# Cost Benchmarking When Deploying Elastic Transponders Accounting for Margins Ageing Versus When Deploying Only 100 Gb/s Interfaces

Jelena Pesic, Nicola Rossi,
Petros Ramantanis, Sébastien Bigo
Nokia, Bell labs
Route de Villejust
91620 Nozay, France
jelena.pesic@nokia.com

Thierry Zami
Nokia, France
Route de Villejust
91620 Nozay, France

Annalisa Morea
Nokia, Italy
Via Energy Park,14
20871 Vimercate, Italy

***Abstract*—We compare the cost efficiency of optical networks based on elastic transponders when accounting for link margins due to network ageing and on fixed 100 Gb/s PDM-QPSK interfaces technologies. Germany50 and Italian photonic backbone networks are used for providing results during a 10-year period given different throughputs, traffic growth rates and the cost erosions of elastic optical transponders. We also investigate the distribution of the ageing margins and modulation schemes that might be changed during the life of the network, before its end-of-life (EoL).**

***Keywords—Elastic optical networks; ageing margin; cost savings;***

## I. INTRODUCTION

The advent of coherent detection improved by electronic post processing has paved the way to elastic optical transponders (EOT). One of the profitable utilizations of EOTs consists in possibly tuning their data rate with respect to the quality of the light path (LP) they bridge [1] and also to the ageing of the connection. In our previous work [2], we quantified the benefit of the adaptation to ageing in terms of return on investment for an Italian photonic backbone topology handling incremental traffic. This paper refines this analysis and compares the cost savings when green field network is planned using EOT with progressive link margins (LM) and with end-of-life (EoL) margins versus when planning the network using only 100 Gb/s interfaces.

This paper is organized as follows. In the second section we explain the concept of margins; more specifically we address the ageing margin. In the third section we present two WDM network topologies considered in this study together with traffic and network assumptions. In the fourth section we present the distribution of the ageing margins obtained for both topologies. Section five and six discuss the refined filtering model developed for different modulation formats together with the difference in cost savings comparing to the previous model. Section seven compares cost savings when deploying EOT with and without progressive ageing link margins and when deploying fixed 100 Gb/s interfaces. Finally, in the last section we present our conclusions.

## II. CONCEPT OF AGEING MARGIN

When an optical network is planned (either when building a new one, or for its upgrade, i.e. consisting of adding new services) optical LMs on the estimated optical signal-to-noise ratio (OSNR) are mandatory to insure the unobstructed service during the life of the network. Operators like France Telecom [3], and British Telecom [4] have shown interest in how to account for margins and the possibilities of using them to increase the total achieved distance and/or to increase the throughput of the link, that is, how to reduce the cost per bit.

We can distinguish three types of link margins: *unallocated*, *design* and *system* margins [3]. *Unallocated* margins are unwanted by-products of the system design and appear when the transponder's reach exceeds the covered transmission distance and/or when the transponder's capacity exceeds the service demand. One of the solutions for overcoming this limitation is by using EOTs which provide the flexibility to adjust baud rate, modulation format and/or channel spacing [5] and to translate these unallocated margins into better spectral efficiency leaving more spectral resources for future connections. *Design* margins are also seen as unwanted by-products of system design and are unlike the unallocated margins, unknown prior to field installations. They appear as a result of the uncertainties of physical parameters used as the input for quality of transmission (QoT) estimator and of its own uncertainties. The solution for overcoming this limitation lies in real time LP monitoring linked to control plane. *System* margins are on the other hand margins voluntarily added to ensure reliable service, resistant to various factors like equipment ageing, fast time varying penalties and impairments of non-linear effects of WDM transmission.

