OTN Switching in Protected Transport Networks: Spectral, Cost and Energy Efficiency Evaluation

Jorge López Vizcaíno[1], Yabin Ye[1], Tamara Jiménez[2], Víctor López[3]

[1] Huawei Technologies Duesseldorf GmbH, European Research Center, Riesstr. 25, 80992 Munich, Germany
[2] Bapsys Consulting S.L, Príncipe de Vergara 89, 28006 Madrid, Spain
[3] Telefónica I+D, Core Network And Transport I+D, Ronda de la comunicación, 28050 Madrid, Spain
jorge.vizcaino @ huawei. com

Abstract— **The introduction of OTN switching on top of the WDM layer is analyzed in terms of spectral, cost and energy efficiency in a core network with mixed-line-rate transmissions and dedicated protection 1+1. The simulation results show significant improvements in the utilization of network resources by solely installing OTN switching matrices in the optical core nodes and applying grooming. The spectral efficiency can be improved in up to 567 percent, whereas the cost and energy efficiency can be enhanced in up to 564 and 1335 percent, respectively, with respect to the conventional scenarios.**

Keywords—cost efficiency; energy efficiency; mixed line rate networks; optical transport networks; OTN switching; network planning; routing and wavelength assignment; spectral efficiency; wavelength division multiplexing.

I. INTRODUCTION

Internet traffic has substantially grown in the last years due to, among other reasons, the increasing number of users and the rising popularity of bandwidth-hungry applications such as Internet video. As a result, operators are facing high pressure to make the telecommunications infrastructure ready for meeting the new capacity requirements. Upgrading the network capacity entails rising capital and operational expenditures (CapEx and OpEx) which certainly impact their profit margin of telecom operators. Energy efficiency is also becoming an increasingly important factor not only to reduce cost but also to mitigate the environmental impact caused by the greenhouse gas emissions. In fact, operators are becoming one of the major electricity consumers in the society [1]. In this context, operators are not only looking for innovative services to improve their revenue, but also to improve the utilization of network resources (e.g., spectrum, equipment and energy) as a way to eventually improve the cost-efficiency.

The core network operates using the wavelength division multiplexing (WDM) technology with the fixed channel spacing specified by the International Telecommunication Union-Telecommunication (ITU-T) grid (the C-Band is divided into a fixed number of channels of typically 50 GHz wide). The transport network will be one of the most affected by the ever-increasing traffic demand, and the common approach to efficiently increase the capacity of this network segment lies in the deployment of higher-speed optical systems (e.g., 400 Gbps). In addition to the obvious benefits in spectral efficiency, these systems commonly offer lower cost and energy consumption per transmitted bit than legacy systems. Nevertheless, the potential advantages provided by higher-speed systems might be limited by: (1) the inefficient utilization of the resources (over-provisioning); and (2) the large network dimensions. First, the suboptimal utilization of the elevated capacity of the transponders (TSPs) may lead to inefficiencies if the transmission rate at the client side is considerably lower than that at the line side. In fact, it is unlikely that a single user/entity solely generates such a high volume of information (~Gbps) and different client signals are often aggregated and transmitted together. Second, these systems employ higher order modulation, such as 16-quadrature amplitude modulation (16-QAM), which require higher optical signal to noise ratio (OSNR) levels to successfully recover the information at the receiver end (i.e., the higher the modulation order, the higher the required OSNR at the receiver). Thus, they are less tolerant to physical impairments and less feasible for transmissions over long distances.

Providing high availability is also essential for operators due to the increasing number of indispensable services that rely on the telecommunication infrastructure. Common methods to protect networks are based on the provisioning of high levels of redundancy to make the network resilient such as dedicated protection 1+1 (DP 1+1). This redundancy may make the two previously mentioned inefficiency problems even more severe. On the one hand, the need to duplicate network resources for protection can increase the number of low-utilized TSPs. On the other hand, the link-disjoint protection paths may become significantly longer making the deployment of high-speed communications system unfeasible.

Traffic grooming techniques are commonly applied to achieve a better utilization of the network resources and allow an optical channel to be shared by different client signals. These techniques are essential to economically justify the deployment of high-speed communication systems like 400 Gbps. Grooming may consider multiplexing together signals aimed to the same destination at the source node, or signals sharing part of the path at intermediate nodes. However, in conventional WDM networks, the latter approach would imply a large number of costly optical-electrical-optical (OEO) conversions (i.e., every signal has to be received and re-transmitted in every intermediate node) which makes it not the most appropriate solution. On the other hand, the application of grooming at the intermediate nodes can reduce the transmission distances and thus allow for using higher-speed systems, which are more spectral efficient.

