Protection in optical transport networks with fixed and flexible grid: Cost and energy efficiency evaluation

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1. Introduction

The proliferation of new services, such as social networks, cloud computing, and especially video streaming, which already accounts for more than 50% of the traffic, is pushing operators to upgrade their networks to meet the new capacity requirements. This exponential Internet traffic increase has resulted in an average annual growth rate of 45% in previous years, with Cisco forecasting a similar trend for the near future [1]: "*Globally, Internet traffic will grow 3.8-fold from 2011 to 2016, a compound annual growth rate of 31%*".

The traffic growth will require capacity upgrades in telecommunications networks, especially in the core or backbone domain. Current optical transport networks are based on Dense Wavelength Division Multiplexing (DWDM), in which the total optical spectrum of the C-band is partitioned into a set of slots or wavelength channels with a fixed spacing defined by the International Telecommunications Union-Telecommunication Standardization Sector (ITU-T): the fixed ITU-T grid. The near future will bring new challenges and needs related to optical transport networks that carriers and the research community will need to address: (1) flexible resource

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allocation, (2) heterogeneous traffic demands, (3) cost- and energy-efficient solutions and (4) reliable service provisioning.

- *Need for a flexible resource allocation*: The fixed ITU-T grid in current WDM networks leads to an inefficient use of the spectral resources (i.e., if the actual traffic demand is lower than the fixed transmission rate of the transponder). Besides, the next generations of "beyond 100 Gbps" transmission technologies cannot be efficiently transmitted with the fixed 50 GHz grid. An alternative to fixed-grid networks that has recently been receiving a lot of attention is Elastic Optical Networks (EON), which operate with a flexible grid (Flexigrid) and thus provide the necessary dynamicity to circumvent the aforementioned efficiency problem. Indeed, in an EON, 12.5-GHz frequency "chunks" are adopted, with a variable number of these chunks being assigned to a channel as a function of the bandwidth requirements.
- *Need to cope with heterogeneous traffic demands*: Services for clients with different traffic requirements have to coexist in the network. In current WDM networks, mixed line rate (MLR) can be a short-term solution to better suit the heterogeneous traffic demand requirements. However, for higher traffic heterogeneity levels, MLR is not efficient due to the limited number of available line rates. EONs enable efficient network resource utilization through a finer adjustment of the channel capacity to the actual service demand.
- *Need for cost- and energy-efficient solutions*: A network capacity upgrade implies an increase in Capital Expenditure (CapEx) and Operational Expenditure (OpEx) resulting from, for instance, the deployment of new telecommunication infrastructure and the related higher power consumption. In 2012, telecommunication networks accounted for 2% of worldwide electricity consumption, showing an average annual growth rate of 10% since 2007 [2].
- *Need for a reliable and highly available service*: An increasing number of indispensable services rely on the telecommunication infrastructure. Providing high service availability by guaranteeing high resilience against common failures is a must for operators. Therefore, it is also essential to consider network protection both for the evaluation of new technologies and for planning new capacity upgrades.

As EONs are a promising solution for network operators [3], this contribution studies how the EON paradigm can help to cope with the above mentioned challenges, extending our previous works on these topics [4–6]. This article includes a thorough description of the proposed heuristic algorithms and parameters considered in the investigation, providing a broad vision of the situations where a particular protection scheme or transmission technology is more beneficial in terms of energy and cost-efficiency. In summary, the main results of this paper are:

(i) A detailed explanation of the power consumption and cost model for both fixed- and flexible-grid optical transport networks.
(ii) Energy-aware heuristic algorithms have been proposed and implemented to solve the network planning problem (offline problem) in both fixed- and flexible-grid networks with different protection schemes: Dedicated protection 1+1 (*DP* 1+1), dedicated protection 1:1 (*DP* 1:1), and shared protection (*SP*), as well as a novel multi-hour protection scheme, called dedicated protection traffic-aware power-aware (*DP TAPA*), that exploits the daily traffic variations to save energy.
(iii) Comprehensive energy- and cost-efficiency analyses of the benefits of each particular protection scheme and transmission technology in two realistic long-haul network topologies, which gives an insight into the impact of the network topology and the geographical distribution of the traffic on the results.

The rest of the paper is organized as follows. Section 2 presents the main network considerations as well as the network model, and also explains the protection schemes that are evaluated in this study. Section 3 summarizes the related work and recent achievements on related topics. Section 4 presents the cost and power consumption models adopted for this work. Section 5 explains the basic methodology for the analyses. Section 6 describes the two network topologies considered in this study. Section 7 presents the simulation results, and Section 8 concludes the paper.