The goal of this study is to assess the possible benefit for WDM network operators when dynamically fitting the modulation of their already deployed EOTs or of their new installed ones with respect to the ageing of their networks. This study assumes that the corresponding ageing margins can be tracked, either thanks to a fine modeling and/or by means of global QoT monitoring if the network is already deployed. The exact implementation of this improved knowledge is still under intensive research investigation [6] and beyond the scope of

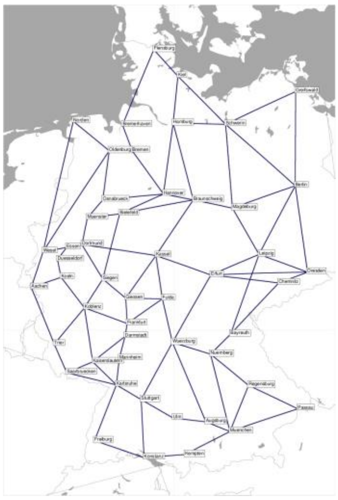

Figure 1. Germany50 topology

this paper. We suppose its feasibility with sufficient accuracy and we quantify the related proposition value for the operators in terms of return of investment.

## III. NETWORK MODEL

We selected two topologies: Germany50 [7], shown in Fig. 1, and an Italian photonic backbone, not presented here [8]. The Germany50 has 50 nodes and 88 links while the Italian topology has 44 nodes and 71 links. We assume that both networks are equipped with WDM links carrying up to eighty 50 GHz-spaced channels and with optical cross connects (OXC) based on broadcast-and-select layout [9], so that each channel in transit goes through exactly one filtering function per traversed node. We investigate the planning of these networks assuming only transparent signal transmission along the LPs without regeneration, connecting all pairs of nodes in the network and relying upon EOTs supporting three different modulation formats: 100 Gb/s PDM-QPSK, 150 Gb/s PDM-8QAM and 200 Gb/s PDM-16QAM modulated at 32 GBaud with soft-decision forward-error-correction (SDFEC) coding [10]. For each pair of nodes, we consider five shortest paths, in terms of distance, bridging the source and destination nodes. Hence, for Germany50 we handle 5x50x49/2=6125 distinct LPs while for the Italian topology we handle 5x44x43/2=4730 distinct LPs. Each LP is a concatenation of spans with the nominal length of 80 km and not less than 30 km. Each span is composed of single-mode fiber with 16.7 ps/nm/km chromatic dispersion (CD) and 0.22 dB/km attenuation, followed by a line optical erbium doped fiber amplifier (EDFA) and without in-line compensation of cumulated CD. In our calculations, the losses for crossing OXC are assumed to be 20 dB.

The received signal to noise ratio (SNR) after propagation along the LP, including both linear and nonlinear noise and directly derived from optical SNR (OSNR) in 0.1 nm, can be expressed as in [10]:

$$SNR = \frac{P}{P_{ASE} + \alpha_{NL} P^3} \qquad (1)$$

where P is the channel power at the input of each transmission fiber section, $P_{ASE}$ is the amplified spontaneous emission noise power from the optical amplifiers, and $\alpha_{NL}$ is the nonlinear interference coefficient that depends on the baud-rate, span length and fiber CD. Applying model from [10], for each LP we calculate the corresponding SNR given by (1). Each modulation format has its own associated SNR requirement for error free SDFEC decoding. In practice, this decoding would also indicate the actual LM. Target OSNR required in 0.1 nm for 100 Gb/s PDM-QPSK is 11 dB [11] while for 150 Gb/s PDM-8QAM and 200 Gb/s PDM-16QAM OSNR values are 15 dB and 18 dB, respectively [10]. Therefore, 100 Gb/s PDM-QPSK carriers can propagate transparently along 3100 km whereas transmission reaches for 150 Gb/s PDM-8QAM and 200 Gb/s PDM-16QAM are 1300 km and 600 km, respectively. To each connection, we assign the modulation format, enabling sufficient performance along its LP, while maximizing its spectral efficiency. This SNR of a LP consists of two factors (1). The first factor is the linear noise contribution, and the second factor is nonlinear one. The linear contributor does not depend on the associated modulation format because our transmission model supposes the input channel power in each fiber span does not depend on its modulation scheme whereas the nonlinear contributor is dependent on the modulation format and therefore not the same for PDM-QPSK, PDM-8QAM and PDM-16QAM.

