Non-Linear Effects of WDM Transmission versus Optical Routing Impairments: Does One Prevail at Network Level?

Thierry Zami[(1)], Matteo Lonardi[(2)], Nicola Rossi[(1)], Bruno Lavigne[(1)]
(1) Nokia, Nozay, France, (2) Nokia Bell-Labs, Nozay, France
Thierry.zami@asn.com

Abstract: The influence on network performance of WDM transmission non-linear effects is compared to the impact of optical filtering and crosstalk induced by the wavelength routing cross-connects, for 3 network topologies and 2 distinct transponder technologies © 2022 Nokia

1. Introduction

Even if they support the relentless growth of the worldwide digital ecosystem, transmitting and routing WDM carriers in optical fiber networks remain basically analogic. In that context, the model of the physical impairments that these carriers undergo is complex, whereas its calculation time should comply with required speed of on/off-line network planning tools [1]. Optical channels experience the following degradations in transparent meshed WDM networks: **i)** imperfection of Elastic Optical Transponder (EOT) [2]; **ii)** accumulation of the Amplified Spontaneous Emission (ASE) from the traversed optical amplifiers [3]; **iii)** spectral tilt of amplifier gains and of fiber losses yielding uneven transmissions for distinct channels of the WDM comb [4]; **iv)** Non-Linear Effects (NLEs) of WDM transmission [3]; **v)** traversals of wavelength-routing Optical Cross-Connects (OXC) more specifically implying filtering [5], optical crosstalk [6], and Polarization Dependent Loss (PDL) [7]. In general, most of the attention is paid to modelling the 4 first distortions of this list as they prevail in the point-to-point transmissions, like in the subsea challenging WDM systems. But the fifth group of degradations cannot be neglected in meshed transparent networks. Hence, we examine the relative influences of Filtering and Crosstalk Impairments (FXI) against NLEs via "what if" network designs comparing ultimate network throughputs by disabling NLEs or FXIs. This assessment is achieved on 3 topologies of meshed transparent core networks and for 62 to 90 Gbaud EOT technologies.

2. Comparison methodology

Our numerical model of NLEs and FXIs impacts relies on [3], [5] and [6] respectively with equation coefficients updated for optical carriers faster than 60 Gbaud. Point-to-point WDM systems are inadequate to fairly compare them, because these systems nearly do not exhibit FXIs, except in their ingress and egress terminals. Whereas FXIs occur in each OXC crossed transparently in meshed WDM networks. Hence, for pertinent assessment, we compare NLEs and FXIs effects on a large set of transparent Light Paths (LP) through a meshed topology. This set should stem from an actual network planning instead of generic set of k-Shortest Paths (k-SP). Because, the distribution of lengths in a k-SPs set related to a given network notably differs from the one of all the LPs really allocated when planning that network. Thus, considering k-SPs may overrate the influence of the physical degradations more dominating for the longest transparent LPs not as present in LPs breakdown resulting from a real network planning [8]. Benchmarking the NLEs and FXIs impacts on LPs from a network design could be done by examining the shift of Signal to Noise Ratio (SNR) they both induce along each LP. However, a SNR change is not directly indicative of the extra carrier capacity its absence could provide, as the related SNR shift does not always cross a SNR boundary in between 2 data rates of the considered EOT technology [8]. Thus, a more insightful method to reflect the respective NLEs and FXIs impacts is via the Maximum Network Capacity (MNC) that could be obtained if each of these degradations was not active. The more prominent a WDM physical degradation is, the larger extra MNC its absence could bring. To determine MNC, we consider a distribution of traffic where demanded bidirectional symmetrical connections are gradually served transparently through the network with a single optical carrier bridging their source and destination OXCs, with respect to the spectral resources available in each traversed network link. When there are not enough free spectral slots for such a LP across the network or if the found LPs are too long to be transparently covered by any modulation of the envisaged EOT, the related demanded connection is discarded. We then allocate to each connection established in that manner the maximum channel capacity possible with the simulated EOT technology with respect to the Quality of Transmission (QoT) along its LP. Once 1% of the total number of demanded connections has been rejected, the MNC is then reached. It is the sum of the data rates of all the connections established so far. In the remainder, we compare mean MNCs on various network topologies and EOT technologies, when NLEs and FXIs are enabled or disabled in turn. Even if switching on/off the NLEs/FXIs is only theoretical, this comparison is done on the same equipment basis. Hence, when disabling NLEs the channel power settings stay the same as with activated NLEs and the maximum output power the in-line amplifiers can deliver is still 23 dBm. Moreover, for fair benchmarking it is also important that toggling FXIs or NLEs keeps the penalty of other physical impairments unchanged. For that reason, even when ignoring FXIs, the channel spectral spacing is kept at the same nominal value as if FXIs are accounted for, still to mitigate the penalty owing to optical crosstalk, particularly between adjacent added channels multiplexed by optical couplers.

