European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Experimental Optimization of Spectrum-Efficient Super-Channels in Elastic Optical Networks

Margita Radovic[1], Andrea Sgambelluri [1], Filippo Cugini [2], Nicola Sambo[1]
[1] Scuola Superiore Sant'Anna, Pisa, Italy, margita.radovic@santannapisa.it
[2] CNIT, Pisa, Italy

Abstract *Automatic super-channel optimization is experimentally demonstrated using a 600Gb/s transponder in the SDN-controlled Elastic Optical Network. Margin reduction while guaranteeing Quality of Transmission allows for a spectrum occupation reduction of 25%. ©2022 The Authors*

Introduction

Super-channel transmission, enabled by Elastic Optical Networks (EONs), is a suitable solution for supporting the high line rates required to satisfy the ever-increasing Internet traffic demands [1]. However, super-channel optimization is challenging especially due to sub-carrier cross-talk and tight filtering [2], which may degrade the overall quality of transmission (QoT).

Current commercial transponders use coherent receivers and digital signal processing (DSP) for modulation/demodulation and for mitigating several physical-layer impairments. High physical-layer margins are typically utilized to cover the change of physical conditions and accompanying modelling uncertainties [3-5]. In particular, physical-layer margins are used to account for statistical variability of equipment performance caused by equipment aging, increasing interference due to the network demands, modelling errors, etc. Lowering the margins and increasing efficiency, significantly reduces the network costs, thus margin reduction has motivated various research studies [5].

The adoption of the SDN paradigm in the control of optical networks has been motivated by the need for automation and flexibility. In this context, the NETCONF protocol may be adopted, enabling both device configuration and the collection of performance monitoring information. NETCONF allows the exchange of information among the SDN controller and devices by exploiting YANG data models.

The OpenConfig (OC) model [6] is a set of YANG models designed to enable both vendor-neutral configuration and monitoring of main transponder parameters. The OC terminal device model defines mapping among client and line ports. At the line port side, the key OTN config and state parameters are stored (pre-FEC-BER, post-FEC-BER, Q-value and ESNR). The OC terminal device model is augmented with a platform component defining optical channel config parameters such as frequency, target output power, and operational modes (OP modes). However, vendor-specific parameters such as forward error correction (FEC) type are not defined within the OC YANG models. In fact, these transmission parameters are defined within the OP modes, thus enabling the model to remain stable and include proprietary advanced transmission solutions maximizing the performance [7-9].

Traditionally, the SDN controller has been applied to configure both channel parameters (e.g. central frequency) and filter parameters (e.g. switched bandwidth), for each channel. However, this approach may not be scalable when applied to each sub-carrier of a super-channel since many iterations may be required to adjust sub-carrier spacing.

In this paper, we propose super-channel sub-carrier spacing optimization (during provisioning) to be performed directly by the transceivers, thus limiting the SDN controller intervention in a super-channel optimization process. Then, we investigate the trade-off between super-channels QoT (pre-FEC – bit error rate – BER degradation) and spectrum saving by reducing the system margins and moving towards the performance threshold, which is achieved by allowing slight sub-carriers overlap and tight filtering. Next, the spectrum-efficient super-channel optimization is experimentally demonstrated by exploiting the Fujitsu T600 1Finity transponder supporting OC OP modes in an SDN-controlled EON testbed. Back-to-back experiments, performed as a proof of concept, are reported. Then, experiments are conducted considering a super-channel of two sub-carriers and optical reach of 80 km, 160 km, 240 km and 320km, respectively.

Method

In this section the proposed procedure designed for optimization of the spectrum-efficient super-channel composed of two sub-carriers of the same OP mode is described. Tx/Rx sub-carrier central frequency is moved by steps of 6.25 GHz towards the filter border and pre-FEC-BER degradation caused by cross-talk and filter effects is monitored.

We define the sub-carrier bandwidth cut for the left-side sub-carrier as an (x,y) pair, where *x* indicates the number of frequency steps cut from the filter side (one step = 6.25 GHz) and *y* represents the number of steps cut from the adjacent sub-carrier side. Therefore, cut per sub-carrier is defined as a sum of x and y values. For example, a (2,1) pair, i.e. cut = 3, saves 18.75 GHz of spectrum *per sub-carrier* by cutting 2 steps (12.5 GHz) from the filter side and 1 step (6.25 GHz) from the adjacent sub-carrier side.