### A. *Traffic Assumptions*

Our simulations do not rely on a given traffic matrix. We conduct a statistical analysis over all the LPs and we assume they all transport the same capacity, X Gb/s at BoL and this capacity grows with Y% yearly traffic growth. This study examines two sets of X values. The first one starting from 50 Gb/s to 200 Gb/s with the granularity of 10 Gb/s {50 Gb/s, 60 Gb/s,…, 200 Gb/s}, whereas the second one is starting from 100 Gb/s to 200 Gb/s with the granularity of 5 Gb/s {100 Gb/s, 105 Gb/s,…, 200 Gb/s}. The results discussed in the following paragraphs are values averaged over one of these two aforementioned sets, respectively.

### B. *Cost erosion model*

We assume that the cost of the network design is largely dominated by the price of the EOT interfaces required, so we consider the sensitivity of cost benefits on the EOT cost. Since the EOT supports three different formats realized by the same hardware, we consider its price to be unique (regardless of modulation format used) and normalized to the value of 1 at the BoL. With time, maturity of the new technologies is expected to lead to price reductions and therefore potential cost benefits for operators. On the other hand, price of the fixed 100 Gb/s interfaces is a parameter that we change in relation to the EOT price. The value that determines this relation is the cost ratio. Cost ratio is the cost of the EOT divided by the cost of the fixed 100 Gb/s interface. We assume two cost ratios, 0.5 and 0.7 at the BoL of the network and different yearly cost erosions for EOT and for fixed 100 Gb/s interfaces.

## IV. DISTRIBUTION OF AGEING MARGINS

In this section we show the distribution of the OSNR ageing margins for the five shortest LPs bridging each pair of

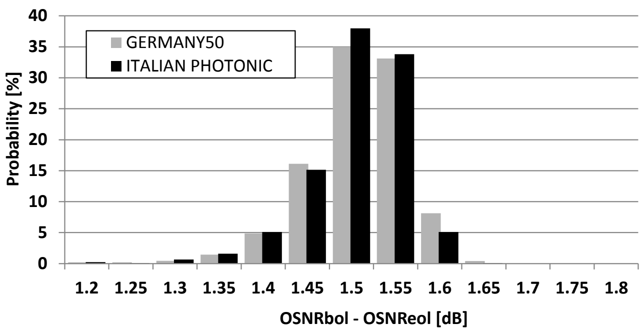

Figure 2. Distribution probability of the OSNR ageing link margin

nodes in the Italian photonic backbone and Germany50 network. This distribution represents OSNR values obtained as the difference between the OSNR of the LP calculated for the EoL (OSNReol), for the highest modulation format that can be associated to that LP and the OSNR of the LP calculated for the BoL (OSNRbol), for the same modulation format. This difference determines the maximum possible OSNR gain over 10-year period, if we account for progressive ageing of the network instead of end of life network.

Value of the ageing link margin depends on several factors: length of the LP, number of the wavelength selective switch (WSS) filters (in OXC) traversed by signal, ageing of the amplifier's noise figure (NF) and the transponder (TRx) ageing. Each time the fiber is cut, additional attenuation is introduced caused by repairing splicing process. Starting from [12] that reports 4.39 cuts/year/1000 miles, we model the yearly additional fiber attenuation of 0.00163 dB/km. This implies that fiber ageing will depend on the fiber plant length. OXC ageing is reflected through the filtering ageing originating from the progressive possible relative detuning between the optical frequency of the carriers and the central frequencies of the filtering and blocking spectral transfer functions of the traversed OXCs. This is why we assume the OSNR penalty associated to passing through one filter degrades with time. This also means the contribution of the OXC ageing in our model depends on the number of OXCs crossed by the LP of the signal. For EDFA ageing we suppose that the output power is not affected by ageing since any degradation (to a normal extent) can be compensated by an internal feedback control on the pump feeding the erbium fiber. Consequently, we only consider its NF ageing during a 10-year period, by changing its value from 4.5 dB to 5.5 dB. EOT ageing is reflected through the need of higher OSNR target values at EoL after several years relatively to BoL in order to properly detect the signal. It comes in addition to a constant margin provision for the distribution of OSNR performances when the EOT comes out from the production line. We model this effect as an additional OSNR degradation of 1 dB (respectively 1.5 dB) at the BoL (respectively EoL).