3. Assumption of network study

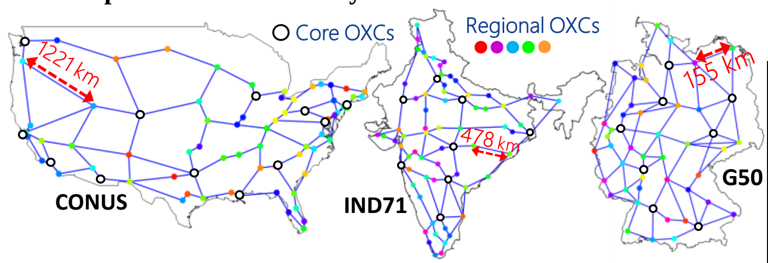

Figure 1: *3 studied WDM network topologies: G50, IND71 and CONUS*

Table 1: *G50, IND71 & CONUS characteristics*

	G50	IND71	CONUS
Max link length (km)	241.4	587.9	1221.2
Min link length (km)	30.75	54.22	24.21
Mean link length (km)	110.15	227.93	395.8
Mean length of fiber span (km)	56.2	63.29	69.16
Mean OXC connectivity	3.52	2.73	2.64

We study the 3 networks G50 [9], IND71 and CONUS [9] illustrated in Fig. 1 and described by Table 1. G50/ IND71/CONUS respectively has 88/97/99 pairs of bidirectional WDM links and 50/71/75 OXCs, split into 8/8/12 core OXCs and 42/63/63 regional ones. We assume WDM links made of spans of G.652 standard single mode fiber interleaved with erbium doped fiber amplifiers operating over the 4800 GHz-wide C band with 5.5 dB noise figure. The fiber local Chromatic Dispersion (CD) is 16.7 ps/nm/km not compensated in-line, with 0.22 dB/km loss, 80 μm^2 effective area and $2.6x10^{-20}$ m^2/W non-linear index. The power of channel launched in the fiber depends on the span loss with a rule similar to [4], leading to 4 dBm for a 67 Gbaud channel and 22 dB span loss. This launched power is proportional to the channel symbol rate in linear domain. The network nodes are "Route&Select" OXCs based on Wavelength Selective Switch (WSS). Thus, a channel is filtered twice when traversing transparently an OXC. The simulated WSS's are in line with the current mature WSS technology featuring 6.25 GHz waveband granularity with 8 GHz "bandwidth optical transfer function" characterizing their filtering sharpness [10]. Owing to the WSS imperfect isolation, each traversed OXC adds to the main channel a detrimental in-band crosstalk signal with at most -40 dB lower power. Our physical model of WDM transmission and routing accounts for each degradation reported in the introduction, with filtering impact modelled as penalty on Optical SNR [5]. NLEs-related noise variances are established by assuming fully loaded WDM links. The traffic can be hierarchical with 33.33% of connections between random pairs of core OXCs and 66.66% of connections between random pairs of regional/core OXCs, the core selected OXC always being among the 2 closest ones of the regional OXC. Alternatively, the traffic can be uniform with connections in between random pairs of OXCs. We envisage 2 types of coherent EOT relying on probabilistic constellation shaping with variable entropy: **EOT67** represents EOTs running from 62 to 67 Gbaud and transmitting 75 GHz-spaced channels with data rate ranging from 100 to 500 Gb/s with 50 Gb/s granularity. **EOT90** corresponds to the most recent EOTs operating with 90 Gbaud channels 100 GHz apart and carrying from 200 to 700 Gb/s also with 50 Gb/s steps [11]. Each combination of EOT technology and topology is simulated 100 times with 100 distinct random traffics and their average MNCs are established as explained in section 2.

