Cost Evaluation for Flexible-Grid Optical Networks

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Abstract— **We have compared the total cost of an innovative elastic network with respect to the conventional WDM ones operating in realistic network scenarios. The results give an insight of the cost benefits that can be obtained with an elastic OFDM-based network for the operation of future optical transport networks with different protection schemes.**

Keywords- flexible-grid; OFDM-based network; cost; energy efficiency; optical transport network, protection.

I. INTRODUCTION

The Internet traffic demand has grown at a rate of approximately 45% per annum during the previous years and, according to a forecast from Cisco [1], a similar tendency can be expected for the near future: "*Globally, Internet traffic will grow 3.8-fold from 2011 to 2016, a compound annual growth rate of 31%*". In this context, telecommunication carriers are continuously exploring new solutions to upgrade their networks in order to handle this ever increasing Internet traffic demand. Such a network upgrade usually implies additional economic efforts by the operators due to the higher CapEx (capital expenditures) and OpEx (operational expenditures) resulting from, for instance the need for new telecommunication infrastructure deployments and higher electrical power consumption. Furthermore, in a network capacity upgrade, not only the network equipment cost, but also the efficiency and the flexibility play important roles when considering the total cost per transmitted bit. Thus, besides the total cost, two other important parameters have to be considered for the adoption of a new technology on the telecom networks, spectral and energy efficiency.

This study is focusing on new approaches for terrestrial long-haul optical transport networks, which play an essential role in coping with the increasing capacity requirements. These transport networks are currently based on dense wavelength division multiplexing (DWDM) technologies, operating with a channel spacing specified by the ITU-T grid (the C-band is partitioned into spectrum slots with a fixed and equal width of 50 GHz), and employing fixed-rate transponders. Therefore, considering a single-layer network design, the resource allocation is rather rigid and may lead to inefficient use of the spectral resources and energy wastage, if actual traffic demands are lower than the wavelength capacity given by the transponders. Accordingly, there is room to make the networks more efficient by performing the resource allocation more flexibly, i.e. by introducing a finer granularity to allow for a better adjustment of the allocated capacity to the actual user demand. In order to obtain this desired network flexibility, the recent progress in coherent technologies can be leveraged to realize the Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) as a promising technology candidate for the operation of optical networks. It allows for an elastic bandwidth transmission (without the ITU-T grid alignment) by allocating the capacity to low-rate subcarriers. Furthermore, the use of Digital Signal Processing (DSP) techniques and coherent detection introduces the possibility of transmitting and receiving subcarriers with different modulation formats at any frequency, which results in finer available capacity granularity. Recently, significant research efforts are being spent by the industry and academia for the development and future standardization of this type of elastic network, as the signal bandwidth of future transmission technologies at bit rates higher than 100 Gb/s (e.g. 400 Gb/s or 1 Tb/s) may not fit into the currently used ITU-T channel spacing. According to the latest achievements in transmission technologies and the availability of grid-less filters, it is believed that the deployment of a flexible-grid network can become a reality in the not so distant future.

In this future scenario, guaranteeing a high resilience will also be a must for operators due to the importance of telecommunication networks for the availability of indispensable services in our society. Thus, protection schemes have to be taken into account in the performance evaluation. In our previous work [2], we showed the benefits in energy efficiency of an elastic OFDM-based network (higher energy efficiency per GHz) compared to conventional WDM networks, considering the most common path protection schemes: dedicated protection 1+1 (*DP 1+1*), dedicated protection 1:1 (*DP 1:1*), and shared protection (*SP*). This contribution aims at complementing our previous analysis by evaluating not only the energy efficiency, but also the cost of each type of network and protection scheme, which is actually one of the main drivers for the adoption of a particular technology by the telecom carriers. There are examples for studies which have already targeted this issue. For instance, Angelou has shown [3] that the main advantage of an elastic network in terms of cost comes from its better spectral efficiency, and Bocoi [4] has evaluated a range of values to determine the cost at which OFDM networks (without protection) result in lower CapEx than conventional WDM networks. This contribution evaluates the cost efficiency of an elastic OFDM-based network compared to the WDM counterpart, including both CapEx and energy cost, in realistic network scenarios using different protection schemes. Furthermore, it also presents the cost values of a CO-OFDM transponder that would make the elastic approach result in lower total network cost than the current WDM approaches for different traffic load conditions.