2. Networking considerations and terminology

2.1. Fixed ITU-T grid wavelength-switched optical networks and elastic optical networks

Fixed grids for WDM networks are specified in ITU-T recommendation G.694.1 [8]. The frequency grid is anchored to 193.1 THz (or 1552.52 nm) and roughly covers 4 THz. Different channel-spacing values, ranging from 12.5 GHz to 100 GHz, have been defined, but we have adopted a channel spacing of 50 GHz in our WDM model, resulting in a total of 80 wavelengths in the 4 THz band (Fig. 1). Furthermore, two different WDM-network configurations are proposed:

- Single line rate (SLR): All the signals on the network are transmitted with the same line rate (e.g. 10, 40 or 100 Gb/s).
- Mixed line rate (MLR): Transmission of 10-, 40- and 100-Gb/s channels concurs on the optical network. Adjacent channels with different transmission technologies may suffer from cross-talk, affecting the signal quality. In order to minimize this effect, the C-band has been divided into two different bands: (1) band with only 10-Gb/s channels (On–Off keying (OOK)), and (2) band with 40- and 100-Gb/s channels, given that both use the same modulation format (Quadrature Phase Shift-Keying (QPSK)) and consequently do not significantly affect the signal quality of each other. These two bands are separated by a guard band of 200 GHz (4

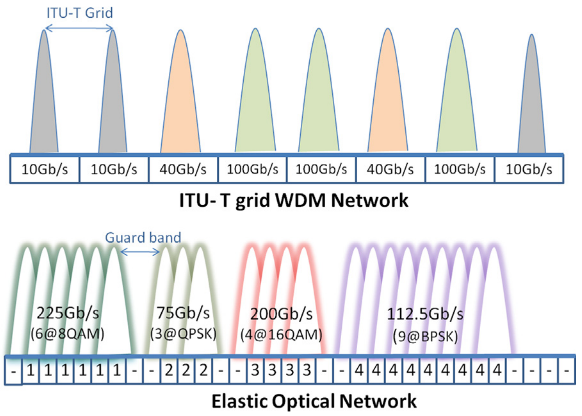

Fig. 1. Spectral allocation in: (upper part) fixed ITU-T grid WDM networks with 10, 40 and 100 Gb/s channels, and (lower part) EON networks which utilize four channels with different bandwidth and modulation formats (8 quadrature amplitude modulation (QAM), quadrature phase shift keying (QPSK), 16QAM, binary phase shift keying (BPSK)).

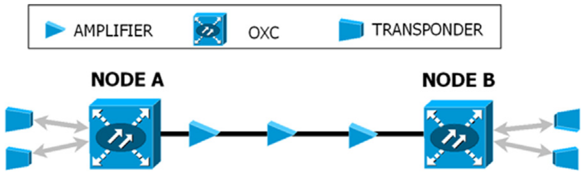

Fig. 2. Network model: transponders, amplifiers, and OXCs.

wavelength channels), and the size of each band is determined according to the traffic conditions.

As a third scenario, we consider that The ITU-T grid is replaced with the concept of frequency slot, which is the spectral width of a given channel. In our model, the slot-width granularity is 12.5 GHz, i.e. the spectrum is partitioned into frequency chunks of 12.5 GHz, resulting in a total of 320 chunks across the 4 THz C-band, a variable number of contiguous chunks being assigned to each frequency slot according to the bandwidth requirements. As transmission technique, we consider Coherent OFDM (CO-OFDM), with the capability of selecting modulation formats allowing different spectral efficiency values (bit/s/Hz), as depicted in Fig. 1. Furthermore, the insertion of a guard band between adjacent channels composed of two subcarriers has to be taken into account in the spectral allocation.

2.2. Network model

The analyses carried out in this study focus on the optical layer, composed of three main building blocks: transponders, optical amplifiers and optical cross connects (OXCs), as depicted in Fig. 2.

In EON deployments, transponders are replaced with bit-rate variable transponders (BVT), and fixed-grid OXCs with flexible grid OXCs (Flexigrid OXCs). A BVT is a transponder capable of providing different transmission rates by modifying the channel bandwidth (using a variable number of subcarriers) and/or the modulation format of the subcarriers. Likewise, a Flexigrid OXC is an OXC that can add or drop any channel regardless of its bandwidth.