These values of the ageing margin are indicators of the potential gain that could be used when deploying EOT with different throughputs at the EoL and at the BoL. Since the difference between target OSNR required in 0.1 nm for 100 Gb/s PDM-QPSK and 150 Gb/s PDM-8QAM is 4 dB while the difference between 150 Gb/s PDM-8QAM and 200 Gb/s PDM-16QAM OSNR target values is 3 dB, the potential gain from the ageing of the link margin would not allow switching from one modulation format to another only as a result of ageing link margin, unless the total LP OSNR is already close to the target limit. Our study of Italian and German networks also showed that if using only the available ageing margin (max 2 dB) there was no LP where PDM-16QAM could be deployed at BoL and PDM-QPSK at the EoL because the difference between target values of these two modulation formats is 7 dB, which is not achievable with only ageing margin (see Table 4). Progressive traffic loading along the life of the network might be viewed as a kind of ageing, since the allocation of additional services carried by new optical carriers will strengthen the non-linear effects of WDM transmission and degrade the QoT of transported signal. This ageing is not considered in our transmission model, assuming fully loaded WDM transmission system from BoL, because so far there have been no demonstration of transmission model capable to capture accurately the diversity of nonlinear noise contribution to OSNR for different sets of WDM channels co-propagating along a fiber (the number of possible configuration is $2^{80}$ for a fiber carrying up to 80 channels).

## V. Refined Filtering Model for Ageing Margin

In our previous work [2], we considered that the total contribution of the OXC ageing along one LP depends on the number of OXCs traversed by the signal and that the OSNR penalty associated with passing though one filter degrades in time. This penalty was the same for all modulation formats used: PDM-QPSK, PDM-8QAM and PDM-16QAM, Table 1.

Table 1. Filtering ageing uniform penalty

| Filtering ageing penalty (through 1 WSS) for different modulation formats: | BoL: | EoL: | Yearly ageing step |
|---|---|---|---|
| QPSK, 8QAM and 16QAM | 0.03 dB | 0.1 dB | 0.007 dB |

In this study, inspired by [13] we refine the ageing model for different modulation formats as shown in Table 2.

Table 2. Filtering ageing refined penalty

| Filtering ageing penalty (through 1 WSS) for different modulation formats: | BoL: | EoL: | Yearly ageing step |
|---|---|---|---|
| QPSK | 0.025 dB | 0.05 dB | 0.0025 dB |
| 8QAM | 0.0375 dB | 0.075 dB | 0.00375 dB |
| 16QAM | 0.05 dB | 0.1 dB | 0.005 dB |

We compared these two models for the Italian photonic backbone topology in terms of the percentage of cost savings for each year accumulated from the BoL of the network, if the progressive LM ageing (Progressive_LM) is taken into account compared to the standard end-of-life LM ageing (EoL LM). The results in Fig. 3, show that for traffic starting from 100 Gb/s to 200 Gb/s with the step of 5 Gb/s, with the 30% yearly traffic increase, despite refining filtering ageing model to account for different modulation formats, difference in terms of cost savings still stays negligible, less than 0.5%.