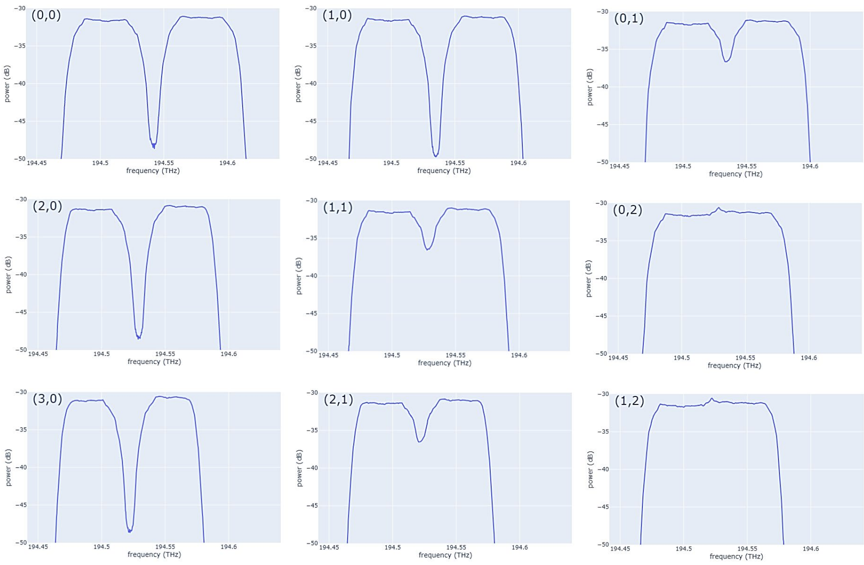

Fig. 1: Spectrum retrieved by an optical spectrum analyzer

Fig. 1 shows different combinations of cut modes, from cut = 3, i.e. (3,0), (2,1), (1,2), and (0,3) pairs, to cut = 0, i.e. (0,0) pair representing the normal conditions, where sub-carriers do not experience pre-FEC-BER degradation caused by either, cross-talk or filtering effects.

Initially, the SDN controller configures 2 sub-carriers, by setting OP modes, Tx/Rx frequencies and target output power, and reserves enough spectrum (i.e. 150 GHz, 75 GHz per sub-carrier). Next, super-channel optimization application is performed in which sub-carrier spacing is optimized by Tx and Rx, utilizing an <edit-config> message (exploiting OC components YANG model) between Tx and Rx agents to synchronize the central frequency. Application starts by investigating cut = 3, and all its possible combinations, i.e. (3,0), (2,1), (1,2) and (0,3).

Once the system applies the configuration it checks if the sub-carriers are both active, to determine if the cut is supported by the system. Application then proceeds to monitor and collect pre-FEC-BER values. It then continues exploring remaining cut (x,y) pairs and repeats the process of reconfiguring and monitoring pre-FEC-BER values for each (x,y) pair. Once all pre-FEC-BER values corresponding to each cut pair are collected, the configuration with the lowest monitored pre-FEC-BER value is selected. If the monitoring system reveals that the selected configuration is acceptable (pre-FEC-BER < TH), the procedure reconfigures the sub-carriers (<edit-config>) based on the configuration provided by the optimal cut pair. Similarly, if the selected configuration of cut = 3 is not acceptable (pre-FEC-BER > TH), the procedure starts exploring cut = 2, 1 and 0, respectively, while repeating the same process of finding the configuration with the lowest and acceptable pre-FEC-BER value. Once the optimal super-channel configuration is determined and applied to both sub-carriers, the application then uses a REST API interface to interact with the SDN controller, sending the final filter configuration (central frequency and bandwidth). Lastly, SDN controller enforces the new filter configuration.