2.3. Survivability

Common survivability mechanisms can be divided into two broad groups: restoration and protection. Restoration is a dynamic recovery performed after a failure has occurred, whereas protection is a pre-planned failure recovery. Since restoration is less reliable and takes longer to recover, protection is more commonly used by operators. Therefore, only protection is considered in our studies. The following schemes are analyzed in our work:

- *Dedicated protection* (*DP*): Spectral resources are reserved along the working and protection or backup (link–disjoint) paths. *DP* schemes can be classified according to the strategy adopted for the transmission on the backup path. In our study, three *DP* schemes

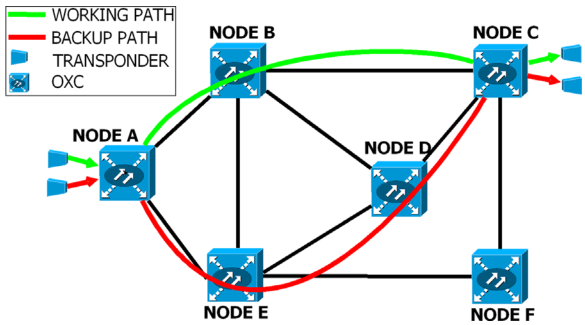

Fig. 3. Example of operation of the *DP* 1+1 scheme.

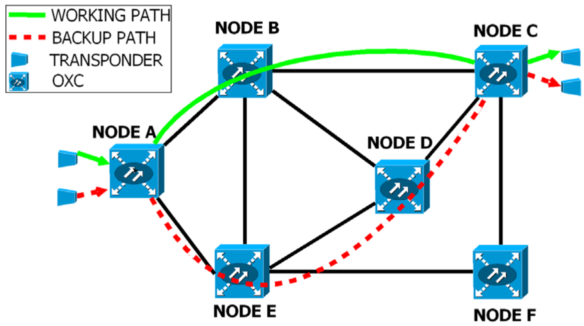

Fig. 4. Example of operation of the *DP* 1:1 scheme.

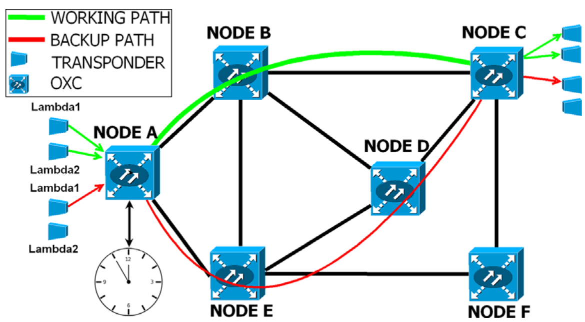

Fig. 5. Example of operation of the *DP TAPA* scheme: Two wavelengths are used for working path, but just one wavelength is used for backup during night.

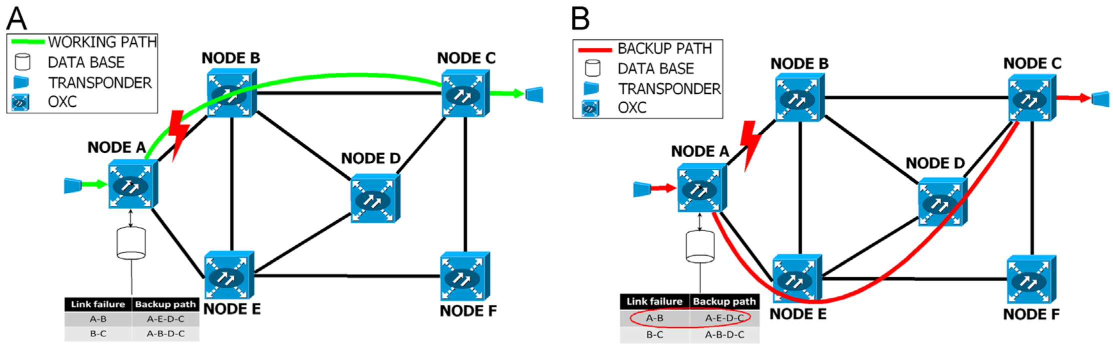

Fig. 6. Example of operation of a *SP* scheme: (A) before failure, (B) after failure.

have been assumed: (1) 1+1, (2) 1:1, and (3) TAPA. *DP* 1+1 (Fig. 3) transmits on both working and backup paths, thus requiring the deployment of duplicated transponders. Transmission based on *DP* 1:1 (Fig. 4) is carried out either on the working or on the backup path at a given time. This scheme can use transponders only for the working paths (no transponder protection), or can duplicate the transponders for the working and backup paths (i.e., as in *DP* 1+1, but keeping the transmission active only on one path at a time). This is the approach adopted in our analysis. Finally, *DP* TAPA (Fig. 5) is a protection scheme proposed in [5] aiming at reducing the energy consumption of the *DP* 1+1 scheme while maintaining its high availability level. It exploits the hourly traffic fluctuations to adapt the rate of the backup transponders to the current traffic requirements. The transmission on the working paths remains fully active (operating for the peak traffic demand value), whereas the transmission on the backup transponders is adjusted to the real traffic, thus permitting to partially deactivate some transponders when the traffic volume is low, e.g., at night.

