Benchmarking of Opaque Versus Transparent Core WDM Networks Featuring 400ZR+ QSFP-DD or CFP2 Interfaces

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Abstract This study illustrates and compares how a German and an Indian core WDM networks perform when equipped with 400ZR+ QSFP56-DD or CFP2-DCO regional transponders, depending on whether they are designed as opaque or as transparent elastic networks.

1 Introduction

Operators of optical fiber telecommunication networks currently expect 400ZR+ Elastic Optical Transponders (EOT) [1][2][3] will greatly streamline their associated capital and operational expenditures. Because plugging these EOTs directly into the Electrical Cross-Connect (EXC) rules out the client interfaces and EOT shelves needed with conventional transponders, provided the required channels do not exceed the maximum electrical power consumption allowed by these small form-factor EOTs. Since their WDM transmission performance is not as optimal as the one of the high-end WDM transponders [1][2], they are mainly intended for regional networks. Coming back to an opaque version of WDM network along with the wide adoption of these pluggable EOTs could comply with larger core networks and maximize their capacity. However, it would also notably augment the number of deployed EOTs per Gb/s with respect to a transparent network design. Nevertheless, considering the potential reduction of cost and of electrical power per Gb/s of these pluggable EOTs, the opaque design could still be deemed as worthwhile. This study assesses the relevance of such a step backward for WDM backbone networks as wide as Germany (G50) or India (IND71) with 2 different matrices of traffic, by comparing the cases with 400 Gb/s QSFP-DD coherent EOTs versus 400 Gb/s CFP2 ones.

2 Simulation assumptions

For this comparison, we model the optical layer of the G50 [4] and IND71 networks sketched in Fig. 1. G50 (resp. IND71) is a German (resp. Indian) WDM core topology consisting of 50 (resp. 71) wavelength-routing

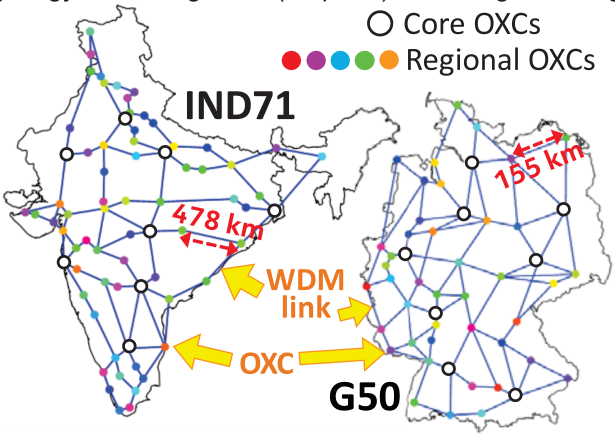

Figure 1: The 2 studied network topologies

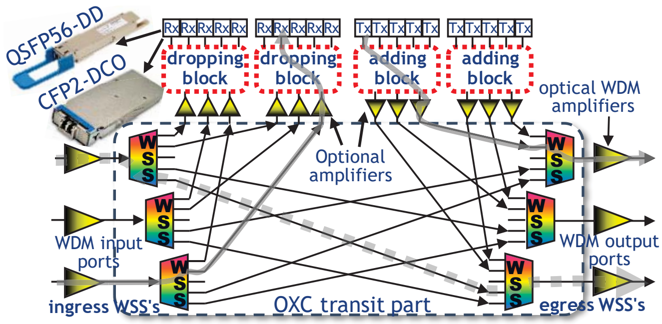

Figure 2: Layout of 3-degree "Route&Select" OXC, **Tx**:transmitter, **Rx**: coherent receiver, **WSS**: wavelength selective switch