Experimental validation and results

The back-to-back experiments, performed as a proof of concept, have been conducted to

Tab. 1: pre-FEC-BER values obtained according to optical reach and OP mode

	BTB	*160 km*	*240 km*	*320 km*
	OP6	*OP6*	*OP5*	*OP7*
	200G	*200G*	*300G*	*200G*
	8psk	*8psk*	*8psk-2*	*dp-qam16*
	75 GHz	*75 GHz*	*75 GHz*	*50 GHz*
(0,0)	2.01E-8	4.62E-5	2.65E-3	2.99E-3
(2,0)	9.33E-8	1.42E-4	5.23E-3	0.0108
(1,1)	1.65E-7	1.23E-4	4.94E-3	7.1E-3
(0,2)	8.64E-4	5.09E-3	0.0262	
(2,1)	1.76E-6	4.47E-4	0.0154	
(1,2)	2.26E-3	0.0106	0.029	

	BTB	*80 km*	
	OP2	*OP2*	*OP3*
	500G	*500G*	*400G*
	dp-qam32	*dp-qam32*	*dp-qam16*
	75 GHz	*75 GHz*	*75 GHz*
(0,0)	7.24E-3	0.02321	4.2E-3
(1,0)	9.99E-3		7.69E-3
(0,1)	0.0215		0.0221

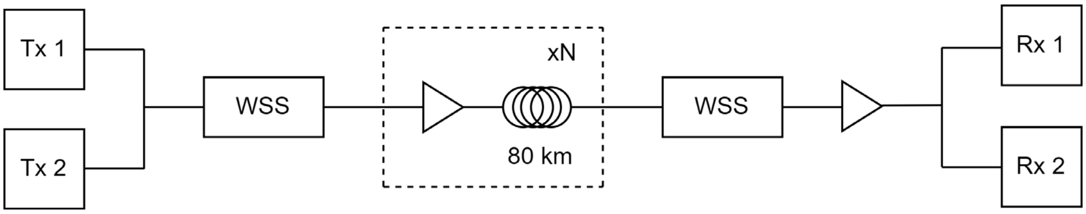

Fig. 2: Experimental testbed

assess the behaviour of the transponder in case of tight filtering (on side sub-carriers) and slight sub-carriers overlap. The results are referred to as BTB in Tab. 1. It can be observed that cross-talk due to sub-carriers overlap has a greater impact on pre-FEC-BER degradation than tight filtering. Furthermore, it is worth noting that system imposes higher margins for higher bit rates, OP2 (500G, DP-QAM16) and OP3 (400G, DP-QAM32). For two 75 GHz wide sub-carriers, (0,0) pair translates to 150 GHz of reserved spectrum, and it is considered the worst-case scenario in terms of bandwidth occupation.

Furthermore, the rest of the experiments is conducted in the context of the testbed reported in Fig. 2 to determine the impact of the optimization procedure on the pre-FEC-BER at varying the optical reach.

Two optical channels are aggregated at the Tx side to build a super-channel of desired capacity. Super-channel then traverses the first WSS filter.

Next, links of 80 km (N = 1), 160 km (N = 2), 240 km (N = 3) and 320 km (N = 4) of optical fibers are traversed. Finally, the super-channel goes through the second WSS and reaches Rx. Pre-FEC-BER values are represented in Tab. 1. It can be observed that the sub-carriers behave in the same way as reported in the back-to-back measurements, and that OP2 and OP3 become unavailable as we increase optical reach, caused by a more critical QoT, due to high-order modulation formats. However, spectrum-efficient super-channels with more robust OP modes can be utilized in case of longer distances. For example, a super-channel composed of two OP7 (50 GHz, 200G, DP-QAM16) sub-carriers is equivalent to a single OP3 (75 GHz, 400G, DP-QAM32) channel in terms of the bit rate, but is achieving longer reach. We can optimize OP7 super-channel using the proposed method, achieving the pre-FEC-BER of 7.1×10^{-3} and spectrum bandwidth of 75 GHz instead the nominal of 100 GHz for the optical reach of 320 km.

Fig. 3 shows the monitored pre-FEC-BER during the optimization procedure. In this case, the optimization process is experimentally validated by considering 80 km reach. The SDN controller configures filters at central frequency of 194.475 THz and 150 GHz of bandwidth, and Tx/Rx of two OP6 sub-carriers at 194.4375 THz and 194.5125 THz. The optimization procedure is triggered and the optimal super-channel configuration is obtained in four algorithm steps (Fig. 3). At the step 3, since the lowest obtained pre-FEC-BER value is below the assumed threshold ($2.5 \times 10^{-4} < 2.5 \times 10^{-2}$), the sub-carriers are reconfigured at 194.425 THz and 194.4875 THz (step 4). Then, the application sends the new central frequency and bandwidth (194.45625 THz and 112.5 GHz) to the SDN controller via REST API, which is used to reconfigure the filter. This process allowed for the saving of 37.5 GHz (25%) of the spectrum.

