Planning and Optimization of Optical Networks Based on Emerging Technologies [Invited]

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Abstract *Optical networks aim at improved capacity and cost efficient data transport solutions. Resulting emerging technologies, such as multi-wavelength transponders with increased rate-adaptivity and multi-band systems, significantly complicate the planning. We provide strategic insights for upgrades from a long-haul optical transport network operator's perspective. ©2023 The Author(s)*

Introduction

Optical transport network operators are confronted with exponential growth in data traffic demands in the coming years[1]. Recent advances in optical communication hardware development offer solutions for more efficient resource utilization in optical networks. One such development is the introduction of next-generation flexible bandwidth-variable transponders (BVTs), capable of symbol rates up to 140 GBd and a fine modulation rate adaptivity through probabilistic shaping (PS)[2]. Higher symbol rates enable the provisioning of high data-rate services at the expense of increased spectral blocking[3], while a fine granularity of BVT configurations enables the efficient utilization of existing optical line systems (OLSs)[4] when utilizing low-margin networking[5] to improve spectral efficiency. Meanwhile, the development of Multi-wavelength sources (MWSs) also creates a promising avenue for network operators as they can reduce the number of lasers that have to be deployed, potentially saving on transponders cost[6]. However, MWSs must be carefully evaluated as they add additional restrictions regarding routing, spectrum assignment, and quality of transmission (QoT)[7]. Finally, the extension to multi-band networks may reduce costs compared to multi-fiber upgrades[8]. Multi-band systems have been studied for network planning and optimization[9],[10]. The added complexity is introduced by frequency-dependent parameters, resulting in band-dependent QoT variations.

While these technologies have been evaluated in a network planning context, we aim to study the joint impact of using one or multiple emerging technologies compared to state-of-the-art optical transport networks. Therefore, in this work, we analyze the potential benefits of different technologies and provide strategic guidelines on technology consideration for optical transport network operators. Furthermore, we propose improvements to traditional heuristic-based network planning algorithms, so as to account for these recent technological advances.

Technologies under Evaluation

Multi-band transmission has been studied extensively, resulting in mature C+L-band systems. S-band systems are still subject to research, as erbium-doped fiber amplifiers (EDFAs) cannot be used but must be replaced by thulium-doped fiber amplifiers (TDFAs)[11]. Network planning for multi-band systems has shown to significantly increase the throughput of a network[10]. Multi-band systems provide added value when additional fiber is not available or expensive. Accurate QoT estimation in multi-band systems requires accounting for inter-channel stimulated Raman scattering (ISRS), e.g. by employing a closed-form ISRS Gaussian-noise (GN) model[12].

Commonly deployed state-of-the-art BVTs enable configurations of up to 600 Gbit/s achieved through a symbol rate of 70 GBd and a modulation format of 64 QAM. The next generation, doubling the possible data rate (up to 1200 Gbit/s) and symbol rate (up to 140 GBd) is already announced[2]. Additional to increasing the maximum possible configuration, finer granularity will be enabled through the use of probabilistically shaped quadrature amplitude modulation (PS QAM)[13]. We utilize previously presented considerations on how to derive conventional Signal to Noise Ratio (SNR) requirements for PS QAM modulations as well as a pre-selection algorithm for relevant configurations[4].

MWSs such as optical frequency combs[6] enable a single optical power supply, i.e., a laser, to generate several lines. The use of MWSs reduces the transmitted optical signal-to-noise ratio ($\mathrm{OSNR_{TX}}$) compared to a single-wavelength source (SWS) due to additionally required amplification. In our previous evaluations, we have presented multi-wavelength transponder architectures, derived realistic specifications, and compared them in a network planning context[7]. In this study, we consider a 4-line MWS with fixed free spectral range, i.e., fixed spacing between MWS lines, and an $\mathrm{OSNR_{TX}}$ penalty of 1 dB.

Modified Heuristic for Network Planning

With the deployment of elastic optical networks (EON) supporting a flexible grid consideration of transponder-specific configuration capabilities, new routing, configuration, and spectrum allocation (RCSA)[14] are required. While finding the optimal solution can be achieved using integer-linear programming (ILP), the problem is NP-hard, and solving the ILP for a typical network topology becomes too computationally complex[15]. Therefore, the problem is usually solved greedily, by utilizing heuristics. We consider aggregated traffic demands per source-destination pair with requested data rates according to a traffic model[10], which takes the population as well as the number of internet exchange points at each node into account. A common heuristic solver employs k-shortest-path routing, where the shortest out of k-shortest paths on which an available spectrum slot is found, will be chosen. The spectral slot is chosen according to first-fit assignment (i.e., assigning the first available slot on the spectrum) and finally, the highest-data rate configuration is chosen, bounded by the required SNR. In case no slot is found in any of those k paths or the requested data rate cannot be fully provisioned the traffic request, the demand is considered as totally or partially blocked, causing underprovisioning[16].