Optical Cross-Connects (OXC) and 88 (resp. 97) optical links drawn as blue lines Fig. 1. Each line stands for a pair of counter-directional cascaded spans of Standard Single Mode Fiber (SSMF) with 0.22 dB/km loss. The average span length is 56.9 km for G50 and 75.5 km for IND71. An erbium doped fiber amplifier offsets the optical loss of each fiber span with 5.5 dB noise figure. The coherent detection of the EOT performs Forward Error Correction (FEC) and compensates for the whole chromatic dispersion not optically balanced in line. Up to 64 WDM 75 GHz-spaced carriers are transmitted per fiber in the 4800 GHz-wide C-band window. The 4 possible carrier modulations are 100 Gb/s at 32 GBaud and 200, 300 or 400 Gb/s at 63 GBaud. We simulate 2 types of EOTs capable of these 4 channel data rates: either 400ZR+ QSFP-DD EOT [1] with very low power consumption, 2.10^{-2} bit error rate at FEC threshold, relatively low transmitter output power and relatively high required power for detected channel; or more powerful CFP2 EOT [3] enabling better (possibly proprietary) FEC and better complying with the add/drop power budgets of the legacy OXCs. The higher compactness of the QSFP-DD version also entails more imperfect optical front-end than the CFP2 one, reflected in their distinct respective required Optical Signal to Noise Ratio (OSNR) at FEC threshold. We account for it by simulating 1.15 dB lower required OSNR with CFP2 EOTs than with QSFP-DD EOTs for 400 Gb/s PDM-16QAM channel modulation. We suppose "Route&Select" OXC layout (see fig. 2) for transparent network designs with suitable intermediate optical amplification in the add/drop blocks ensuring high enough power for added/dropped channels (at least -5 dBm power for the detected channel). To assess the physical feasibility of each tested transparent Light Path

Table 1: Parameters of the 2 considered categories of hierarchical traffic: T1 and T2

Traffic	X	Y	X' distribution, with 100 Gb/s granularity	Y' distribution, with 100 Gb/s granularity
T1	1 Tb/s	500 Gb/s	Uniform, from 500 Gb/s to 1 Tb/s	Uniform, from 100 Gb/s to 400 Gb/s
T2	2 Tbs	800 Gb/s	Uniform, from 1.2 Tb/s to 2 Tb/s	Uniform, from 400 Gb/s to 800 Gb/s

(LP), we establish its filtering-induced OSNR penalty [5] as well as its optical linear and non-linear noises created by the WDM transmission [6]. We assume hierarchical geographical distribution of traffic as proposed by [7] to be more representative of actual traffic in core WDM networks than the usual spatial distribution. To that aim, we consider 2 classes of OXC. The ones depicted as black and white (resp. colorful) points in fig. 1 are respectively core (resp. regional) OXCs. Regional OXCs do not directly exchange traffic. For each simulated network planning, one part of the traffic matrix is fixed with X Gb/s bidirectional connections between each pair of core OXCs and 2 distinct Y Gb/s bidirectional connections between each regional OXC and its 2 closest core OXCs. The additional part of the traffic matrix consists of connections carrying X' (resp. Y') Gb/s random throughput between randomly drawn pairs of core OXCs (resp. random pairs of core and regional OXCs), with uniform distribution between all the pairs of OXCs. For this study we simulate 2 traffic types, T1 and T2, depending on the values of X, Y, X' distribution and Y' distribution, as defined in Table 1.

If the capacity of a sole simulated EOT is insufficient to serve a connection, it is split over several EOTs by assuming inverse multiplexing in the EXCs associated to its source and destination OXCs. The related subcarriers follow the same LP through the network and are regenerated in the same network nodes. If the network is opaque, each optical signal is regenerated at each network node it crosses via its associated EXC capable of further intermediate Traffic Aggregation (TA). After serving the first fixed part of traffic, its extra random part is gradually accommodated one connection after another if an appropriate LP exists with the requested throughput, up to the point when more than 1% of the total demanded traffic has been rejected. The total throughput allocated so far is then considered as the Maximum Network Capacity (MNC) for this traffic and we also establish the corresponding mean number of deployed EOTs per 100 Gb/s transmitted, denoted N_{EOT}. The higher MNC the better, whereas the lower N_{EOT} the better. Each outcome reported in the following tables is a mean value averaged over 100 draws of random traffic as reported in Table 1.