A novel mechanism to perform grooming in optical core networks lies on the switching capabilities of the optical transport network (OTN) technology. In fact, OTN offers flexible bandwidth management capabilities by switching data transport containers known as optical channel data units (ODUs). The installation of OTN switching matrices at the optical nodes (realized by ODU cross connect (ODU-XC) boards) enables sub-wavelength grooming and switching *ODUk* connections of different capacity, where *k* can be 0, 1, 2, 2e, 3, 4, or flex. This functionality permits decoupling the clients from the WDM transport interface, which results in reduced service over-provisioning levels and smooth upgrades that do not require hardware modifications at the tributary side. In fact, OTN switching brings advantageous features compared to conventional WDM networks where sub-wavelength grooming cannot be realized within and between wavelengths (i.e., any traffic re-grooming requires de-multiplexing the wavelengths into client signals).

The potential advantages of OTN switching have been preliminary investigated in the literature. For instance, Takita et al. define a new measure known as "grooming index" to judge whether OTN grooming can provide economical advantages depending on the traffic conditions in [2]. Melle et al. also show in [3] the potential spectral efficiency enhancements provided by OTN grooming and the reduction of the number of client ports that can be achieved with an integrated OTN/WDM node architecture over a conventional node with and without stand-alone OTN equipment.

In this work, we provide an extensive evaluation of the spectral, cost and energy efficiency advantages that OTN switching can bring to WDM networks when protection is considered. In fact, the application of OTN switching can bring enhanced utilization of network resource to networks requiring DP 1+1 without sacrificing reliability. The study is carried out for a realistic long-haul network scenario, with mixed-line-rate (MLR) transmission (40/100/200/400 Gbps).

The paper is organized as follows. Section II presents a description of the node architecture and an example of the OTN switching concept. Section III describes the network scenario, the parameters of the network elements regarding cost and power consumption (PC), and the transmission model. Section V explains the heuristic algorithms utilized for this study. Section VI presents the simulation results, and finally Section VII concludes the paper.

II. OTN SWITCHING

A. Node architecture

OTN switching relies on the installation of ODU-XC boards in between the line boards and the OTN tributary boards as shown in the add/drop stage part of the node architecture in Fig. 1. In this study, a node architecture based on a multicast switch (MCS) is assumed [5]. The nodes are composed of several wavelength selective switches (WSS) that depend on the number of incoming and outgoing fibers in the node (i.e., node degree *N*) and also include a set of optical amplifiers (OAs) such as the pre-amplifier and booster at the input and output of the nodes to compensate for the fiber loss and the insertion and splitting losses of the node, respectively. A MCS is used for the adding and dropping of the optical signals, together with an amplifier array to compensate for the potential losses inserted by this element.

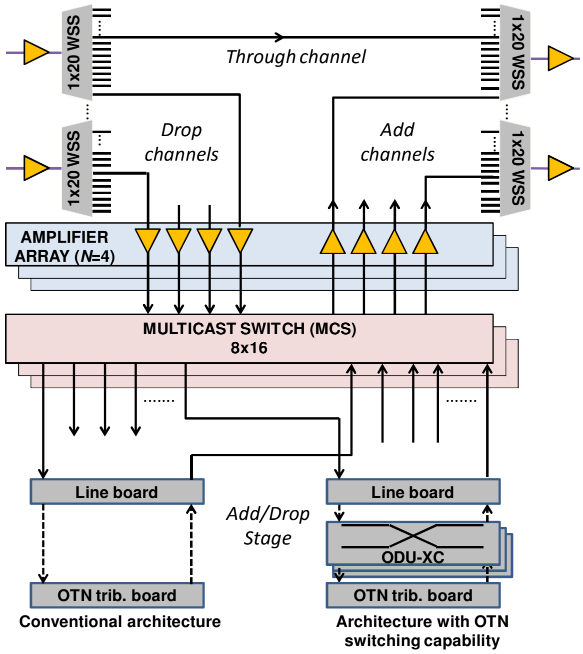

Fig. 1. Node architecture model with two different add/drop stage approaches: (left) Conventional; and (right) Including OTN switching matrix.