The inclusion of next-generation rate-adaptive transponder configurations significantly increases the number of considered configurations and leads to a maximum spectral slot size of 150 GHz. In order to reduce computational complexity, a pre-selection of configurations is performed[4]. Additionally, choosing the highest feasible data-rate configuration becomes more suboptimal for demands that do not require it, as a large part of the spectrum is blocked unnecessarily. According to the objectives of i) minimizing the number of deployed lightpaths (LPs) and ii) minimizing the spectral usage, we employ the strategy of choosing the highest data-rate configuration that is feasible, in case it does not fully satisfy the demand. If several feasible configurations are able to meet the demanded data rate, the one with the lowest symbol rate is chosen. For multi-band systems, in order to keep the flexibility to only upgrade the OLS when it becomes necessary, we prioritize placing LPs in the C-band and additional bands (L-band first, followed by the S-band) will only be considered if no C-band slot is found on any of the k paths[10].

Network Planning Study

Let us apply the discussed emerging technologies in a network planning study. The heuristic-based planning approach is used with k=3-shortest-path routing. The SNR of LPs is computed using the closed-form ISRS GN model[12]. The network links are assumed to consist of 80 km standard single-mode fiber spans followed by an EDFA in the C- and L-band and a TDFA in the S-band, compensating for the attenuation. Per band attenuation and amplifier noise figure values are considered[10] as well as frequency-dependent optimized launch powers[9]. We consider a used bandwidth of 5 THz in each band with a guard-band of 500 GHz in-between. The evaluation compares the following metrics: provisioned traffic, underprovisioning (UP)[10], and required LPs. Planning scenarios with rate-adaptive PS QAM-capable BVTs ("PS") and conventional BVTs using only uniform QAM configurations ("Uniform") are compared in C-band, C+L-band and C+L+S-band systems. 4-line Fixed-FSR MWSs are assumed to be deployed whenever a demand requires more than three LPs to be fulfilled[7]. While the results are consistent over multiple topologies, we focus on the Nobel-EU topology[17], due to space constraints.

Results

The scenarios are compared in terms of provisioned traffic, number of provisioned LPs and UP for a range of aggregate requested traffic (ART) achieved by scaling the considered traffic model. The results confirm the anticipated result of an increasing capacity when considering an additional band as well as an increased capacity for "PS" scenarios as compared to "Uniform". These relations are evident in the provisioned traffic for different scenarios and ART values (Fig. 2 (a)). The provisioned traffic for the C-band scenarios

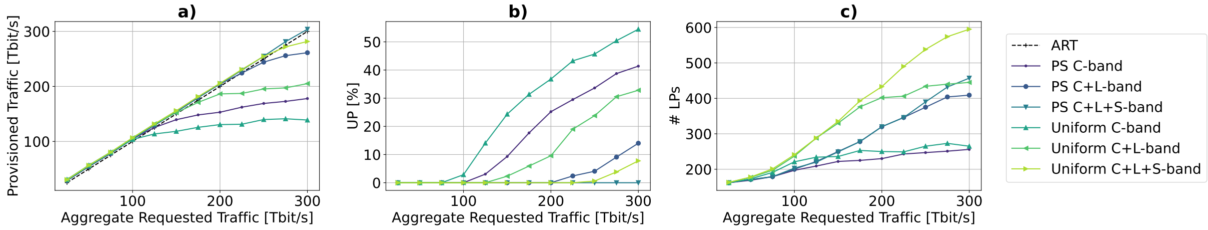

Fig. 1: Planning results on Nobel-EU topology. a) Provisioned traffic, b) underprovisioning (UP) and c) number of provisioned LPs over aggregate requested traffic (ART).