- *Shared protection* (*SP*) (Fig. 6): The spectral resources not being reserved for the working traffic can be used for backup transmission in the case of failure. It is important to point out the difference between *SP* and restoration. In *SP*, the backup paths are pre-computed (thus ensuring a possible recovery), whereas in network restoration the backup paths are computed "on-the-fly" after a failure event, thereby entailing a longer recovery time. Also note that with restoration, the recovery might be unsuccessful if sufficient spectral resources are not available for the establishing of a new backup path. Since *SP* is a failure-dependent scheme (i.e., the backup path is selected depending on the link which has failed), failure localization is required which will increase the recovery time with respect to *DP* schemes. *SP* can be provided on the basis of different node configurations: (1) duplicated transponders are deployed for the working and the backup transmission; (2) transponders are deployed that can be indistinctively used for working or backup transmission just by applying the appropriate OXC reconfiguration (no transponder protection); and (3) transponders are deployed for the working transmission, and so are spare transponders, which can be used by any backup path if required (some transponder protection is provided). The second approach is assumed for the present study.

It is worth mentioning that the above protection schemes can be applied at different levels: path, link or segment. In the present study, we only consider path protection.

3. Related work

The EON paradigm has been a topic under extensive research over the last years, as it will bring operational changes to different fields of telecommunications networks. Lately, some surveys have been published summarizing the most recent work, as well as the main enablers and potential advantages that can be achieved with an EON [9]. This concept has been experimentally demonstrated in several publications such as [10], where the authors showed the first demonstration of elastic transmission of channels with bit rates from 40 Gb/s to 400 Gb/s. Besides, commercial enabler devices such as BVT and FlexiGrid OXC are becoming a reality.

One of the research topics that has received more attention is the routing and resource allocation in EON. Most of these publications focus on the spectral savings of EON conducted by means of simulations and/or static optimization. For instance, integer linear programming (ILP) is proposed to solve this problem for small networks in [11], whereas for large networks, high efficient heuristics are proposed such as the ones in [12] and [13]. A promising functionality of EON is the distance-adaptive modulation (i.e., using a robust modulation format for long distances and a high spectral efficient one for short path lengths), which can improve further the spectral efficiency benefits as shown in [14] and [15]. Furthermore, significant research effort is being spent on developing network planning algorithms considering dynamic provisioning (i.e., online provisioning with time-varying traffic demands) to reduce the blocking probability. For instance, references [16] and [17] propose an ILP formulation and a multipath routing as a strategy to reduce the blocking probability, respectively.

The adoption of EON can also introduce some novelties in the survivability mechanisms in optical transport networks. In particular, bandwidth elasticity can be exploited to reach a better utilization of the spectral resources in EON by the application of, for instance, bandwidth squeezed restoration [18] and intelligent backup path sharing [19].

Regarding energy efficiency in optical networks, many publications targeted this topic in the previous years (references [20] and [21] present a complete survey). As far as EON is concerned, its potential energy efficiency benefits with respect to WDM networks were shown in static and dynamic network scenarios [22]. EON showed improved energy efficiency thanks to the elastic bandwidth and the selection of modulation format.

Despite the numerous publications on energy efficiency in telecommunications networks, only a limited number focus on energy efficient survivability. Most of them focus on the savings achieved by concentrating backup paths into a set of links or fibers. Power savings of up to 25% and 40% were achieved with dedicated [23] and shared backup protection [24], respectively. In [25], authors evaluated power-aware design of a protected network with dedicated link protection and dedicated path protection. Power savings up to 20% can be achieved by introducing sleep-mode on the equipment used for protection purposes. In our previous work, we compared for the first time the energy efficiency per GHz of three path protection schemes (*DP* 1+1, *DP* 1:1 and *SP*) for EON and WDM networks [4], showing better results for EON with respect to WDM. In [5], we proposed a traffic and power-aware protection strategy to reduce the power consumption of *DP* 1+1 by exploiting the traffic variations on the backup transmission. In [6], we extended our work by comparing the energy efficiency of an unprotected and protected network for EON and WDM networks.

As mentioned above, the cost will be one of the main drivers for the adoption of EON. There are several publications on this topic, like [26] and [27], in which the spectral efficiency of EON was shown as the main cost advantage. Authors in [28] evaluate a range of values to determine the cost at which OFDM networks (without protection) result in lower CapEx than conventional WDM networks. In our work presented in [6], we extended our work in [4] to evaluate the cost efficiency (taking into account both the equipment and the energy cost) of EON with respect to WDM networks with different protection schemes and cost models.

The aim of this paper is to present a global picture of both the energy and cost efficiency of optical transport networks with Flexigrid (EON) and fixed ITU-T grid (current WDM networks) with different protection schemes in two nationwide realistic scenarios, accompanied by a detailed methodology and a deep analysis of the results.