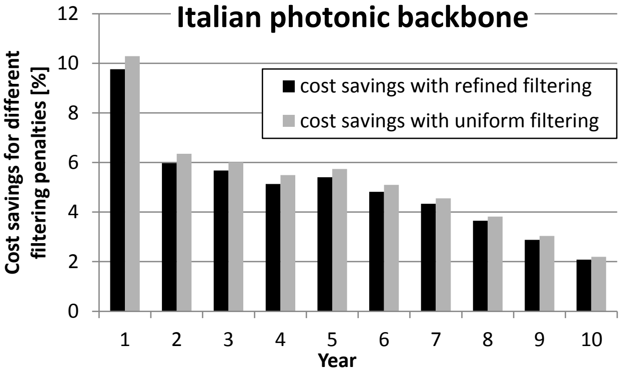


Figure 3. Cost savings refined filtering vs uniform filtering

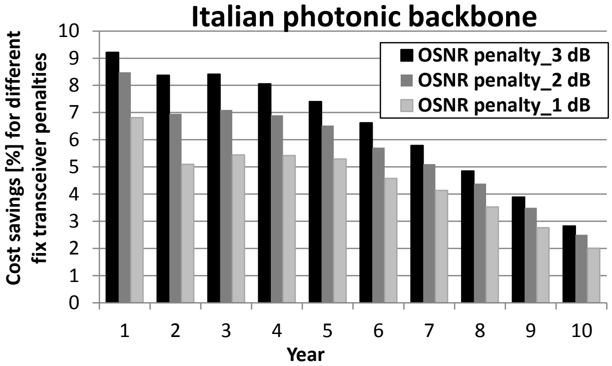


Figure 4: Cost saving for different EOT penalties

## VI. Elastic optical transponder margin

EOT ageing is reflected through the need of higher OSNR target values at EoL after several years relative to BoL, in order to properly detect the signal. It comes in addition to several margins provisioned to account for various factors. The first one is constant margin provision for the distribution of OSNR performances, when the EOT comes out from the production line. The second one accounts for fast time varying parameters like polarization dependent loss (PDL) which cannot be compensated for because they are far faster than any control plane or transponder reaction time, with variations linked to state of polarization changes. CD and polarization mode dispersion are ignored, assuming full compensation in the digital signal processing (DSP). The third and the fourth factors are unwanted by-products related to two types of inaccuracies: one that comes from parameters used as the input for QoT estimator and inaccuracies that come from QoT estimator itself. Consequently different EOT qualities and/or various accuracies of network knowledge may lead to different fixed EOT margins, ranging over a large interval. This is why we considered three different constant values: 1 dB, 2 dB, and 3 dB that are applicable from BoL as indicated in Table 3.

Table 3. Elastic optical transponder margin

| Elastic optical transponder margin | BoL: | EoL: | Yearly ageing step |
|---|---|---|---|
| OSNR penalty_1 | 1 dB | 1.5 dB | 0.05 dB |
| OSNR penalty_2 | 2 dB | 2.5 dB | 0.05 dB |
| OSNR penalty_3 | 3 dB | 3.5 dB | 0.05 dB |

Fig. 4 presents results obtained for three EOT margins, given in Table 3, for the Italian photonic backbone topology in terms of the percentage of cost savings, if the progressive LM ageing is taken into account, compared to the standard EoL LM. Simulations are done for traffic starting from 50 Gb/s to 200 Gb/s with the step of 10 Gb/s, with the 30% yearly traffic increase. By comparing different models for EOT margin, it appears that the larger it's fixed part, the higher the associated cost saving. This results from the fact that the diameter of Italian topology is not so large and therefore at BoL, most the connections can be carried with 200 Gb/s PDM-16QAM or 150 Gb/s PDM-8QAM modulation formats.

When the fixed margin associated to each EOT raises, the proportion of LPs of which final OSNR get closer to the limit between 16QAM and 8QAM as well as between 8QAM and QPSK increases. Therefore, more LPs can favorably benefit from changing modulation format during the network's life as compared to the case when from BoL their modulation formats would be the ones of EoL. This evolution is reported in Table 4.

Table 4. Percentage of LPs changing its modulation

| Elastic optical transponder margin | Percentage of LPs that change from 16QAM to 8QAM | Percentage of LPs that change from 8QAM to QPSK | Total [%] |
|---|---|---|---|
| OSNR penalty_1 | 20.85% | 3.93% | 24.78% |
| OSNR penalty_2 | 23.3% | 9.45% | 32.75% |
| OSNR penalty_3 | 21.78% | 16.17% | 37.95% |