The paper is organized as follows. Section II presents the main aspects to be considered in the resource allocation. Section III contains the values of power consumption and cost for each network element. Section IV explains the heuristic algorithms for the routing and resource allocation. Section V presents the simulation results and discusses the cost efficiency of the elastic OFDM-based approach, and Section VI concludes the paper.

II. NETWORK CONSIDERATIONS

A. *Elastic OFDM-based network.*

For the operation of the elastic network, a frequency slot of 12.5 GHz has been adopted, for a total of 320 frequency slots in the C-band. In order to maintain the orthogonality condition among the subcarriers, this subcarrier spacing must be equal to the symbol rate of 12.5 GHz. Thus, the transmission rate of a single subcarrier can be 12.5, 25, 37.5, 50, 62.5 and 75 Gb/s for BPSK, QPSK, 8QAM, 16QAM, 32QAM, and 64QAM respectively. Then, several subcarriers can be combined to create super-channels with higher transmission rate. In addition to the subcarriers used for data transmission, a guard band of two frequency slots (25 GHz) is used to separate adjacent channels, in order to allow the bandwidth variable Optical Cross Connect (OXC) to switch any optical channel consisting of a single or multiple subcarriers. A transmission reach [4] of 4000, 2000, 1000, 500, 250 and 125 km has been assumed for BPSK, QPSK, 8QAM, 16QAM, 32QAM, and 64QAM respectively.

B. *Current WDM Networks.*

For the WDM networks, up to 80 wavelengths within the 50 GHz channel spacing in the C-band and line rates of 10 Gb/s, 40 Gb/s, and 100 Gb/s, with reaches of 3200, 2200, and 1880 km [6] respectively, have been assumed. Two types of operation are considered: Single Line Rate (SLR) of 10, 40 or 100 Gb/s per fiber, and Mixed Line Rate (MLR), which combines the transmission of the three mentioned line rates in a single fiber (10/40/100 Gb/s). In this latter approach, in order to minimize the cross-talk effect between adjacent channels of different transmission technologies, the C-band has been divided into two independent wavebands, separated by a guard band of 200 GHz. The first one is used for 10 Gb/s (NRZ-OOK) transmission, and the second one for both 40 and 100 Gb/s transmissions, which are assumed to be based on a similar modulation format (DQPSK), and thus can be placed on adjacent frequency slots without significantly affecting the signal quality of each other.

III. COST AND POWER CONSUMPTION VALUES

The three network elements which have been considered for the cost and energy consumption evaluation in the optical layer are the transponders, the OXCs, and the optical amplifiers. The purpose of this section is to specify the power consumption and relative cost values that have been assumed. The relative cost values for current WDM equipment are based on a model used by Telefónica in similar studies; whereas several assumptions have been made to estimate realistic values for the elastic network.

A. *Transponders*

For the WDM transponders, electrical power consumption values of 34, 98 and 351W [7], and normalized cost values of 1, 3 and 7.5 have been considered for the transponders with bit rates of 10, 40 and 100 Gb/s respectively. Power figures require an additional 20% overhead for each transponder to take into account the contribution to additional energy consumption in other node elements.

For the elastic OFDM-based network, a bandwidth-variable transponder (BV-T), more specifically a Coherent Optical OFDM (CO-OFDM) transponder allowing for modification of the signal properties (i.e. number of subcarriers and modulation format) by means of software is necessary. However, due to the current commercial unavailability of such a device, several assumptions have been made to estimate corresponding values of power consumption and overall cost. As far as power consumption is concerned, the values for the transmission of a single subcarrier with different modulation format are presented in Table I. Besides it is necessary to consider an additional 20% overhead contribution for each transponder. A detailed explanation on calculating these figures can be found in [2]. Regarding the cost value, the abovementioned commercial unavailability as well as the existing uncertainty about the final transponder architecture makes the estimation equally difficult. The high-level architecture of the transmitter part of such a transponder will probably consist of several low speed modulators in parallel, together with a DSP module and high-speed DACs (Digital-to-Analog Converters). The receiver part will also be composed of multiple coherent receivers at low speed. In this study, two main assumptions have been made in order to estimate the cost of a CO-OFDM transponder:

1) Its maximum transmission rate will determine the final cost: The cost of a CO-OFDM transponder on its release date will be determined by its maximum achievable transmission rate.