4. Network elements: power consumption and cost values

This section analyzes the power consumption and cost models used in the present analysis. The power consumption values have been taken from [5], whereas the relative cost values for current WDM equipment are based on a model used by Telefónica I+D for internal studies.

4.1. Transponders

4.1.1. WDM transponders

Electrical power consumption values of 34, 98 and 351 W [29], and normalized cost values of 1, 3 and 7.5 have been considered for transponders with bit rates of 10 Gb/s (OOK), 40 Gb/s (Differential QPSK (DQPSK)), and 100 Gb/s (Polarization Division Multiplexing-QPSK (PDM-QPSK)), respectively. It is worth mentioning that the transponders of 10 Gb/s and 40 Gb/s employ direct detection, whereas the one of 100 Gb/s is based on coherent technologies, and so its power consumption is higher due to the digital signal processing (DSP). Power figures require an additional 20% overhead for each transponder due to the contribution of other node elements to power consumption. Transmission reaches of 3200, 2200, and 1880 km [30] are assumed for 10, 40 and 100 Gb/s, respectively.

4.1.2. BVT for the EON

A BVT (CO-OFDM transponder) enabling the modification of the signal properties (i.e. number of subcarriers and modulation format) by means of software configuration is considered for our studies. Due to the commercial unavailability of such a device, some assumptions (detailed in [22]) have been made to estimate reasonable power consumption values. The power consumption of a BVT depends not only on the number of subcarriers, but also on the modulation format used. Table 1 presents the power consumption for the transmission and reception of a single subcarrier (with bandwidth 12.5 GHz) for several modulation formats. Transmission reaches of 4000, 2000, 1000, 500, 250, and 125 km [22] have been assumed for Binary Phase Shift Keying (BPSK), QPSK, and Quadrature Amplitude Modulations (QAM) of order 8, 16, 32 and 64 (8QAM, 16QAM, 32QAM, and 64QAM), respectively

The abovementioned commercial unavailability as well as the uncertainty about the final architecture of a BVT makes the cost estimation difficult. Our cost model is then based on two main assumptions:

1. The maximum achievable transmission rate is likely to determine the cost.
2. The cost per bit may be initially higher than that of usual 40- and 100-Gb/s coherent WDM transponders. This is explained by the presence of additional elements, such as DSP modules and digital to analog converters (DACs) at the transmitter part used to

Table 1
Power consumption of a BVT for the transmission and reception of a single subcarrier with different modulation formats.

Mod. Format	Subc. Cap.(Gb/s)	P. Cons. (W)
BPSK	12.5	112.374
QPSK	25	133.416
8 QAM	37.5	154.457
16 QAM	50	175.498
32 QAM	62.5	196.539
64 QAM	75	217.581

generate signals with high order modulations. Therefore, the cost per bit is assumed to be 20% higher for a BVT than that of current coherent WDM transponders with the same overall capacity.

According to the previous assumptions, a BVT with a maximum transmission rate of 400 Gb/s would cost 36 units, i.e. 20% higher than four times the cost of a 100-Gb/s WDM transponder ($1.2 \times 4 \times 7.5$).

Furthermore, we assume that a BVT can be "sliced" into a set of virtual lower-capacity transponders. The idea of a sliceable transponder was introduced in [9], and, if not considered in our analysis, it would be difficult to economically justify the investment in such a high-speed transponder (400 Gb/s) for serving an aggregated demand of, for instance, 170 Gb/s. Consequently, three possible cost models can be taken into account for a BVT, according to the manner in which the capacity of the transponder is used:

- *Transponder non sliceable* (*TNS*)*:* The full capacity of the BVT, 400 Gb/s, is dedicated to a single aggregated demand regardless of its actual value.
- *Transponder sliceable in capacity* (*TSC*)*:* The traffic demands are mapped to a set of subcarriers with a common modulation format. A maximum transmission rate of 400 Gb/s is assured by each transponder, which can be achieved by a different number of subcarriers depending on the modulation format (e.g. 32 subcarriers with BPSK, 4 subcarriers with 16QAM, etc). A transponder can then be "shared" by the transmission of several low-rate demands provided that the aggregated demand does not exceed the maximum transmission rate of a transponder, 400 Gb/s,
- *Transponder sliceable in subcarriers* (*TSS*)*:* In contrast to TSC, there is a limit on the number of subcarriers that a transponder is able to transmit, i.e. six in our study. Therefore, the transmission rate of a transponder can range from a minimum value of 75 Gb/s with BPSK, to a maximum of 450 Gb/s, when 64 QAM is used. Then, a transponder can be used for the transmission of several traffic demands with different modulation formats, provided that the number of subcarriers does not exceed the maximum number of subcarriers

Fig. 7 presents an example of the allocation of two traffic demands of 100 Gb/s and 200 Gb/s with the three approaches described above.