B. Example of service provisioning with OTN switching

Fig. 2 shows the provisioning of 3 different services with DP 1+1 in a network with conventional nodes (Fig. 2a) and OTN-switching capable nodes (Fig. 2b). In particular, three services are provisioned (A to B, A to D, and B to C) considering working path (WP) and protection path (PP) transmissions.

As shown in Fig. 2b, the availability of OTN switching allows the lightpaths (LPs) to carry together signals aimed to different destinations, which can correspond to working and/or protection transmissions. It is worth mentioning that OTN switching can be applied ensuring that the WP and PP of a traffic demand do not share any potential link failure point since they are assigned completely link-disjoint paths. For instance, the LP between nodes C and D convey the WP transmission of service 1 (*wp1*) and the PP transmission of service 3 (*pp3*).

The spectrum occupancy in all the links can be halved by applying OTN switching. Moreover, the overall number of line boards can also be reduced, which may decrease the total cost and PC if the savings are higher than the extra cost/PC of the new ODU-XCs.

III. NETWORK SCENARIO AND PARAMETERS

A. Network scenario and architecture

An ITU-T grid WDM network with MLR operation of 40, 100, 200 and 400 Gbps, and a total number of 80 wavelengths is considered. The first three mentioned line rates occupy one slot of 50 GHz, whereas the 400 Gbps, whose signal bandwidth does not fit on a 50 GHz slot, requires two slots (100 GHz).

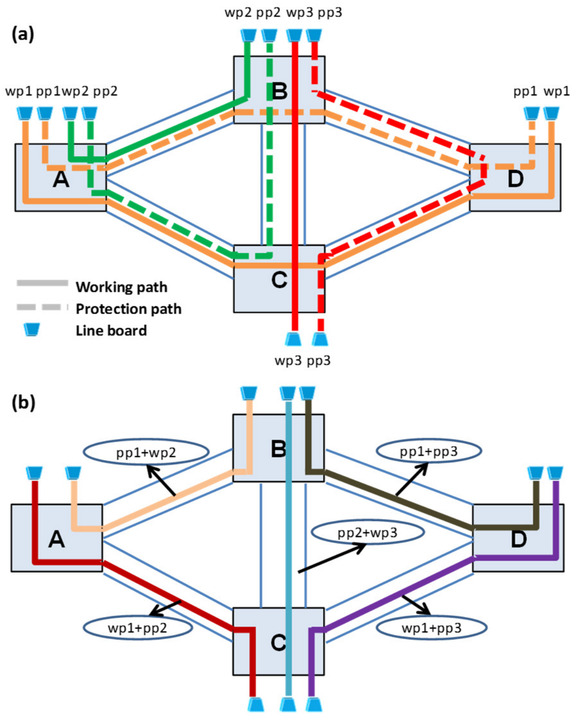

Fig. 2. Provisioning of 3 services with DP 1+1 with: (a) Conventional node architecture without OTN switching; (b) Node architecture with OTN switching matrix.

The performance of a network with OTN switching capabilities is compared with that of a conventional network where this functionality is not available. The network scenario considered is the Spanish core network model of Telefónica I+D (TID) depicted in Fig. 3, which has 30 nodes and 56 bi-directional links including a total of 66 amplifier locations. A single-fiber pair per link and no regeneration possibilities are assumed.

B. *Network elements: Cost, power consumption and transmission parameters*

The main parameters regarding cost, PC and transmission of the different network elements are presented in this subsection.

1) *Transponders (TSPs)*

Four types of TSPs (including the line and tributary boards) are considered in this study (40, 100, 200 and 400 Gbps). Table I presents the cost in cost units (CU) and PC values in watts of the different TSPs. The required OSNR (ROSNR) values are also presented in Table I. ROSNR gives the minimum OSNR value necessary to successfully recover the information at the receiver node.

TABLE I. TRANSPONDER PARAMETERS

Capacity (Gbps)	Mod. format	PC (W) [5]	Cost (CU) [4]	ROSNR (dB) [5]
40	QPSK	173.8	6	12
100	DP-QPSK	243.4	15	14.5
200	DP-16QAM	280	17.5	20.5
400	DP-16QAM	481.9	22.5	23.5

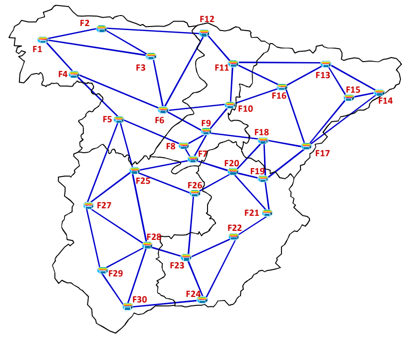

Fig. 3. TID network model scenario [7].