3 Simulation results with traffic T1

Our simulation results MNC and N_{EOT} appear in Table 2 for traffic T1 and for various implementations of G50 and IND71. For G50, the opaque cases do not differ with QSFP-DD or CFP2 interfaces, because with both types of EOT the maximum 400 Gb/s channel data rate can cover all the G50 links. By contrast, MNC improves by 12.6% (241 vs. 214 Tb/s) from QSFP-DD to CFP2 EOTs in the IND71 opaque case, because 88 of the 97 IND71 links can be bridged by 400 Gb/s channels with CFP2 EOTs, against only 73 links with 400ZR+ QSFP-DD EOTs. The maximum benefit of TA performed in case of opaque network reaches up to 6% of extra MNC and -8% N_{EOT} saving for IND71 with QSFP-DD EOTs, because the lower mean connection throughput of traffic T1 (than traffic T2, see Table 1) leaves room for higher filling ratio of the carrier capacities via TA. Despite this better N_{EOT} efficiency, the opaque network still requires 2.5 times more EOTs per Gb/s than the transparent version in average, as far as the ultimate network capacity is concerned. This also means 2.5 times more 400 Gb/s EXC ports, which is not effective for only 45% extra MNC in the best case (from 166.7 Tb/s to 241.2 Tb/s for IND71). By definition, designing transparent networks implies longer LPs than the opaque design and then leads to lower mean spectral efficiencies with much lower MNC. For the same reason of longer transparent LPs, the more performant CFP2 EOTs reduce N_{EOT} by 3% to 5% against deploying QSFD-DD EOTs, even for the IND71 opaque version because of its longest OXC-to-OXC links. The benefit of the CFP2 EOTs in terms of MNC ranges from 12.6% for opaque IND71 to only 3.4% (166.7 vs 161.1 Tb/s) for transparent IND71. This 3.4% smaller gain stems from the breakdown of the lengths of the transparent LPs in IND71, that less favorably matches the intervals of transmission distance over which the CFP2 EOTs can provide 100 Gb/s more channel capacity than the QSFP-DD ones.

4 Simulation results with traffic T2

The outcomes of Table 3 are like those of Table 2, but for traffic T2. The higher average capacity of exchanged traffic T2 leads to higher filling ratio of the allocated optical carriers than traffic T1, and then to significantly

Table 2: Mean MNC and N_{EOT} for G50 and IND71 topologies with traffic T1, as a function of the network implementation

	G50 with 400ZR+ QSFP-DD EOTs	G50 with regional CFP2 EOTs	IND71 with 400ZR+ QSFP-DD EOTs	IND71 with regional CFP2 EOTs
MNC (opaque, no TA)	300.6 Tb/s	300.6 Tb/s	201.7 Tb/s	227.4 Tb/s
MNC (opaque, with TA)	313.5 Tb/s	313.5 Tb/s	214.2 Tb/s	241.2 Tb/s
MNC (transparent)	238.6 Tb/s	255 Tb/s	161.1 Tb/s	166.7 Tb/s
N_{EOT} (opaque, no TA)	2.47 per 100 Gb/s	2.47 per 100 Gb/s	3.14 per 100 Gb/s	3 per 100 Gb/s
N_{EOT} (opaque, with TA)	2.31 per 100 Gb/s	2.31 per 100 Gb/s	2.88 per 100 Gb/s	2.75 per 100 Gb/s
N_{EOT} (transparent)	0.91 per 100 Gb/s	0.85 per 100 Gb/s	1.2 per 100 Gb/s	1.12 per 100 Gb/s

Table 3: Mean MNC and N_{EOT} for G50 and IND71 topologies with traffic T2, as a function of the network implementation

	G50 with 400ZR+ QSFP-DD EOTs	G50 with regional CFP2 EOTs	IND71 with 400ZR+ QSFP-DD EOTs	IND71 with regional CFP2 EOTs
MNC (opaque, no TA)	361.8 Tb/s	361.8 Tb/s	251 Tb/s	286 Tb/s
MNC (opaque, with TA)	366.4 Tb/s	366.4 Tb/s	262.9 Tb/s	289.8 Tb/s
MNC (transparent)	289.1 Tb/s	310 Tb/s	205.8 Tb/s	213 Tb/s
N_{EOT} (opaque, no TA)	2 per 100 Gb/s	2 per 100 Gb/s	2.44 per 100 Gb/s	2.31 per 100 Gb/s
N_{EOT} (opaque, with TA)	1.98 per 100 Gb/s	1.98 per 100 Gb/s	2.42 per 100 Gb/s	2.3 per 100 Gb/s
N_{EOT} (transparent)	0.73 per 100 Gb/s	0.69 per 100 Gb/s	0.99 per 100 Gb/s	0.92 per 100 Gb/s