4.2. Optical cross connect (OXC)

We consider two types of OXC: a conventional fixed-grid OXC (ITU-T grid compliant) and a Flexigrid OXC, capable of switching channels of any bandwidth (multiple of 12.5 GHz). Similar power consumption figures, dependent on the node degree N and the add/drop degree α, have been assumed for both variants, as can be seen in the equation

$$PC_{\mathrm{OXC}}[W] = N85 + \alpha 100 + 150 \quad (1)$$

where an overhead of 150 W per node has been introduced to account for additional contributions to power consumption, such as fans, power supply, and control cards [29].

On the other hand, the cost of an OXC strongly depends on its internal architecture. In this study, we assume an OXC composed of several wavelength selective switches (WSSs), as shown in Fig. 8. The WSS units are assumed to be the main cost contributor in an OXC, so that the cost of the node can be calculated as a function of the number of these elements at each node. This number depends again on the node degree N and the add/drop degree α, and it can be demonstrated that, assuming 1×9 WSSs, the cost of an OXC would be given by

$$Cost_{\mathrm{OXC}}[c.u.] = \left(N + 2 + 2\left\lfloor\left(\frac{x-9}{8}\right)\right\rfloor\right) Cost_{\mathrm{WSS}} \times \begin{cases} x = 9 & 0 < a < = 9 \\ x = a & a > 9 \end{cases} \quad (2)$$

where the costs of a WSS unit ($Cost_{\mathrm{WSS}}$) with fixed grid and Flexigrid are 4 and 5 cost units (c.u.), respectively. Note that two WSS units are necessary per node degree and that the add/drop stage initially requires two WSS units for the first group of 9 channels, with two extra WSSs required for

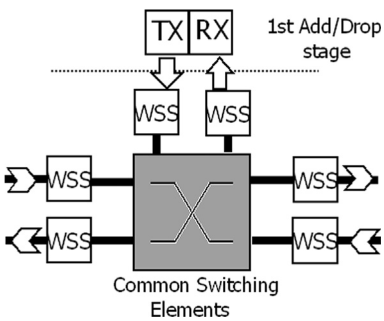

Fig. 8. OXC node architecture.

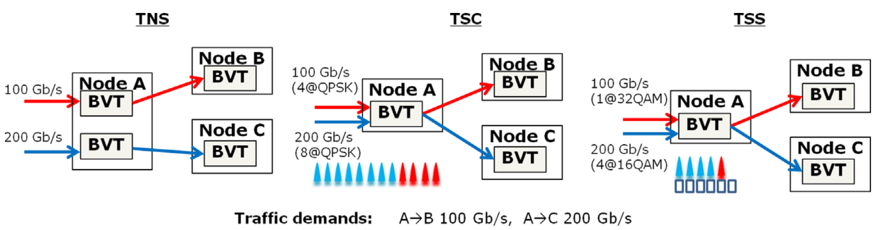

Fig. 7. Representation of the allocation of transponders for two traffic demands of 100 Gb/s and 200 Gb/s with the BVT cost models for *TNS*, *TSC*, and *TSS*.

each subsequent group of 9 channels that needs to be added to the add/drop stage.

4.3. Optical Amplifier (OA)

An erbium-doped fiber amplifier (EDFA) card is assumed to consume 30 W per direction [29], with an overhead contribution of 140 W per amplifier located at the end of a span (to account for controller cards and fans at the in-line amplifiers). The cost of each EDFA unit is 1 c.u. per direction.

4.4. Energy contribution to final cost

Energy costs of 2.05×10^{-5} and 2.086×10^{-5} c.u. per kilowatt-hour (kWh) have been assumed for Germany and Spain, respectively (based on the values for industrial customers in 2012 [31]).

5. Resource allocation algorithms

This section introduces the basic methodology used for energy and cost evaluation with different network technologies and protection schemes. Even though the algorithms presented in this section just take into account static traffic conditions, they could be extended to consider dynamic provisioning by including the appropriate modifications required to operate with time-varying demands (e.g., flow creation, grooming, flow termination, etc) as in the methodology described in [22].