2) Its initial higher cost per bit than usual coherent WDM 40 and 100 Gb/s transponders: The BV-T has additional elements, such as the DSP module and the DACs at the transmitter part (used to generate signals with high order modulation) that could initially increase the cost per bit. Therefore, an additional cost per bit of 20% with respect to current coherent WDM transponders has been assumed for such initial implementations, though technology maturity will bring significant cost reductions.

Accordingly, based on the previous assumptions, and considering 400 Gb/s the maximum transmission rate that the transponder is capable to achieve, the cost of a flexible transponder has been chosen to be 36 cost units, i.e. 20% higher than 4 times the cost of a 100 Gb/s WDM transponder (1.2*4*7.5). The transponder has been assumed to be "sliceable" [5], meaning that the transmission capacity of this bandwidth-variable transponder (400 Gb/s) can be shared by several traffic demands simultaneously. This presents a more beneficial scenario for the elastic approach in terms of cost, as otherwise it would be difficult to justify the investment on a 400 Gb/s transponder for the transmission of a single low traffic demand, e.g. 50 Gb/s.

TABLE I. POWER CONSUMPTION OF A CO-OFDM TRANSPONDER FOR DIFFERENT MODULATION FORMATS

Mod. Format	Subcarrier Capacity (Gb/s)	Power Consumption (W)
BPSK	12.5	112.374
QPSK	25	133.416
8QAM	37.5	154.457
16QAM	50	175.498
32QAM	62.5	196.539
64QAM	75	217.581

B. *Optical Cross Connect (OXC)*

It has been assumed that the power consumption model of a flexible-grid OXC will be similar to that of the fixed-grid variant [7], i.e. it is dependent on the node degree N and the add/drop degree α, with an additional 150 W consumption to account for the overhead contribution (control cards, fans, power supply) as specified in equation (1).

$$PC_{OXC}[\mathrm{W}] = N \cdot 85 + \alpha \cdot 100 + 150 \qquad (1)$$

With respect to the cost of an OXC, the Wavelength Selective Switch (WSS) has been assumed as the main contribution to the final cost. Therefore, the cost of an OXC can be estimated as being proportional to the number of WSS units in the node as specified in equation (2). As depicted in Figure 1, for a common OXC implementation the number of WSS units (of the type 1x9 WSS in this case) in the node also depends on N and α, i.e. one WSS unit is necessary per node degree, whereas the add/drop stage requires two initial WSS units (one for adding and the other one for dropping channels) for the first group of 9 channels, and two extra WSS units for each additional channel group with up to 9 channels. The costs of a single 1x9 WSS ($Cost_{WSS}$) are 4 and 5 cost units for the fixed-grid and the flexible-grid approaches, respectively (flexible-grid is assumed to have a 25% additional cost with respect to the fixed-grid variant).

$$Cost_{OXC}[\mathrm{c.u.}] = \left(N + 2 \cdot \left\lceil \left(\frac{\alpha - 8}{9} \right) \right\rceil \right) \cdot Cost_{WSS} \qquad (2)$$

C. *Optical Line Amplifiers*

An Erbium Doped Fiber Amplifier (EDFA) card consuming 30 W [7] per direction, and an overhead contribution of 140 W (including controller cards and fans) per amplifier location, has been considered. The cost of each EDFA per direction is 1 cost unit.

D. *Energy Cost*

A cost of 0.1043€ per kilowatt-hour (kWh) is assumed, taking the energy cost for industrial customers in Spain for 2011 [8]. The normalized cost value is 2.086×10^{-5} /kWh.

IV. SURVIVABLE RESOURCE ALLOCATION ALGORITHMS

The resource allocation for a set of static demands resilient to any single link failure, the dominating form of failure in optical networks, has been evaluated in this study. For this purpose, the heuristic methodology for the calculation of the resource allocation in a static scenario [9] has been employed and complemented to calculate the total cost of each network based on the respective technologies (elastic network, and current WDM networks operating with SLR and MLR) with three of the most common path protection schemes [2]: *DP 1+1*, *DP 1:1*, and *SP*. In these algorithms, the demands from the traffic matrix are in a first step sorted in descending order with the highest demand first, and then it is evaluated whether, from a set of candidate paths (k-shortest paths), a working and protection path can be provided for each particular demand (i.e. whether enough and contiguous spectral resources can be assigned along two link-disjoint paths from source to destination nodes). If the resource allocation is not successful on both working and protection path, the demand is marked as blocked.