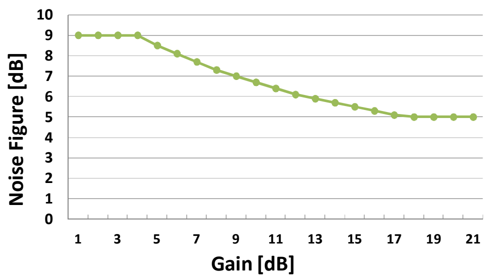

Fig. 4. Gain versus NF values for an EDFA [5].

2) *Optical Amplifier (OA)*

Erbium-doped fiber amplifiers (EDFAs) are placed in the links and nodes of the network. Each EDFA has a cost value of 1 CU and consumes 30 watts per direction with and overhead of 140 watts per inline amplifier location [5]. The noise figure (NF) is the most relevant parameter regarding amplifier performance, as it indicates the amount of noise that the OA adds to the signal. *NF* is related to the gain provided by the OA. The *NF* versus gain relationship is presented in Fig. 4 for gain values in the range between 10 and 20 dB [5].

3) *Optical cross connect (OXC)*

The assumed node architecture is presented in Fig. 1 and is based on [6]. As shown, the OXC is composed of 1x20 WSS modules at the input and output of the nodes and 8x16 multicast switch (MCS) modules at the add/drop stages. Furthermore, OAs are used to compensate for the insertion and splitting losses of the node (i.e., pre-amplifier, booster and an amplifier array which supports up to *N*=4 each) [5].
The cost of an OXC (C_O) in CU can be calculated as in (1) based on *N* and the add/drop degree (*a*):

$$C_O[CU] = N\left(C_{pa} + C_b + 2C_{WSS}\right) + 2\left\lceil \frac{N}{4} \right\rceil C_{AA} + 2\left\lceil \frac{a}{16} \right\rceil C_{MCS} \quad (1)$$

where C_{pa}, C_b, C_{WSS}, C_{AA} and C_{MCS} are the cost values for the pre-amplifier (0.8 CU), booster (0.8 CU), WSS unit (6 CU), amplifier array (12 CU) and MCS (24 CU), respectively. Further details about the cost model can be found in [4].

Regarding the PC of an OXC, its value in watts also depends on *N* and *a* as described in (2):

$$PC[W] = N\,85 + a\,100 + 150 \quad (2)$$

As mentioned before, the OAs insert noise which affect the optical transmission. Accordingly, the *NF* of the OAs installed in the node, whose gain is adjusted to compensate for the node insertion losses [5], have also to be taken into account when evaluating the physical transmission feasibility.

4) OTN switching matrix

The OTN switching matrix is placed in between the line and tributary boards as depicted in Fig. 1. This matrix can be composed of one or several ODU-XC boards, according to the maximum switching traffic supported by each board. A maximum switching capacity of 1 Tbps per board is assumed. Each ODU-XC costs 18 CU and consumes 96 W.

5) Optical fiber

A fiber attenuation factor (α) of 0.22 dB/km is assumed [7]. Moreover, there are some additional contributions to consider in the calculation of the span loss as modeled in equation (3):

$$SpanLoss[dB] = \alpha L[km] + \frac{0.05L[km]}{2} + 2 + 1.5 \quad (3)$$

where *SpanLoss* is given in dB and *L* is the span length in km. The second factor accounts for the loss due to a fused splice after each 2 km fiber segment (typical value in real deployment scenarios). The extra 2 dB and 1.5 dB factors account for the losses due to the connections between amplifiers and line cards and the splices from maintenance tasks, respectively [7].

C. Transparent reach feasibility

The transmission feasibility with a particular TSP in a given path is assessed based on the OSNR value obtained at the receiver in dB ($OSNR_{RXdB}$) which is calculated following the methodology in [5] or [8]. $OSNR_{RXdB}$ is then compared with the corresponding ROSNR value in Table I (i.e., according to the line rate of the TSP) plus an additional margin of 3 dB (Mar_{dB}) to guarantee that penalties due to nonlinear effects will not affect the feasibility of the transmission as in (4).

$$OSNR_{RX}[\text{dB}] \geq ROSNR[\text{dB}] + Mar_{dB}[\text{dB}] \quad (4)$$

IV. Optimization Algorithms

The study considers the conventional static (or offline) network planning problem in WDM MLR networks. Routing and wavelength assignment (RWA) algorithms are employed to evaluate the performance of network architectures with and without OTN switching capabilities. In a MLR network, different line rate combination (*LRComb*) or TSPs can be selected to provision a service. This selection can be based on different criteria. In this study, the algorithms attempt to allocate the maximum traffic in the network while optimizing one of the three following metrics: Spectral efficiency, cost efficiency per GHz or energy efficiency per GHz.