5.1. Introduction to the heuristic algorithms and I/O parameters

An offline algorithm is considered for the assignment of the spectral resources to the lightpaths according to the forecast peak traffic demand between node pairs. Given a network topology with a set of links with limited resources (wavelengths or subcarriers), the objective is to find the appropriate routes and the most convenient spectral allocation from source to destination nodes, so that the maximum amount of traffic can be served. Due to the NP-complete nature of the routing and resource allocation problems, we propose a set of heuristic algorithms targeted to serve the maximum traffic, while optimizing the overall energy efficiency. Survivability has also been taken into account, so lightpaths have to be protected against, at least, any single link failure in the network (this being the dominating form of failure in optical networks). If the demand cannot be reliably served (protected against any single link failure), it is considered to be blocked. The following input and output parameters are employed in the algorithms:

- *Input* (I) *parameters*: Information about physical network topology, the traffic demand matrix, a scaling factor (used to uniformly scale the traffic matrix for higher traffic loads), the transmission reach of each modulation format/line rate, the power consumption of the network elements, the cost values of the network elements, and the energy cost.
- *Output*(O) *parameters*:
  i) *Energy efficiency per* GHz (*EnergyEffPer*GHz): Ratio between the energy efficiency (*EnergyEfficiency*) and the average spectral occupancy of the links in the network (3), with *BandwidthCBand* being the available ITU-T C-band spectrum, i.e. around 4 THz. *EnergyEfficiency* (4) is obtained by dividing the overall traffic demand successfully allocated in the network (*TotalTrafficNetwork*) by the total power consumption (*TotalPowerConsumption*), which is the summation of the power consumption of all the deployed network elements (transponders, amplifiers, and OXCs).

$$EnergyEffPer\text{GHz}[\text{bits/Joule/GHz}] = \frac{EnergyEfficiency[\text{bits/Joule}]}{AvgSpectrumOccupancy\ BandwidthCBand[\text{GHz}]} \quad (3)$$

$$EnergyEfficiency[\text{bits/Joule}] = \frac{TotalTrafficNetwork[\text{bits}/s]}{TotalPowerConsumption[\text{W}]} \quad (4)$$

  ii) *Cost efficiency per GHz* (*CostEffPerGHz*): This measure accounts for the number of bits that are transmitted with a single cost unit per GHz (bit/c.u./GHz) as in (5). The term *TransmittedData* refers to the total data transmitted in a given time frame, whereas *TotalCost* accounts for both the equipment and the energy cost during this time frame.

$$CostEffPerGHz[\text{bits/c.u./GHz}] = \frac{TransmittedData[bits]/TotalCost[c.u.]}{AvgSpectrumOccupancy \times \text{BandwidthCBand}\ [GHz]} \quad (5)$$

  iii) *The service blocking ratio*: This measure gives an estimation of the amount of resources that are required to operate with a given traffic load, which will have an impact on the energy and cost efficiency. It is given by the ratio of the transmission rate of the demands that were blocked (*TRBlockedDemands*) and the total traffic demand (*TRTotalDemands*) as in (6). A demand is blocked when the network resources are not sufficient to provide a reliable service (i.e. provide the required protection).

$$ServiceBlockingRatio = \frac{\Sigma TRBlockedDemands}{\Sigma TRTotalDemands} \quad (6)$$

5.2. Constraints of and differences between the routing and resource allocation in WDM SLR, WDM MLR and EON.

The basic methodology for the routing and resource allocation in [22] has been taken as a reference. More specifically, we have taken into account the heuristic algorithms used to solve the Routing and Wavelength Assignment (RWA) for SLR and MLR WDM networks, and the Routing, Modulation Level, and Spectrum Assignment

(RMLSA) for EON. These algorithms are energy-aware, as the power consumption of the network elements is used as a metric to decide the route, the spectral resources to be reserved, and the modulation format or line rate combination to be used with EON and WDM MLR, respectively. This metric is based on the contribution to power consumption of transponders and OAs and OXCs that would be traversed by a candidate lightpath along that route. Simulations were also carried out using a *cost efficiency per* GHz metric, offering similar results in terms of cost, but smaller energy efficiency in some particular cases (specially in the MLR, where the selection of the most cost-efficient line rate combination may result in higher power consumption).In fact, from the simulation results we concluded that an optimization in terms of power consumption commonly results in lower cost as well.

The main difference between RMLSA and WDM RWA lies in the use of a variable-width spectrum slot, in which all individual carriers of a multicarrier structure must be allocated in a contiguous manner. A higher number of carriers (320 in our analysis vs. 80 in the RWA case) are supported over a fiber link, and each of them can be modulated according to different formats (having diverse transparent reaches). A First-Fit allocation strategy is followed by RWA SLR and RMLSA (i.e. lowest subcarriers or wavelengths in the spectrum are assigned first), whereas RWA MLR follows two different allocation strategies: First-fit in the first waveband (i.e. that used for 10 Gb/s channels) and Last-fit in the second waveband (i.e. that used for 40 and 100 Gb/s). These two different allocation strategies allow for a movement of the guard bands if required by the traffic conditions (i.e., if more wavelengths of a specific line rate are needed). Further details about these heuristic algorithms can be found in [7].