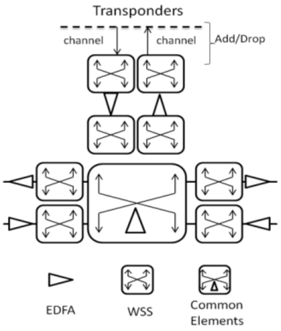

Figure 1. Architecture of the OXC node.

Once the resource allocation has been evaluated for all the demands from the traffic demand matrix, it is possible to obtain the total cost of the network. This value results from adding the total cost of the deployed network elements and the cumulative energy expenses in a given time frame. The chosen protection scheme will influence both the CapEx and the total energy cost as follows:

a) DP 1+1: Nodes are equipped with transponders for both working and protection paths, and energy consumption takes into account the simultaneous transmission on both working and protection paths (higher energy consumption).

b) DP 1:1: Same node architecture as that in *DP 1+1*, but energy consumption will only account for the transmission in the working path.

c) SP: No spare transponders are considered in the node, the same transponders are used for working or backup path.

Provided that the analysis was limited to a single fiber pair per link, it is also necessary to consider the performance with respect to spectral efficiency and the blocking ratio, as the maximum traffic accommodated on a single fiber definitely affects the final network cost. Thus, we have defined a measure (*Cost Efficiency per GHz*) to account for the number of bits that is transmitted with a single cost unit (c.u.) per GHz (bits /c.u./GHz) as presented in equation (3). The term *TransmitedData* is the total amount of data transmitted in the considered time frame: *TotalCost* contains both the equipment and the energy cost during the specified time frame, and *AvgSpectrumOccupancy* is the average of the spectrum occupancy in the links of the network.

$$\frac{TransmittedData[\text{bits}] / TotalCost[\text{c.u.}]}{AvgSpectrumOccupancy * \text{BandwidthCBand [GHz]}} \tag{3}$$

V. SIMULATION RESULTS AND DISCUSSION

A. *Simulation Scenario*

The network scenario that has been evaluated is the reference model of the Spanish core network provided by Telefónica for the studies that have been performed in the frame of the Trend NoE (Network of Excellence) project. This network topology is composed of 30 nodes and 96 bi-directional links, as depicted in Figure 2. In order to emulate different traffic conditions, the realistic traffic demand matrix of 2012 has been scaled up to a factor of 20 to obtain a total traffic ranging from 3.22 to 64.48 Tb/s. Besides, it is important to note that transparent communication has been assumed in this study (no regeneration is considered).

Different time frames (2, 5 and 10 years) were evaluated in order to analyze the influence of the energy cost. The simulation results for one of the time-frames (10-year term), in which the energy cost is more relevant, are presented in this section. It is important to note that the presented results for different technologies and protection schemes are under non-blocking conditions, i.e. for those traffic scaling factors at which zero blocking is provided and all the traffic demands are protected against any single link failure. For instance, for the SLR 40 Gb/s and 100 Gb/s with dedicated path protection, the results are only shown up to a traffic scaling multiplier of 4 and 10, respectively. Moreover, the results for SLR 10 Gb/s network are not shown in the figures, as it is not reasonable to consider a network deploying only transponders of 10 Gb/s to cope with the future capacity requirements. This assumption is supported by the blocking results obtained (see Table II), which showed the impossibility of scaling up the traffic matrix even by a factor of 2, implying that it would be necessary to deploy additional fibers and network elements in order to accommodate more traffic in the network.

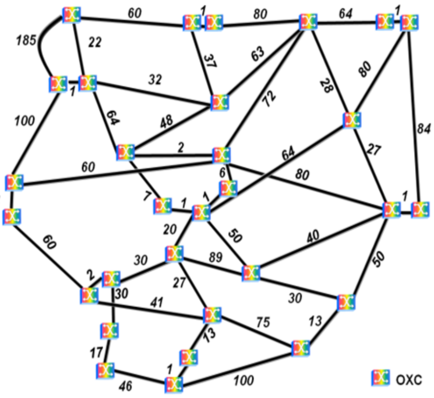

Figure 2. Telefonica´s Spanish core network.