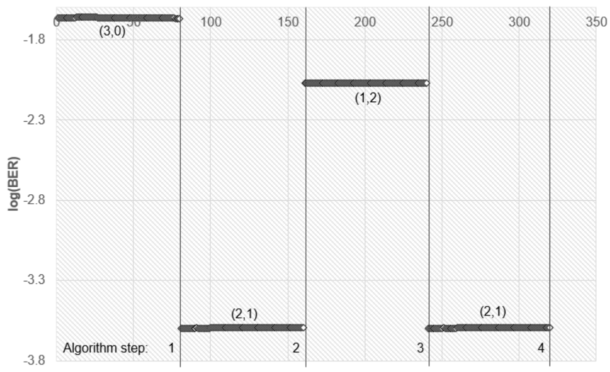

Fig. 3: Monitored pre-FEC-BER during the optimization procedure

Conclusions

We successfully demonstrated through experiments automatic optimization of the spectrum-efficient super-channel in an EON testbed. The SDN controller is not involved during sub-carrier spacing optimization. We experienced that cross-talk may be more detrimental than filtering effects. The proposed method allows for spectrum reduction of 25%. Future works will investigate the support of multiple sub-carriers, considering each carrier set with a different OP mode.

Acknowledgements

The authors thank Fujitsu Network Communications for providing the T600 C-band PIU transponder. This work has been supported by the MIUR PRIN2017 "FIRST" Project (GA 2017HP5KH7 002) and by the MISE JUMP.

References

[1] N. Sambo, G. Meloni, F. Paolucci, F. Cugini, M. Secondini, F. Fresi, L. Poti, and P. Castoldi, “Programmable transponder, code and differentiated filter configuration in elastic optical networks,” J. Lightwave Technol., vol. 32, no. 11, pp. 2079– 2086, June 2014, DOI: 10.1109/JLT.2014.2319859.

[2] A. P. Vela et al., "BER Degradation Detection and Failure Identification in Elastic Optical Networks," in Journal of Lightwave Technology, vol. 35, no. 21, pp. 4595-4604, 1 Nov.1, 2017, DOI: 10.1109/JLT.2017.2747223.

[3] J. -L. Augé, "Can we use flexible transponders to reduce margins?" 2013 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC), 2013, pp. 1-3, DOI: 10.1364/OFC.2013.OTu2A.1.

[4] Yvan Pointurier, "Design of Low-Margin Optical Networks," J. Opt. Commun. Netw. 9, A9-A17, 2017, DOI: 10.1364/JOCN.9.0000A9.

[5] K. Christodoulopoulos et al., "Toward efficient, reliable, and autonomous optical networks: the ORCHESTRA solution [Invited]," in Journal of Optical Communications and Networking, vol. 11, no. 9, pp. C10-C24, September 2019, DOI: 10.1364/JOCN.11.000C10.

[6] https://www.openconfig.net/

[7] D. Scano, A. Giorgetti, S. Fichera, A. Sgambelluri and F. Cugini, "Operational Mode and Slicing Adaptation in OpenConfig Disaggregated Optical Networks," 2020 Optical Fiber Communications Conference and Exhibition (OFC), 2020, pp. 1-3, DOI: 10.1364/OFC.2020.W3C.4.

[8] A. Sgambelluri, A. Giorgetti, D. Scano, F. Cugini and F. Paolucci, "OpenConfig and OpenROADM Automation of Operational Modes in Disaggregated Optical Networks," in *IEEE Access*, vol. 8, pp. 190094-190107, 2020, DOI: 10.1109/ACCESS.2020.3031988.

[9] R. Casellas et al., "Advances in SDN control for Beyond 100G disaggregated optical networks," 2021 European Conference on Optical Communication (ECOC), 2021, pp. 1-44, DOI: 10.1109/ECOC52684.2021.9605881.