A. Optimization metric

1) Spectral efficiency (SE) metric

The SE metric is calculated in (5) considering the value of the end-to-end traffic demand (*TrDem*) and the spectral occupancy (*SOP*) of the selected *LRComb* which is given by the required number of wavelength channels of 50 GHz.

$$SE\ metric[bps/GHz] = \frac{TrDem[bps]}{SOP\ [GHz]} \quad (5)$$

2) Cost efficiency per GHz (CEPG) metric

The CEPG metric is calculated in (6) based on *TrDem, SOP* and the cost of the TSPs of the selected *LRComb* (C_{TSP}).

$$CEPG\ metric\left[\frac{bps}{CU}/GHz\right] = \frac{TrDem\ [bps]/C_{TSP}\ [CU]}{SOP[GHz]} \quad (6)$$

3) Energy efficiency per GHz (EEPG) metric

The EEPG metric is calculated similarly to the CEPG metric, but considering the PC of the TSPs included in *LRComb* (PC_{TSP}) as in equation (7):

$$EEPG\ metric\left[\frac{b}{J}/GHz\right] = \frac{TrDem\ [bps]/PC_{TSP}[W]}{SOP[GHz]} \quad (7)$$

B. Initial scenario- without OTN switching functionality

The demands of the initial traffic matrix (*InitialTM*) are sorted according to the demand value, i.e., highest demands first. For each traffic demand, the following steps are followed:

- *Route computation*: Since DP 1+1 is assumed as protection scheme, a service is provisioned with a WP and a PP. Thus, for each traffic demand, a set of candidate WPs (*k*-shortest paths) and corresponding link-disjoint PPs (*k*-shortest paths in a modified network graph where the links of the WP have been pruned) are provided.
- *LRComb calculation:* As mentioned before, in a MLR network, a service can be provisioned by different *LRComb*. Accordingly, all the potential *LRComb* to meet the throughput requirements (*TrDem*) are calculated and listed in descending order of the evaluated metric (i.e., SE metric, CEPG metric or EEPG metric) in *LRCombList*.
- *WA evaluation*: The WA evaluation starts with the first *LRComb* (i.e., the one providing the highest metric) so that the most convenient solutions according to the evaluated metric are prioritized. First, the allocation with the first *LRComb* is analyzed on the first candidate WP. For a successful service provisioning, the two following constraints must be fulfilled: (1) Wavelength continuity constraint; and (2) Physical transmission constraint (based on the OSNR computation described in Section III C). If the two previous constraints are fulfilled with the first *LRComb* on the first candidate WP, the WA evaluation is repeated on the candidate PPs. If the WA evaluations on both the WP and PP are successful, the corresponding LPs are established. Otherwise, the WA is re-evaluated with the same *LRComb* on the following combinations of WP and PP. If no solution is achieved in any of the candidate paths, the procedure is repeated with the following *LRComb* of *LRCombList* until reaching a feasible solution, or until concluding that the demand is blocked if no solution is found with any *LRComb* on any combination of WP and PP.

C. OTN swiching scenario

The availability of OTN switching permits the application of traffic grooming in the optical core nodes (i.e., conveying different traffic flows onto the same LP) as show in Fig. 2. More specifically, the LPs established for each demand of the *InitialTM* can be partitioned into a set of shorter-distance LPs. We assume that the OTN switching matrix is only available in the so-called active nodes (i.e., those nodes that are source or destination of traffic of the *InitialTM*). Thus, in the active nodes it is possible to perform traffic grooming, whereas the remaining nodes can perform only as mere transit nodes. This scenario entails a modification of the *InitialTM*, so that an auxiliary TM (*AuxTM*) has to be generated. In order to obtain *AuxTM*, the RWA is performed for each traffic demand over the shortest feasible WP and PP (*k*-shortest paths with *k* equal to 1). Then, these paths are segmented into smaller paths by finding the next active node from source to destination. For instance, in the example of Fig. 2, *wp1* and *pp1* are divided into two "sub-demands" each (i.e., *wp1* in demands from A to C, and C to D, and *pp1* in demands from A to B and B to D). This procedure is repeated for all the traffic demands of the *InitialTM,* allowing for summing in *AuxTM* all the traffic demand values (*TrDem*) that share the same source and destination nodes (e.g., in Fig. 2 the resulting *TrDem* value between node A and node B will be the summation of service 1 (*pp1*) and service 2 (*wp2*).