TABLE II. MAXIMUM TRAFFIC SUPPORTED WITHOUT BLOCKING

Network Type	Traffic with DP (Tb/s)	Traffic with SP (Tb/s)
Elastic	54.808	61.256
SLR 10 Gb/s	3.224	3.224
SLR 40 Gb/s	12.896	16.12
SLR 100 Gb/s	32.24	41.912
MLR	32.24	45.136

Figure 3 presents the total energy cost during a 10-year frame vs. traffic scaling multiplier for the different network technologies and protection schemes. The curves in the upper part present the energy cost for DP 1+1, which obviously consumes more energy than the other options due to the simultaneous transmission in the working and in the protection path. On the other hand, the curves in the lower part identify the energy consumption for *SP* and *DP 1:1* schemes for the different technologies, which are lower than the one for the *DP 1+1* scheme. The only difference between the SP and the DP 1:1 schemes in terms of energy usage is the lower blocking provided by the *SP* schemes possibility of accommodating more traffic (i.e. the lower blocking ratio with *SP* scheme permits to scale up the original traffic matrix by higher scaling multiplier factors).

B. *Case Study with transponders “Sliceable” in capacity*

A “sliceable” transponder in which the total capacity of the transponder (400 Gb/s) can be shared among different demands has been considered. Figure 4 shows the results concerning the *cost efficiency per GHz* in a 10-year term. As in the previous figure, only the values in which all the traffic demands can be satisfied are presented. Concerning the evaluated network approaches, the elastic network provides the best performance and clearly outperforms WDM networks at any traffic load conditions. The results show that the difference in *cost efficiency per GHz* between the elastic network and the other networks is becoming more significant as the traffic increases because of its better spectral efficiency. The WDM SLR 100 Gb/s network also increases its performance when the traffic increases, but its spectrum occupancy increases faster. In the same manner, the WDM SLR 40 Gb/s is also penalized by this fact when the traffic increases. In the WDM MLR, the presence of a guard band of 200 GHz to separate the different transmission technologies reduces the available spectrum that can actually be used for transmission, and thus its performance is deteriorated in *cost efficiency per GHz*. The main reason for the notable *cost efficiency per GHz* of the elastic network is the

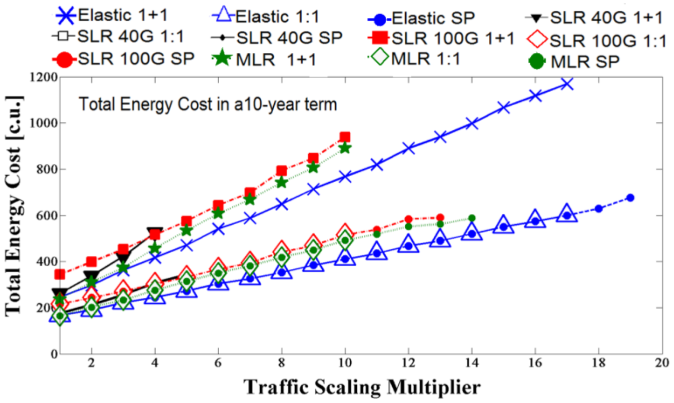

Figure 3. Total energy cost [c.u.] in 10-year term for the different network technologies and protection schemes.

fact that the high traffic demands will occupy a considerably higher spectrum in WDM networks due to the operation restricted to ITU-T grid, as there will be many parts of the spectrum unoccupied between the different wavelengths; whereas in an elastic network, the channel bandwidth can be expanded in a contiguous manner, creating super-channels with higher spectral efficiency. Besides, the considerably low blocking ratio of this technology also implies an advantage in terms of cost, as more traffic can be accommodated in a single fiber and thus fewer network devices (such as signal regenerators) would be required in the network to fulfill high traffic demands. Regarding the comparison of the different protection schemes, the *SP* scheme is clearly the one in equipment and energy consumption, and, especially, to its lower spectrum occupancy (i.e. the spectral resources for the protection paths are shared among several working lightpaths).