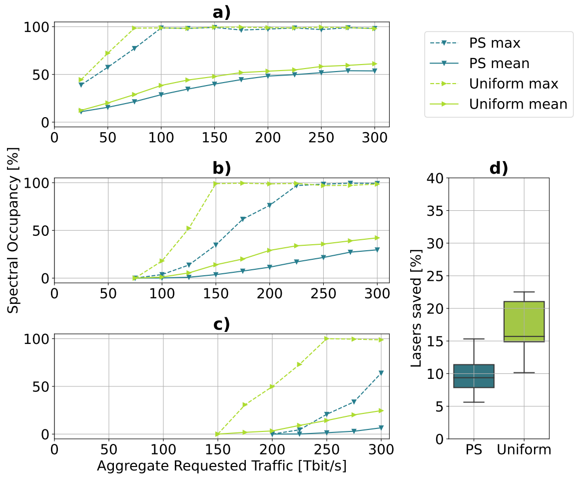

Fig. 2: Mean and maximum link spectrum used over aggregated requested traffic in (a) C-band, (b) L-band and (c) S-band and (d) saved lasers by using MWSs for the C+L+S-band scenarios from 150 Tbit/s ART.

lies below the ART for ART values of 125 Tbit/s and 150 Tbit/s for ”Uniform” and ”PS”, respectively. For the C+L-band scenarios, this occurs at 175 Tbit/s and 225 Tbit/s, showing an increasing difference between ”PS” and ”Uniform” performance in multi-band scenarios. At 300 Tbit/s, only the provisioned traffic for the C+L+S-band ”PS” scenario lies above the ART. It is the only one that can provision 300 Tbit/s ART without UP as shown inf Fig. 2 (b), while C-band ”Uniform” scenario has an UP of over 50 %. In line with the results for provisioned traffic, UP of ”PS” is significantly reduced compared to ”Uniform” (up to 17 %) when considering the same band-scenario. Similarly, the addition of a band reduces the UP substantially (up to 25 %).

Within the range of provisioning ART without UP, ”Uniform” scenarios provision up to 45 % more LPs than ”PS” scenarios (Fig. 2 (b)). Therefore, ”PS” not only increases the ART that can be provisioned, it can also lead to cost savings as less transponders are required than for ”Uniform”. Additional bands enable significantly more LPs to be provisioned in the network. The ”Uniform” scenario provisions a maximum of 270 LPs in the C-band scenario compared to 600 LPs in the C+L+S-band scenario for a 2.2 times increase. Although the usable bandwidth is tripled, the average SNR in the C+L+S-band is considerably lower, leading to a lower than linear increase in network capacity for additional bands. For the C+L+S-band scenarios, Fig. 1 shows mean and maximum link spectral occupancy for (a) C-band, (b) L-band and (c) S-band, respectively. Due to the topology and the routing algorithm, a few bottleneck links will be filled up quickly, while the mean spectral occupancy increases slower. ”Uniform” fills the spectrum faster than PS. While both scenarios start provisioning in the L-band for 75 Tbit/s ART, ”Uniform” provisions the first LP in the S-band at 150 Tbit/s ART while ”PS” requires the S-band only at 200 Tbit/s. The use of PS-BVTs can therefore delay the requirement of additional bands in the network. The deployment of MWSs enables savings in the number of required lasers as opposed to a pure SWS planning scenario. Higher relative savings are achieved for ”Uniform” than for ”PS”. As, lower data rate configurations are deployed for ”Uniform”, the deployment strategy of using MWSs is triggered more often. In absolute terms, however, ”PS” leads to significantly higher savings. While ”PS” requires 387 lasers (only considering the transmitter side) for 457 deployed LPs at 300 Tbit/s ART, for ”Uniform”, 461 lasers are required to deploy 595 LPs.

Conclusions

An improved heuristic-based planning algorithm accounting for the emerging technologies of multi-band systems, rate-adaptive transponders has been evaluated in a case study. We show that these technologies substantially increase the requested traffic that can be fully provisioned by more than a factor of three. Additionally, we observe significant savings in number of required LPs by 30 % and the number of lasers by 15 %.

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References

[1] W. Jiang, B. Han, M. A. Habibi, and H. D. Schotten, “The road towards 6g: A comprehensive survey”, *IEEE Open Journal of the Communications Society*, vol. 2, pp. 334–366, 2021. DOI: 10 . 1109 / OJCOMS . 2021 . 3057679.

[2] Acacia, *Acacia Unveils Industry’s First Single Carrier 1.2T Multi-Haul Pluggable Module*, https://acacia-inc.com/blog/acacia-unveils-industrys-first-single-carrier-1-2t-multi-haul-pluggable-module/, 2022.

[3] J. Pedro, N. Costa, and S. Pato, “Optical Transport Network Design Beyond 100 GBaud [Invited]”, *Journal of Optical Communications and Networking*, vol. 12, no. 2, A123–A134, 2020. DOI: 10.1364/JOCN.12.00A123.