After obtaining *AuxTM*, the RWA described in the previous section (Section IV B) is repeated considering *AuxTM* instead of *InitalTM*. In this scenario, it is also necessary to obtain the total traffic switched per node by the OTN matrix as this value determines the number of required ODU-XC boards.

D. Final performance measures

1) Average spectral occupancy (ASO)

ASO is calculated considering the average spectral occupancy of the links in the network, i.e., occupied spectrum/total bandwidth in the C-band (4000 GHz).

2) Overall CEPG

The overall CEPG of the network is obtained in equation (8) where *TotalTraf* is the summation of all the demands in *InitialTM* and *TotalCost* is the CapEx of the network elements in the network which includes the TSPs, OAs, OXCs and ODU-XC boards (only in the OTN switching scenario).

$$CEPG\left[\frac{\text{bps/CU}}{\text{GHz}}\right] = \frac{TotalTraf\,[\text{bps}]/TotalCost\,[\text{CU}]}{ASO\ [\text{GHz}]} = \frac{\sum TrDem/(\sum C_{TSP}+\sum C_{OA}+\sum C_{O}+\sum C_{ODU-XC})}{ASO} \quad (8)$$

3) Overall EEPG

The overall EEPG of the network is obtained in equation (9) by the ratio of the energy efficiency (*EE*) and the ASO in GHz of the network. *EE* is calculated by dividing *TotalTraf* by *TotalPC,* where *TotalPC* is the power consumed by all the equipment deployed in the network and includes the PC of the TSPs, OAs, OXCs, and also ODU-XC boards if the OTN switching scenario is considered.

$$EEPG\left[\frac{\text{b/J}}{\text{GHz}}\right] = \frac{EE\,[\frac{b}{J}]}{ASO\,[\text{GHz}]} = \frac{TotalTraf\,[\text{bps}]/TotalPC\,[\text{W}]}{ASO\,[\text{GHz}]} = \frac{\sum TrDem/(\sum PC_{TSP}+\sum PC_{OA}+\sum PC_{O}+\sum PC_{ODU-XC})}{ASO} \quad (9)$$

V. SIMULATION RESULTS

An *InitialTM* with 46 bi-directional demands, resulting in an overall traffic of 825 Gbps (based on [7]) has been adopted as a reference and scaled up to 24.75 Tbps. In this section, the final performance measures achieved with each of the corresponding metrics (Section IV A) are presented for both the conventional and the OTN switching scenario.

A. Spectral efficiency

Fig. 5 presents the comparison of the ASO of the network with and without OTN switching capabilities, using the SE metric for the RWA. As shown, the utilization of spectral resources can be significantly reduced by the application of OTN switching at all the evaluated traffic conditions. The reduced spectral occupancy may eventually enlarge the overall capacity of the network. At low traffic, in the conventional scenario, the capacity of the TSPs is not efficiently utilized in most of the cases since the average demand is approximately 9 Gbps. This inefficiency problem is even more severe when considering that both WP and PP must be provided. Thanks to OTN switching, the number of assigned wavelengths can be dramatically decreased when several traffic demands are groomed onto the same LP. As traffic grows, the advantages provided by the grooming become less relevant. However, OTN switching can still be advantageous to reduce spectral occupancy as the segmentation of long paths of the *InitialTM* (especially for the PP) into smaller sub-paths allows for using more spectral-efficient transmissions (e.g., 200/400 Gbps). The SE improvements of OTN switching over the conventional scenario range from 567 (at low traffic) to 65 percent (at high traffic).