C. Maximum acceptable cost of a BV-T to minimize total network cost

This section is dedicated to the determination of the cost of a BV-T, for which the elastic network will become the most economic approach for the different traffic load conditions. It is worth mentioning that the final cost of the elastic network will depend not only on the cost of the BV-T, but also on the manner in which the transmission capacity of the transponder is utilized. In the previous section, the benefits in *cost efficiency per GHz* of an elastic network using a “sliceable” transponder allowing for “sharing” its capacity for different demands were shown. However, due to the uncertainty about the final architecture of a BV-T, it may occur that, in the first implementations, the capacity of the transponder cannot be shared as flexibly. Therefore, two alternatives that could be available in the short term have been investigated. Thus, the following three cost models that have been considered to estimate the maximum acceptable cost of a BV-T:

1) Transponder “sliceable” in capacity (TSC): This is the approach studied in the previous section, in which the total capacity of the transponder, 400 Gb/s, can be “shared” and used by several low-rate demands, independently of the number of subcarriers that are used.

2) Transponder not sliceable (TNS): A BV-T with maximum transmission rate of 400 Gb/s is dedicated exclusively for a single traffic demand independently of its value.

3) Transponder “sliceable” in subcarriers (TSS): A transponder can transmit a maximum of six subcarriers, which can be shared for serving different demands with different modulation formats (up to 450 Gb/s if 64 QAM is used).

In order to turn the elastic network into more cost-efficient solution than any of the current WDM approaches, it should provide a lower total cost, considering both CapEx and energy cost. From the simulation results, the WDM approach that provides the lowest cost for both SP and DP schemes is the WDM MLR network. Since transponders are the main contribution to the total cost of the network (more significant than the cost of the OXCs, the EDFAs or energy expenses), the objective is to determine the cost of a BV-T allowing for a lower total cost than the WDM MLR network for the different traffic load conditions and protection schemes. Figure 5 shows the maximum acceptable cost for a BV-T, meaning that any cost lower than the values presented in that figure will result in more cost-efficient elastic network than any investigated approach. For instance, at low traffic load conditions, it can be seen that the BV-T should approximately cost the same as a 100 Gb/s WDM transponder (7.5 c.u.) in order to obtain benefits in terms of cost with respect to WDM networks, but lower energy cost of the elastic network will be advantageous. Then, when the traffic increases, the elastic approach starts to take advantage of its better performance at high traffic load, so it would be possible to tolerate higher cost for the BV-Ts in order to provide similar cost to that of the MLR network.

From the three cost models, the *TSC* can be identified as being the most beneficial from the economic point of view. For instance, with a traffic matrix scaled by a factor of 10, the total cost of the network will become more economical with the elastic approach if the BV-T has a cost per bit somewhat lower than that of a 100 Gb/s WDM transponder (approximately 4% and 11% lower cost per bit with *SP* and *DP*, respectively). Regarding the other two cost models, the *TNS* is considerably penalized by the need of dedicating a 400 Gb/s transponder to a single traffic demand, even if the traffic is much lower. As the traffic increases and the average traffic demand gets closer to 400 Gb/s, its cost-efficiency is notably improved. On the other hand, the *TSS* provides intermediate results between the most optimistic cost model (*TSC*) and the pessimistic one (*TNS*).

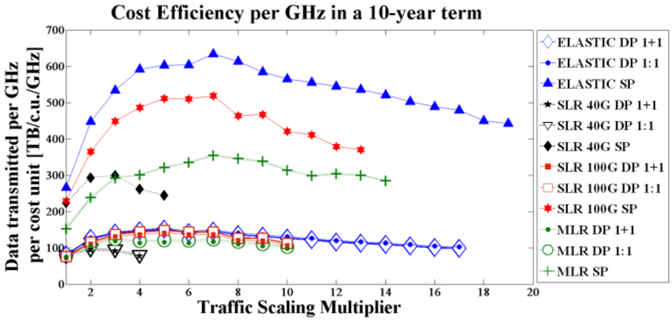

Figure 4. Cost Efficiency per GHz [TB/c.u./GHz] in a 10-year term for the different network technologies and protection schemes.

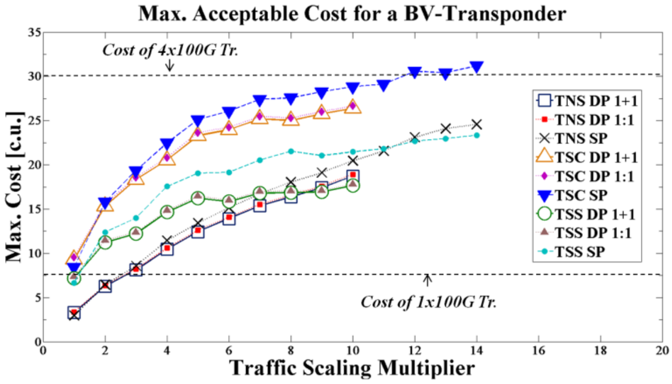

Figure 5. Maximum acceptable cost (c.u.) for a BV-T to turn the elastic network into the most cost-efficient solution, for the three cost models and protection schemes.