4. Simulation results and discussion

Fig. 2 reports our simulation results in terms of extra MNC percentage when FXIs or NLEs are disabled. It shows 2 distinct patterns depending on the EOT technology. With EOT67, most of FXIs and NLEs impacts are equivalent regarding their effect on MNC reflected by the bar heights. These bars grow along with the mean length of the LPs covered transparently, which lengthens when the traffic changes from hierarchical to uniform or when the topology changes from G50 up to CONUS. The possible gains on MNC are the smallest for G50 equipped with hierarchical

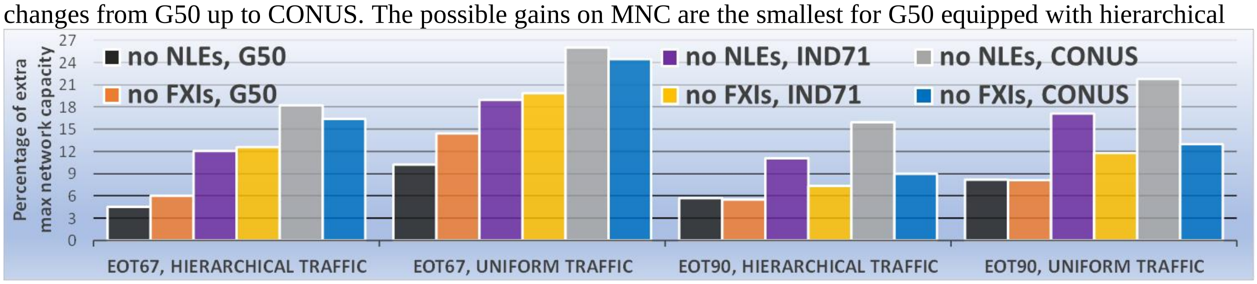

Figure 2: *Comparison of percentages of extra MNC when disabling NLEs or FXIs impairments on G50, IND71 and CONUS networks serving hierarchical or uniform traffic, with 62/67 Gbaud or 90 Gbaud EOT technologies*

traffic, because even when all the physical impairments are considered at least 74% of the established LPs already support the maximum 500 Gb/s data rate. So, disabling NLEs or FXIs only marginally changes the global MNC. For all the other network setups simulated with EOT67, the longest LPs lead to most of them running with channel data rates not larger than 400 Gb/s in case of nominal physical impairments. This leaves more room for larger channel data rate and then MNC growth if neglecting the NLEs or FXIs impact, as depicted in Fig. 2. The second noticeable pattern can be seen with EOT90. Fig. 2 shows a visible discrepancy between the effects of NLEs vs. FXIs. The former ones remain comparable with those observed with EOT67, whereas the latter ones substantially drop with respect to those with EOT67. Because when the channel symbol rate grows from 67 to 90 Gbaud while keeping the same OXC filtering spectral edge sharpness, the penalty of filtering from 75 GHz-wide to 100 GHz-wide bandwidth notably decreases, as quantified by [12]. The values reported in Fig. 2 also strongly depend on the channel data rate granularity. Hence, we also ran the same simulations with 100 Gb/s instead of 50 Gb/s data rate granularity and these additional results appear in Fig. 3. It reports the same relative trends as Fig. 2, but with globally halved extra percentages of MNC because of widest SNR intervals in between the boundaries of the carrier data rates [8].