## VII. Low cost 100G interfaces

In this section we compare the potential cost savings when deploying EOT transponders supporting three modulation formats: PDM-QPSK, PDM-8QAM and PDM-16QAM, with and without progressive ageing link margins and when deploying fixed 100 Gb/s PDM-QPSK interfaces. In a middle range of time, EOTs are expected to remain more expensive than fixed 100 Gb/s PDM-QPSK transponders, because they leverage more numerous and more complex hardware (more client ports, larger ASIC with more logical gates for more complex coherent detection, additional digital to analog converters and an extra linear amplifier in the transmitter side). For these reasons we are interested in benchmarking

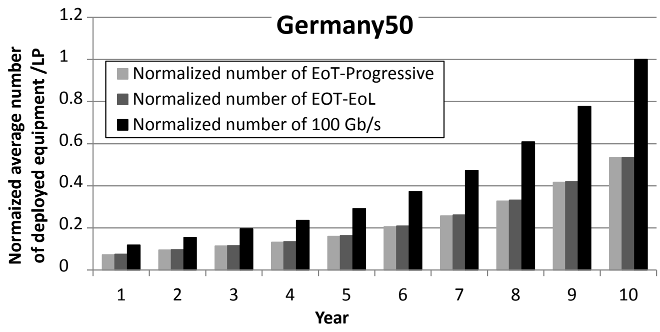


Figure 5: Total normalized number of deployed EOTs and 100 Gb/s interfaces per year, per LP