B. Cost Efficiency per GHz (CEPG).

The overall CEPG for both evaluated scenarios is presented in Fig. 6 (using the CEPG metric). As shown, OTN switching can improve CEPG at any traffic load, especially at low traffic. In fact, when traffic is low, the application of grooming can significantly reduce the total number of TSPs and also enable the transmission with higher-speed TSPs, which offer lower cost per bit than legacy systems. Thus, despite the extra cost of the ODU-XC boards, the cost savings achieved in the TSPs result in improved overall CEPG. As traffic grows, the CEPG with OTN switching is reduced. Actually, at high traffic, the chances of applying grooming are decreased (lower over-provisioning levels) and the application of OTN

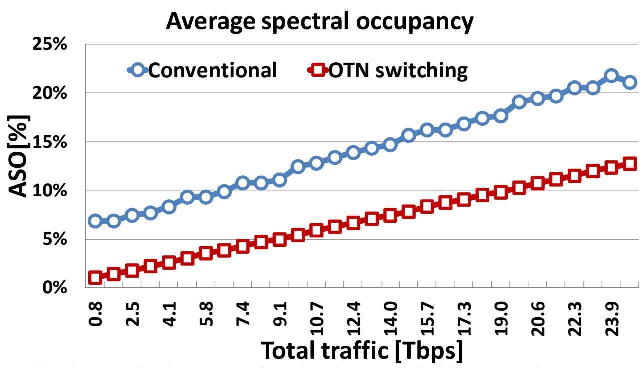

Fig. 5. ASO in the conventional and OTN switching scenarios.

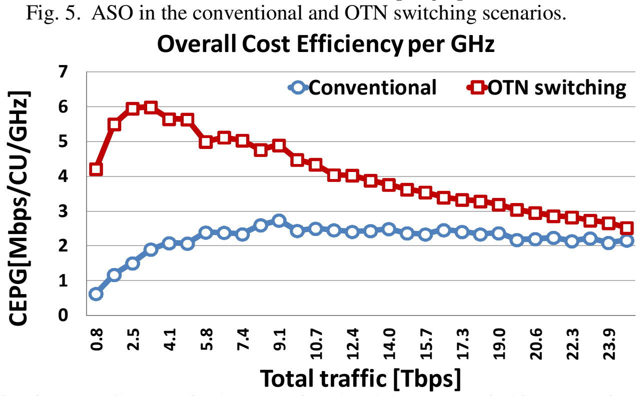

Fig. 6. Overall CEPG in the coventional and the OTN switching scenarios.

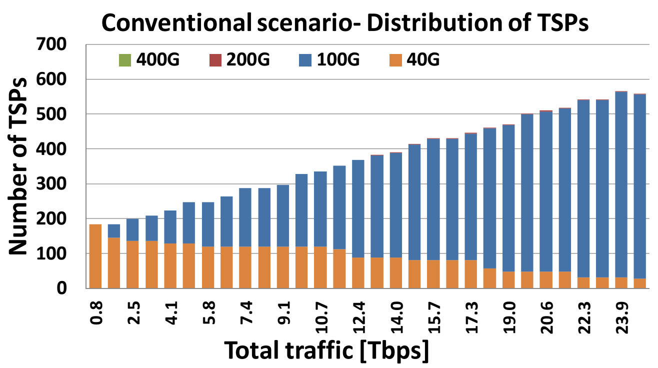

Fig. 7. Distribution of TSPs per line rate in the conventional scenario.

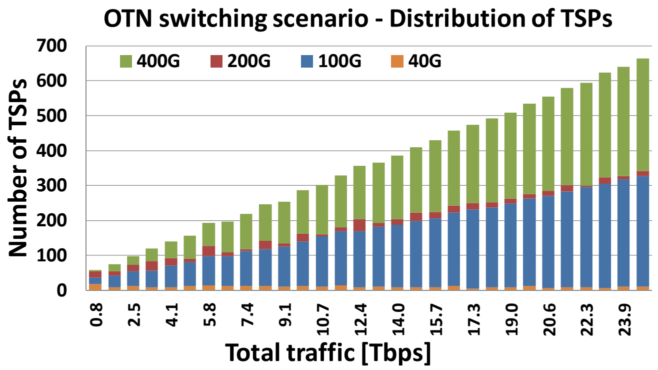

Fig. 8. Distribution of TSPs per line rate in the OTN switching scenario.

switching may result in a greater number of TSPs (i.e., more end-to-end traffic demands) which eventually affects the cost of the network. This effect can be observed in the distribution of TSPs of the conventional and the OTN switching scenarios in Fig. 7 and Fig. 8, respectively. In fact, at high traffic, the overall cost of the OTN switching scenario becomes higher than the conventional one, but the greater utilization of spectral resources still makes it a more cost-efficient solution at any of the evaluated traffic conditions. The enhancements in CEPG are in a range between 564 (at 0.8 Tbps) and 29 percent (at 24.75 Tbps) over the conventional scenario.