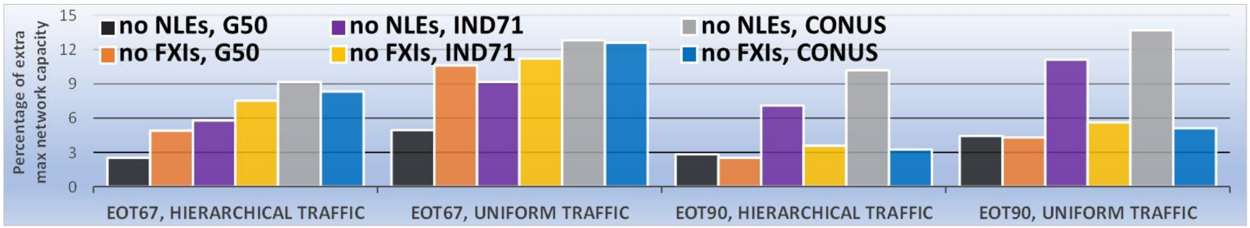

Figure 3: *Same results as Fig.2, but with 100 Gb/s data rate granularity instead of 50 Gb/s in Fig. 2*

5. Conclusions

The results of this study are representative for core WDM meshed networks based on G.652 optical fibers without in-line CD offset, as they stand for the most widespread currently deployed greenfield networks. For networks based on notably more non-linear fibers (like non-zero dispersion shifted fibers) and/or with compensation of in-line CD, the NLEs might be significantly larger. However, we do not expect the related effects on the maximum network capacity to notably change relatively to what Fig. 2 and 3 report. Because under more non-linear conditions, the nominal channel power settings will be brought down accordingly. The optical filtering assumptions of this study were also far from worse possible ones, as some more modern upcoming WSS's, like 8x8 WSS [13] or C+L WSS [14], are expected with filter shapes less optimal than the start-of-the-art current WSS's [13]. The most noteworthy outcome of this study is that ignoring the impact of wavelength routing network elements might be as misleading as neglecting the impact of the WDM transmission non-linear effects for assessing the performance of some backbone transparent networks, like G50. This is insightful to put pertinent effort in developing the most appropriate model for the impact of each physical impairment undergone by the WDM channels.

6. References

[1] M. Angelou et al., "Benefits of Implementing a Dynamic Impairment-Aware Optical Network: Results of EU Project DICONET", IEEE Communications Magazine, Page 79, August 2012.
[2] T. Gerard at al., "Relative impact of channel symbol rate on transmission capacity", IEEE/OSA Journal of Optical Communications and Networking, Vol. 12, No. 4, April 2020.
[3] B. Lavigne et al., "System design tool for high bit rate terrestrial transmission systems with coherent detection", Bell Labs Technical Journal, Vol. 18, n°3, Page 251, December 2013.
[4] J.-L. Auge et al., "Open design for multi-vendor optical networks", Paper Th1I.2, OFC'2019, March 2019.
[5] I. Fernandez de Jauregui Ruiz et al., "An Accurate Model for System Performance Analysis of Optical Fibre Networks with In-line Filtering", Paper P78, ECOC'2019, September 2019.
[6] T. Zami et al., "Impact of crosstalk on 800 Gb/s 90 GBaud 64QAM channel", Paper M5C.3, OFC'2021, June 2021.
[7] C. Xie, "Polarization-Dependent Loss Induced Penalties in PDM-QPSK Coherent Optical Communication Systems", Paper OWE.6, OFC'2010, March 2010.
[8] T. Zami et al., "Benefit of ageing of margins in WDM elastic networks when accounting for regeneration", Paper TuA1-2, OECC/PSC 2019, July 2019.
[9] http://sndlib.zib.de for G50 network and http://monarchna.com/topology.html for CONUS network
[10] C. Pulikkaseril et al., "Spectral modeling of channel band shapes in wavelength selective switches", OSA Optics. Express, Vol. 19, n°9, page 8458, https://doi.org/10.1364/OE.19.008458 , April 2011.
[11] S. Melle et al., "Comparing IP-Optical Architectures & WDM Transport Technologies in Metro, Regional and Long-Haul Networks", Paper M3E.2, OFC'2021, June 2021.
[12] T. Zami et al., "Filter-induced OSNR penalty in WDM fiber networks when optical channel symbol rate grows beyond 80 GBaud", Paper NeTu1B.4, in proceedings of conference Network/APC'2020, July 2020.
[13] I. Fernandez de Jauregui Ruiz et al., "Implications of NxM WSS in terms of filtering" Paper TuF2-4, OECC/PSC'2019, July 2019.
[14] N. K. Fontaine et al, " Low Loss Wavelength Selective Switch with 15-THz Bandwidth", Paper Mo3H.5, ECOC'2018, September 2018.