higher MNC with lower N_{EOT}. This initial higher filling ratio also makes TA less profitable with traffic T2, since it only enhances N_{EOT} by 1% and MNC by 4.7% at most for IND71 (from 251 to 263 Tb/s). Like in Table 2, transparency in Table 3 notably affects MNC by -21% in average versus opaque design. But it still favorably and strongly reduces N_{EOT} as well, by a factor of 2.87 for G50 equipped with CFP2 EOTs (0.69 vs. 1.98) and a factor of 2.63 in average. These savings also concern the number of 400 Gb/s EXC ports. This demonstrates the paradigm of transparent WDM networks remains relevant against the opaque network setup even if 400ZR+ QSFP-DD EOTs and regional CFP2 EOTs better streamline cost, power and footprint than the usual WDM transponders. Thus, interfacing these 2 novel EOT technologies directly with the EXCs without intermediate usual shelves of WDM transponders can still be profitable on top of an underlying optical wavelength-routing layer, provided the power budget inside the OXC add/drop stages is adapted to suit their relatively low emitted power and high required power for the detected channels. Comparing data of Tables 1 and 2 shows that the missed opportunities of further TA disabled by the optical transits will gradually become negligible, as the mean exchanged throughput between the OXCs will keep on growing and will then better fill the throughputs of the channels even without TA.

The differences of MNC and N_{EOT} from QSFP-DD to CFP2 EOTs do not exceed 7% for each line of Tables 1 and 2, due to their only 1.15 dB gap of required OSNR assumed for this study at 400 Gb/s channel modulation. Their actual OSNR difference might be larger as several distinct vendors of WDM systems are still developing more or less proprietary versions of these EOTs [1][8][9].

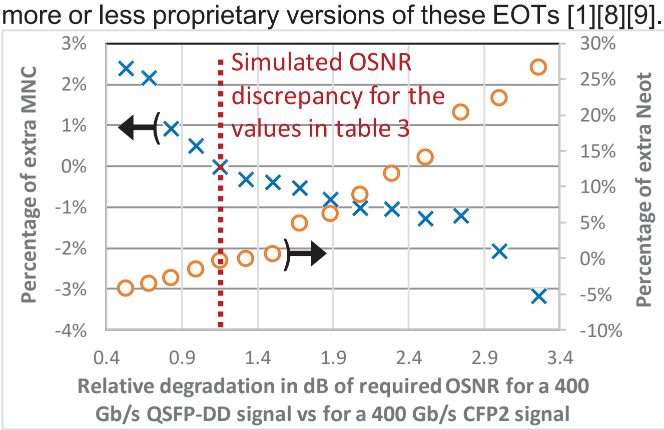

Figure 3: Evolution of MNC and N_{EOT} for transparent IND71 design, with respect to the QSFP-DD vs. CFP2 discrepancy of required OSNR for a 400 Gb/s channel

For a more comprehensive view of its impact, we design IND71 transparently with traffic T2 by scanning this gap of required OSNR in between the CFP2 and QSFP-DD EOT implementations. We expect further OSNR divergence will reduce global spectral efficiency reflected in lower MNC and imply more regeneration leading to higher N_{EOT}. Our results depicted in fig. 3 show that while the IND71 ultimate capacity does not decrease by more than -3.2% even when this OSNR gap culminates at 3.2dB, this is at the expense of 27% growth of N_{EOT}.

5 Conclusion

The first evident finding from our network study is the large multiplication of EOTs to be installed if designing core networks as wide as G50 or IND71 in an opaque way with 400 Gb/s pluggable interfaces. Such an opaque planning can increase the ultimate total network throughput by up to 30% in average versus the transparent one, but at the cost of 2.46 to 2.87 times as many EOTs per transmitted Gb/s (for the tested network topologies and for the assumed geographical traffic breakdowns). Since the transparent network version can leverage as well these 400 Gb/s EOTs, the sole potential simpler management of an opaque network in absence of wavelength routing layer will hardly counterbalance this surge of required EOTs and the associated 400 Gb/s electrical ports. We have also illustrated that advocating the benefit of further intermediate traffic grooming by the electrical layer to push for opaque networks will gradually become less relevant, because of the unceasing annual traffic growth making the channel capacity filling ratio already high enough without extra grooming. Moreover, the WSS-based transparent networks will be more capable to handle seamlessly the future upgrades with channels featuring faster symbol rate. These transparent networks will as well better fit the demand than the opaque networks for minimum latency of the most modern services, like 5G and IoT.

We have ultimately exemplified with the IND71 network topology how the networking benefit of the less compact 400 Gb/s regional CFP2 EOTs vs the 400ZR+ QSPF-DD ones depends on their respective required OSNR at FEC limit at 400 Gb/s channel data rate. Further advantages of the CFP2 EOTs (not addressed in this paper) are their wider compliance with the power budget of the legacy OXC thanks to their higher emitted power and lower detection sensitivity, as well as the larger range of client services they could handle (Ethernet and OTN) than the QSFP-DD EOTs, which are limited to Ethernet to maintain their power consumption as low as possible.

6 References

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