[4] J. Müller, G. Di Rosa, T. Fehenberger, *et al.*, “On the Benefits of Rate-Adaptive Transceivers: A Network Planning Study”, in *27th International Conference on Optical Network Design and Modelling (ONDM)*, 2023.

[5] Y. Pointurier, “Design of low-margin optical networks”, *Journal of Optical Communications and Networking*, vol. 9, no. 1, A9–A17, 2017. DOI: 10 . 1364 / JOCN . 9 . 0000A9.

[6] G. Di Rosa, F. Smyth, M. Deseada Gutierrez, J. Müller, B. Wohlfeil, and J.-P. Elbers, “Advancements and Applications of Comb-Based Transceivers in Coherent Optical Networks”, in *Signal Processing in Photonic Communications (SPPCom)*, 2023.

[7] J. Müller, O. Jovanovic, T. Fehenberger, G. Di Rosa, J.-P. Elbers, and C. Mas-Machuca, “Multi-Wavelength Transponders for High-capacity Optical Networks: A Physical-layer-aware Network Planning Study”, *J. Opt. Commun. Netw.*, 2023. DOI: 10.1364/JOCN.483320.

[8] R. K. Jana, M. A. Iqbal, N. Parkin, *et al.*, “Multi-fiber vs. ultra-wideband upgrade: A techno-economic comparison for elastic optical backbone network”, in *European Conference on Optical Communication (ECOC) 2022*, Optica Publishing Group, 2022, We1A.5. [Online]. Available: https://opg.optica.org/abstract.cfm?URI=ECEOC-2022-We1A.5.

[9] B. Correia, R. Sadeghi, E. Virgillito, *et al.*, “Power control strategies and network performance assessment for c+l+s multiband optical transport”, *Journal of Optical Communications and Networking*, vol. 13, no. 7, pp. 147–157, 2021. DOI: 10.1364/JOCN.419293.

[10] S. K. Patri, A. Autenrieth, J.-P. Elbers, and C. Mas-Machuca, “Multi-band transparent optical network planning strategies for 6g-ready european networks”, *Optical Fiber Technology*, vol. 74, p. 103 118, 2022, ISSN: 1068-5200. DOI: https : / / doi . org / 10 . 1016 / j . yofte . 2022 . 103118. [Online]. Available: https : / / www . sciencedirect . com / science / article / pii / S1068520022003017.

[11] R. Emmerich, M. Sena, R. Elschner, *et al.*, “Enabling S-C-L-Band Systems With Standard C-Band Modulator and Coherent Receiver Using Coherent System Identification and Nonlinear Predistortion”, *Journal of Lightwave Technology*, vol. 40, no. 5, pp. 1360–1368, 2022. DOI: 10.1109/JLT.2021.3123430.

[12] H. Buglia, M. Jarmolovičius, A. Vasylchenkova, *et al.*, “A closed-form expression for the gaussian noise model in the presence of inter-channel stimulated raman scattering extended for arbitrary loss and fibre length”, *Journal of Lightwave Technology*, pp. 1–10, 2023. DOI: 10. 1109/JLT.2023.3256185.

[13] J. Cho and P. J. Winzer, “Probabilistic constellation shaping for optical fiber communications”, *Journal of Lightwave Technology*, vol. 37, no. 6, pp. 1590–1607, 2019. DOI: 10.1109/JLT.2019.2898855.

[14] A. Varasteh, S. K. Patri, A. Autenrieth, and C. Mas-Machuca, “Towards dynamic network reconfigurations for flexible optical network planning”, in *2021 Optical Fiber Communications Conference and Exhibition (OFC)*, 2021, pp. 1–3.

[15] B. C. Chatterjee, N. Sarma, and E. Oki, “Routing and spectrum allocation in elastic optical networks: A tutorial”, *IEEE Communications Surveys Tutorials*, vol. 17, no. 3, pp. 1776–1800, 2015. DOI: 10 . 1109 / COMST . 2015.2431731.

[16] C. Mas-Machuca, S. K. Patri, and S. Amjad, “Long-Term Capacity Planning in Flexible Optical Transport Networks”, in *2022 Optical Fiber Communications Conference and Exhibition (OFC)*, 2022, pp. 1–3.

[17] Zuse Institute Berlin, *SNDlib Problem Instances*, http: //sndlib.zib.de/, Accessed: 2023-01-17. [Online]. Available: %5Curl%7Bhttp://sndlib.zib.de/%7D.