As far as protection schemes are concerned, scheme it would be possible to accept a higher cost for a BV-T with the *SP* scheme, as nodes are only equipped with transponders for the working path, whereas the *DP* schemes require to purchase transponders for both working and backup paths.

The results in Figure 5 are only shown for those traffic scaling multipliers providing no blocking for the MLR network, but it is important to note that the elastic network allows for scaling up the traffic matrix by higher factors without blocking (i.e. up to 19 and 17 scaling factors with *SP* and *DP* respectively). In these conditions, it might be possible to accept an even higher cost for a BV-T since, as abovementioned, deploying additional fibers and/or network elements, such as regenerators, would entail a higher cost.

D. Additional cost-benefits

Besides the already mentioned benefits in cost of the elastic network, there are some other factors that may also speak in favor of the adoption of such a technology. An interesting advantage is the possibility of deploying a single type of transponder in the network independently of the demand value, which may bring significant benefits thanks to the economy of scale (i.e. mass production of a single product), reduced inventory of different spare parts, and also the decrease in installation cost. Furthermore, using a transponder capable of transmitting at a high transmission rate (e.g. 400 Gb/s) may also simplify the tasks of an eventual capacity upgrade, since in many cases the operators will not be forced to deploy additional network elements or to provide accurate forecasts on traffic requirements, but just to modify the transmission signal properties by software configuration (i.e. extend bandwidth or increase modulation order). This modification of the signal properties by software configuration allows for the adaptation of the transmission rate to dynamic variations of the traffic. For instance, [10] shows the benefits in energy savings of a protection scheme which adapts the transmission on the backup path to the traffic variations throughout the day in order to save energy consumption. This study showed how the elastic network can clearly adapt better to traffic variations thanks to its bandwidth elasticity and different modulation formats. More advantages can also come from the offered trade-off between transmission reach and spectral efficiency that would allow, for instance, for employing robust modulation formats for long distances in order to reduce the number of regenerators deployed in the network. Moreover, a super-channel transmitting at a high bit-rate can be treated in the network as a single entity, which may also help to reduce the number of ports in the OXC and make the OXC less expensive.

VI. CONCLUSION

The ever growing Internet traffic is becoming a challenge for telecom operators. Relevant research efforts are focused on finding mechanisms to increase both the energy and spectral efficiency of the networks while maintaining a high level of resilience to guarantee an appropriate quality of service. The elastic OFDM-based network can increase the flexibility in the resource allocation by its elastic bandwidth usage and the possibility of employing different modulation formats. However, besides these potential advantages, the cost is one of the main drivers for the operators when it comes to the decision of deploying a new technology. In a realistic network scenario, allowing service protection, simulations showed that even if the cost per bit of a BV-T is initially higher than that of current WDM transponders the elastic network can be a more affordable approach. This is especially due to its lower blocking, which permits to accommodate more traffic in a single fiber. Besides the actual expenditures in network elements and the energy cost, the spectral efficiency has also a relevant impact, as it determines the maximum traffic in the network, and therefore the number of fibers and network elements that are necessary for a given traffic load. In this manner, it is possible to find conditions for which the data that can be transmitted per GHz with a single cost unit (*cost efficiency per GHz*) is higher in an elastic network than in any other WDM network approach with the assumed cost model. In addition to the better performance in spectral and energy efficiency, there are some other potential factors that can turn this technology into a more cost-efficient solution, such as the possibility of having a single transponder model in the network (reducing installation complexity, progressive cost reduction due to mass production, etc). In summary, the elastic OFDM-network has an enormous potential to offer additional benefits in the long-term as the traffic load increases. The final cost of such an elastic network strongly depends on the cost of a BV transponder, and the manner in which its capacity is shared for the transmission of different demands.

Some interesting topics for future research are to extend this analysis to a multi-layer scenario considering the cost and energy contribution of the data layer, and to investigate some other contributions and factors that may affect the total network cost.

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