual link is plotted in Fig. 4 for BP $= 10^{-2}$.

Finally, it is worth noting that capacity can also be increased using only the C-band if high-end line interfaces supporting finer-granularity line rates can be deployed [22], which is supported by the results obtained with the Ideal TRX. The lower average capacity fill ratio shown in Table II is a result of the substantially higher capacity available in each established LP and the fact that although these LPs have a very fine granularity (e.g. below 25G increments) the analysis reported in this work only considers coarser 100G demands.

TABLE II: Multiplicative factor at BP = 1%. Total traffic, Total energy, and Normalized TRX count normalized to the Flex C as a reference case.

	Total Traffic	Total Energy	Normalized TRX Count	Average Capacity fill ratio [%]	Average LP length [km]
Flex C	1	1	1	55.61	514.96
Flex C+L	2.38	1.03	1.07	66.4	518.1
Fix C	1.27	1.21	1.66	68.9	279.77
Ideal C	2.53	-	0.17	44.84	516.12

IV. Conclusion

This paper compared different options to increase capacity in an optical transport network. A comprehensive optical performance model, which has been shown to accurately model the impact of detrimental effects arising when using more spectrum bands, was utilized. The results obtained in a reference network topology provide evidence that exploiting more spectrum bands (namely the L-band) not only ensures that capacity can be doubled, but also that this is attained with energy consumption and cost figures that scale in a similar proportion. Conversely, relying on additional regenerators to improve spectral efficiency and LP capacity fill ratio has been shown to lead to only moderate capacity improvements and at the expense of higher energy consumption and the number of required transceivers. Future work includes assessing the impact of using additional spectrum bands (e.g., S-, E- or U-band) and considering a wider set of reference network topologies and traffic patterns.

ACKNOWLEDGMENT

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

REFERENCES

[1] OECD, “Keeping the internet up and running in times of crisis,” tech. rep., OECD, 2020.

[2] F. Musumeci, M. Tornatore, and A. Pattavina, “A power consumption analysis for IP-over-WDM core network architectures,” J. Opt. Commun. Netw., vol. 4, pp. 108–117, Feb 2012.

[3] P. S. Khodashenas, J. M. Rivas-Moscoso, D. Siracusa, F. Pederzolli, B. Shariati, D. Klonidis, E. Salvadori, and I. Tomkos, “Comparison of spectral and spatial super-channel allocation schemes for SDM networks,” Journal of Lightwave Technology, vol. 34, no. 11, pp. 2710–2716, 2016.

[4] B. Correia, R. Sadeghi, E. Virgillito, A. Napoli, N. Costa, J. Pedro, and V. Curri, “Networking performance of power optimized c+l+s multiband transmission,” in GLOBECOM 2020 - 2020 IEEE Global Communications Conference, pp. 1–6, 2020.

[5] R. Sadeghi, B. Correia, E. Virgillito, N. Costa, J. Pedro, A. Napoli, and V. Curri, “Multi bands network performance assessment for different system upgrades,” in IEEE Photonics Conference (IPC), pp. 1–2.

[6] E. Virgillito, R. Sadeghi, A. Ferrari, G. Borraccini, A. Napoli, and V. Curri, “Network Performance Assessment of C+L Upgrades vs. Fiber Doubling SDM Solutions,” in Optical Fiber Communication Conference (OFC) 2020, p. M2G.4, OSA, 2020.

[7] E. Virgillito, R. Sadeghi, A. Ferrari, A. Napoli, B. Correia, and V. Curri, “Network Performance Assessment with Uniform and Non-Uniform Nodes Distribution in C + L Upgrades vs . Fiber Doubling SDM Solutions,” in International Conference on Optical Network Design and Modelling (ONDM) 2020, 2020.

[8] A. Ferrari, A. Napoli, J. K. Fischer, N. M. S. da Costa, A. D’Amico, J. Pedro, W. Forysiak, E. Pincemin, A. Lord, A. Stavdas, et al., “Assessment on the achievable throughput of multi-band itu-t g. 652. d fiber transmission systems,” Journal of Lightwave Technology, 2020.

[9] D. Moniz, V. Lopez, and J. Pedro, “Design strategies exploiting c+l-band in networks with geographically-depedent fiber upgrade expenditures,” in 2020 Optical Fiber Communications Conference and Exhibition (OFC), p. M2G.3, IEEE, 2020.

[10] V. Lopez, B. Zhu, D. Moniz, N. Costa, J. Pedro, X. Xu, A. Kumpera, L. Dardis, J. Rahn, and S. Sanders, “Optimized design and challenges for cl band optical line systems,” Journal of Lightwave Technology, vol. 38, no. 5, pp. 1080–1091, 2020.

[11] W. M. Holt, “1.1 moore’s law: A path going forward,” in 2016 IEEE International Solid-State Circuits Conference (ISSCC), pp. 8–13, 2016.

[12] C. Laperle, “Advances in high-speed ADCs, DACs, and DSP for optical transceivers,” in Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013, p. OTh1F.5, Optical Society of America, 2013.

[13] D. A. Morero, M. A. Castrillón, A. Aguirre, M. R. Hueda, and O. E. Agazzi, “Design tradeoffs and challenges in practical coherent optical transceiver implementations,” J. Lightwave Technol., vol. 34, pp. 121–136, Jan 2016.

[14] O. Ishida, K. Takei, and E. Yamazaki, “Power efficient dsp implementation for 100G-and-beyond multi-haul coherent fiber-optic communications,” in 2016 Optical Fiber Communications Conference and Exhibition (OFC), pp. 1–3, 2016.

[15] M. Kuschnerov, T. Bex, and P. Kainzmaier, “Energy efficient digital signal processing,” Optical Fiber Communication Conference, p. Th3E.7, 2014.

[16] “OIF 400ZR IA.” https://www.oiforum.com/wp-content/uploads/OIF-400ZR-01.0$_reduced2.pdf$.

[17] “Open ZR+ MSA Technical Specification.” https://openzrplus.org/site/assets/files/1075/openzrplus$_1p0.pdf$.

[18] V. Curri, M. Cantono, and R. Gaudino, “Elastic all-optical networks: A new paradigm enabled by the physical layer. how to optimize network performances?,” Journal of Lightwave Technology, vol. 35, pp. 1211–1221, March 2017.

[19] M. Cantono, D. Pilori, A. Ferrari, C. Catanese, J. Thouras, J.-L. Augé, and V. Curri, “On the interplay of nonlinear interference generation with stimulated Raman scattering for QoT estimation,” Journal of Lightwave Technology, vol. 36, no. 15, pp. 3131–3141, 2018.

[20] V. Curri, “Software-defined WDM optical transport in disaggregated open optical networks,” International Conference on Transparent Optical Networks (ICTON), vol. 2020-July, p. We.C2.1, 2020.

[21] J. Pedro and S. Pato, “Capacity increase and hardware savings in dwdm networks exploiting next-generation optical line interfaces,” in 2018 20th International Conference on Transparent Optical Networks (ICTON), pp. 1–6, 2018.

[22] J. Pedro, N. Costa, and S. Sanders, “Scaling regional optical transport networks with pluggable and integrated high-capacity line interfaces,” in Optical Fiber Communication Conference and Exhibition (OFC) 2021, pp. 1–3, OSA, 2021.