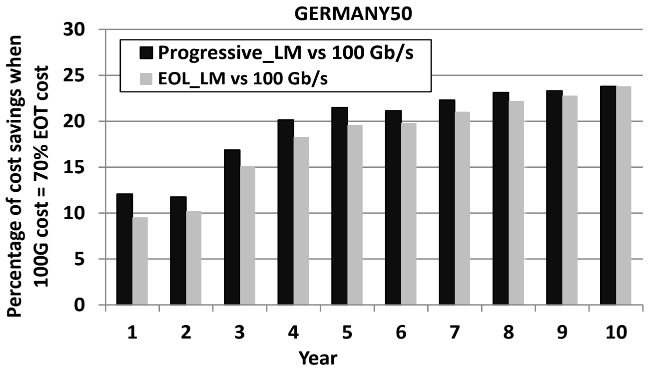


Figure 6. Percentage of cost savings when 100 Gb/s cost = 70% EOT

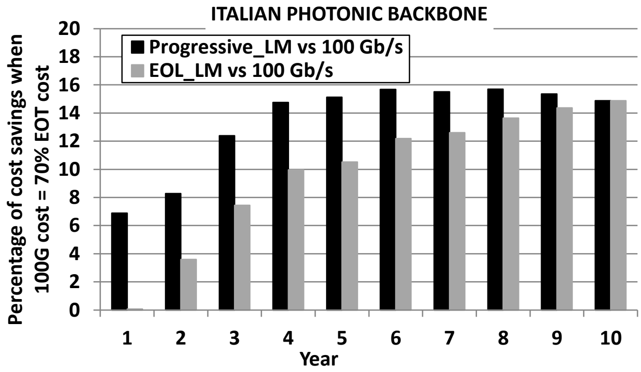


Figure 7. Percentage of cost savings when 100 Gb/s cost = 70% EOT cost

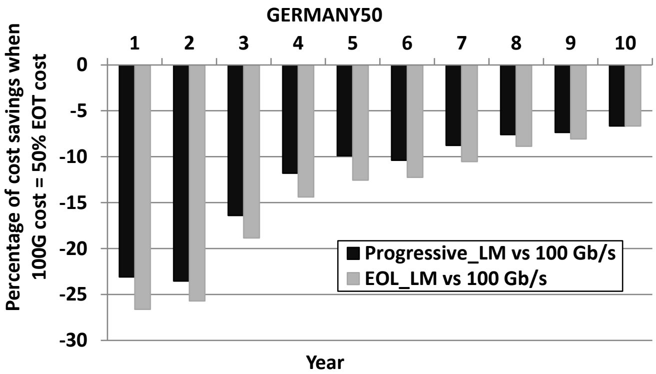


Figure 8. Percentage of cost savings when 100 Gb/s cost = 50% EOT cost

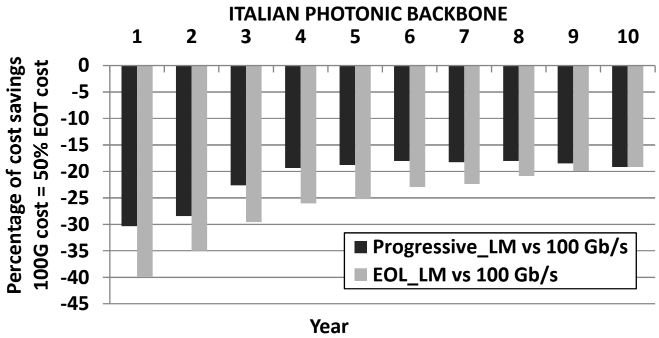


Figure 9. Percentage of cost savings when 100 Gb/s cost = 50% EOT cost

their deployment costs.

In our study, for comparison reasons, we considered Italian photonic backbone and Germany50 topology, to capture the possible differences for traffic starting from 50 Gb/s to 200 Gb/s, in 10 Gb/s steps, with the 30% yearly traffic increase. When planning the network only using fixed 100 Gb/s interfaces, compared to planning with only EOT, the difference in terms of the normalized number of equipment used increases by the factor of 2, which is explained by the difference in their maximum capacities 200 Gb/s vs 100 Gb/s, Fig. 5. For example, traffic of 200 Gb/s can be carried by one EOT or by 2 fixed 100 Gb/s interfaces.

Fig. 6 and Fig. 7 present cost savings when network planning with progressive LM and EoL, compared to network planning based only on 100 Gb/s interfaces, when price of the 100 Gb/s interface is 30% less than EOT interface (100 Gb/s cost = 70% EOT cost). Cost savings when using progressive LM planning with respect to 100 Gb/s interfaces reach up to 22% for Germany50 and up to 16% for Italian photonic backbone topology (Fig. 6 and Fig. 7 respectively). When lowering the cost ratio of EOT and fixed 100 Gb/s interfaces to 50%, there are no more cost savings when deploying EOT, neither with progressive nor with EoL planning method. For both topologies, deploying 100 Gb/s interfaces appears more cost effective (Fig. 8 and Fig. 9). We explain these negative values related to three traffic (*d*) cases: when traffic is the exact multiple of maximum EOT capacity *(n·200 Gb/s)*, where n =[0,1,2..), when traffic is between two successive multiples of maximum EOT capacity *(n·200 Gb/s+ε)* where *0<ε<100 Gb/s* and when traffic is between two successive multiples of maximum EOT capacity *(n·200 Gb/s+ε)* where *100 Gb/s <ε<200 Gb/s* as indicated in (2).

$$d = \begin{cases} n \cdot 200\frac{Gb}{s},\ n = [0,1,2..) \\ n \cdot 200\frac{Gb}{s} + \varepsilon,\ 0 < \varepsilon < 100\ \frac{Gb}{s}, \\ n \cdot 200\frac{Gb}{s} +\ \varepsilon,\ 100\ \frac{Gb}{s} < \varepsilon < 200\ \frac{Gb}{s}; \end{cases} \tag{2}$$

When traffic is the exact multiple of maximum EOT capacity and when it is between two successive multiples of maximum EOT capacity (n·200 Gb/s + ε) where 100<ε<200 Gb/s, cost of the EOT or 100 Gb/s deployment is the same if the cost ratio of EOT and fixed 100 Gb/s interfaces is 50%, since we need to deploy exactly twice as many 100 Gb/s interfaces than EOT interfaces. Deploying twice as many fixed interfaces when the price is 50% less expensive, results in the same final cost. However, if the traffic is in the range of (n·200 Gb/s+ε) where 0<ε<100 Gb/s, deploying EOT becomes more expensive, because we deploy less than twice as many 100 Gb/s interfaces. For example, for supporting traffic of 250 Gb/s we would need two EOT or three 100 Gb/s interfaces, which favors deploying 100 Gb/s instead of EOT.