C. Energy Efficiency per GHz (EEPG).

The overall EEPG of the network is presented in Fig. 9 (using the EEPG metric in the RWA). As shown, the EEPG of the network can be remarkably enhanced when the OTN switching functionality is available in the nodes. The performance in terms of EEPG follows a similar trend to the results obtained for CEPG. Accordingly, the EEPG improvements are significantly relevant at low traffic, where grooming allows for reducing the high over-provisioning levels and the number of active TSPs (i.e., a TSP consumes constant power independently of the traffic load). Then, when moving to higher traffic loads, the EEPG of the OTN switching scenario decreases as it is less probable to take advantage of the grooming possibilities and the overall number of TSPs consuming power is increased (similarly to the distribution of TSPs obtained with the CEPG metric in Fig. 8). Nonetheless, even at high traffic, OTN can improve EEPG thanks to its notably better spectral efficiency (Fig. 5). OTN switching can improve EEPG in a range between 1335 (at 0.8 Tbps) and 25 percent (at 24.75 Tbps).

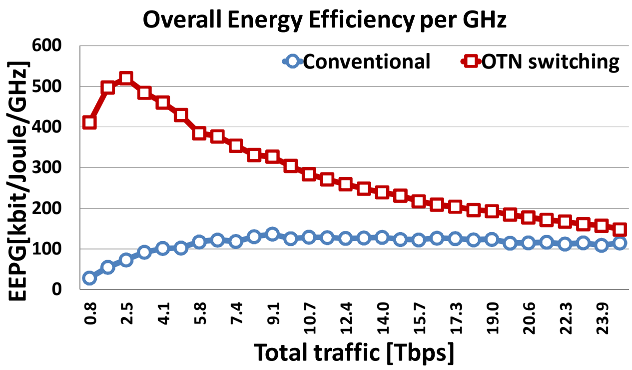

Fig. 9. Overall EEPG in the conventional and the OTN switching scenarios.

VI. CONCLUSIONS

Telecom operators are facing high pressure to upgrade the telecommunications infrastructure to meet the ever-increasing traffic requirements. In this context, approaches allowing for improving the cost efficiency and the utilization of the scarce spectral and energy resources are gaining momentum. OTN switching is a promising candidate to address these challenges in a simple manner as it only requires the installation of ODU-XC boards at the existing optical nodes. In this paper, we aimed at evaluating the potential improvements in terms of spectral, cost and energy efficiency that OTN switching can offer to operators of nation-wide networks with WDM MLR transmissions and DP 1+1. As shown in the results, this functionality can dramatically decrease the number of utilized wavelengths as well as enhance the overall cost and energy efficiency of the network (despite the extra cost and power consumption of the ODU-XC boards). OTN switching can be notably beneficial at low traffic where the application of grooming can significantly enhance the utilization of the capacity of the TSPs. Improvements of up to 567, 564 and 1335 percent over the conventional scenario can be achieved in terms of SE, CEPG and EEPG, respectively

REFERENCES

[1] F.Cucchietti, "Telecom Italia -Energy Efficiency and ICT: short term needs long term opportunities," Dec. 2010.

[2] Y. Takita, T. Hashiguchi, K. Tajima, T.Naito, "Grooming Index for OTN/WDM networks," OFC/NFOEC 2013, pp. NTh1I.3, Mar. 2013.

[3] S. Melle, A. Deore, O. Turkcu, S. Ahuja, S. Hand, "Comparing Optical & OTN Switching Architectures in Next-Gen 100Gb/s Networks," OFC/NFOEC 2013, pp. NM3F-2, Mar. 2013.

[4] J. López Vizcaíno, Y. Ye, V. López, P. Krummrich, "Cost Evaluation of Amplification Strategies for WDM Mixed-Line-Rate Networks," ICTON 2015, Jul. 2015.

[5] J. López Vizcaíno, Y. Ye; F. Jiménez, P.M. Krummrich,"Amplifier placements optimization for enhanced energy efficiency in optical transport networks," IEEE International Conference on Communications (ICC), 2014, vol., no., pp.3700-3706, Jun. 2014.

[6] Fujitsu, "CDC ROADM applications and cost Comparison,"Mar. 2014.

[7] F. Jiménez, EU FP7 IDEALIST, "WP1 preliminary inputs for WP2 analysis. General considerations on network reference architectures and physical layer details for Telefónica model," Dec. 2012.

[8] B. Chomycz, "Planning Fiber Optics Networks," McGraw-Hill, , Chapter 3 and Appendix B, 2009.