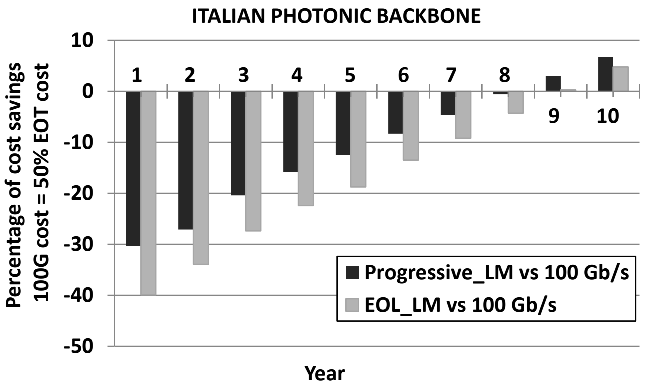


Figure 11. Percentage of cost savings when 100 Gb/s cost = 50% EOT cost and for different cost erosions: EOT (15%), 100 Gb/s (10%)

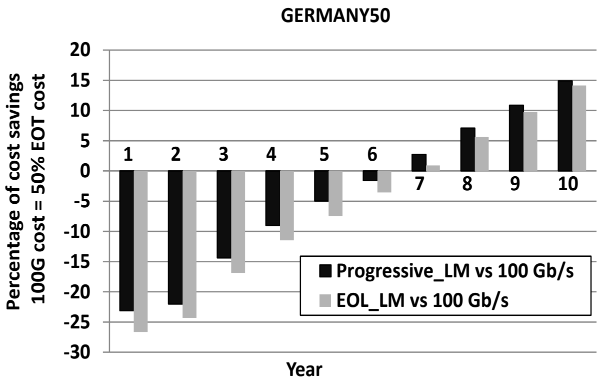


Figure 12. Percentage of cost savings when 100 Gb/s cost = 50% EOT cost and for different cost erosions: EOT (15%), 100 Gb/s (10%)

### *A. EOT and 100 Gb/s cost erosion*

In this section we examine the effect of different cost erosions of the EOT and fixed 100 Gb/s interfaces on the final cost savings in the network. As previously presented, if the cost ratio between EOT and 100 Gb/s is 0.5, deploying 100 Gb/s appears more interesting while when the ratio becomes 0.7 EOT takes precedence. Fig. 11 and Fig. 12 show the cost savings for two topologies when accounting for traffic starting from 50 Gb/s to 200 Gb/s with the step of 10 Gb/s, with the 30% yearly traffic increase if the progressive LM ageing and standard EoL LM are taken into account, compared to the fixed 100 Gb/s. In both figures we applied 15% of yearly cost erosion on EOTs and 10% of yearly cost erosion on 100 Gb/s interfaces. We were led by the fact that the lower cost interfaces (100 Gb/s) will benefit from the lower cost erosion of 10%, in our example, compared to higher cost interfaces (EOT) that will benefit by 15%. Results show that even when accounting for the different cost erosions, if the starting cost ratio is 0.5, cost savings will not be comparable to the ones with the 0.7 cost ratio. They also show that at EoL deploying EOT can finally be as cost effective (for Italian topology) or even 15% more cost effective (for Germany50) than deploying 100 Gb/s interfaces.

## CONCLUSION

Our study comparing cost saving when deploying elastic transponders versus 100 Gb/s low cost transponders, demonstrates the latter deployment is still more cost effective than the former one, once the cost ratio between these two types of transponders is less than, or equal to 0.5. However this is only a partial comparison, because the relevance of better spectral efficiency enabled by EOTs, when compared to 100 Gb/s low cost transponders, is not considered here. The related benchmarking will be reported in our future work. Moreover, it remains to be seen to what extent the cost ratio better than 0.5 would be maintained on a medium or long term basis. EOTs will also get more mature and some current trends, like the advent of CFP2-ACO modules capable of QPSK, 8QAM, and 16QAM modulation indicate that even EOT will evolve toward relatively low cost implementation.

## ACKNOWLEDGMENTS

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