5.3. Algorithms for dedicated path protection (DP)

A basic description of the heuristics employed for the routing and resource allocation with *DP* is presented in Fig. 9. The routing and resource allocation procedures are performed in a similar manner for the three *DP* variants (i.e. *DP* 1+1, *DP* 1:1, and *DP TAPA*), but the computation of the power consumption differs depending on the *DP* scheme.

The allocation is jointly evaluated for the possible combinations of candidate working paths (*k*-shortest paths), and their corresponding candidate backup paths (*k*-link-disjoint paths) according to the corresponding network approach (i.e. RWA for SLR, RWA for MLR, and RMLSA for EON), which are further detailed in [22]. Then, for the possible combinations of working and backup paths (i.e., those providing sufficient and common resources along the links of the path), a joint power consumption metric is calculated with the contribution from both paths. This allows for the selection of the most energy-efficient

```
► Sort the connection requests from the traffic matrix in descending order of demand value (highest demand first)
while list is not empty
  ► Calculate k candidate working paths from source to destination (k-shortest paths)
  ► LowestMetricPCTotal=0
  ► Calculate candidate backup paths (k shortest-link-disjoint paths)
  if number of candidate backup paths > 0
    for each candidate working path
      ► Determine possible line rates combinations (WDM) or modulation formats (EON) in the candidate working path
        (TX reach >= path length)
      ► LowestMetricPCWorkPath=0
      if transparent reach in the candidate working path (at least with one line rate comb./mod. format)
        for each possible line rate combination/ modulation format
          ► Calculate number of required spectral resources (wavelengths or subcarriers)
          ► Search-for common resources (No. wavelengths in WDM or block of contiguous subcarriers in EON) in the links
          if allocation possible in candidate working path
            ► Calculate MetricPCWorkPath
            if (MetricPCWorkPath<LowestMetricPCWorkPath) or (LowestMetricPCWorkPath==0)
              ► LowestMetricPCWorkPath= MetricPCWorkPath
            end
          end
        end
        if LowestMetricPCWorkPath!=0
          for each candidate backup path (link-disjoint path)
            ► Determine possible line rate combination (WDM) or mod. formats or the candidate working path
              (TX reach >= path length)
            ► LowestMetricPCBUPath=0
            if transparent reach in the candidate backup path (at least with one line rate comb. or mod. format)
              ► Calculate number of required spectral resources (wavelengths or subcarriers)
              ► Search-for common resources (number of required wavelengths in WDM or block of contiguous subcarriers
                in EON) in the links of the path
              if allocation possible in backup path
                ► Calculate MetricPCBUPath
                ► TotalMetricPC=MetricPCWorkPath+MetricPCBUPath
                if (TotalMetricPC<LowestMetricPCTotal)or (LowestMetricPCTotal==0)
                  ► LowestMetricPCTotal=TotalMetricPC
                  ► Save allocation information in MostEfficientAllocation
                end
              end
            end
          end
        end
    end
    if TotalMetricPC!=0
      ► Perform spectrum allocation in the working and backup paths according to MostEfficientAllocation
    else
      ► Demand is blocked
    end
    ► Update performance measures (blocking ratio, power consumption, avg. spectrum occupancy )
  end
end
```

Fig. 9. Heuristic algorithm for the routing and resource allocation with DP.

working-backup path combination and transmissions (e.g. line rate combination in MLR or modulation format for EON) among the feasible ones. Once a solution has been reached; the spectral resources are reserved for the working and backup paths with the appropriate logical cross-connections at the OXCs for all the *DP* schemes. If a working and a backup path cannot be provided for a particular traffic demand, then it is blocked.

The computation of the total power consumption is different for the three *DP* schemes, as described in Fig. 10. For *DP* 1+1, the transmissions are simultaneous on both working and protection paths, which implies higher energy consumption. For *DP* 1:1, the transmission occurs only in one of the paths (backup transmission does not normally consume power). Finally, in *DP TAPA* the power consumption of the backup transponders varies according to hourly traffic fluctuations throughout the day (and therefore some transponders could be switched off for the backup path when traffic is lower than the peak value). For *DP TAPA*, we calculate the average power consumption during a week (considering 5 working and 2 weekend-days), and that value is used to compare the power consumption of this scheme with the other schemes.

Regarding the different network approaches, note that for SLR, *DP* implies the reservation of twice the spectral resources used for working paths, as well as the duplication of the number of transponders. However, in EON and MLR, the backup transmission may require a different modulation format to achieve transparent reach (i.e. in case it is not possible to apply the same modulation format used for the working transmission to the backup one due to the longer length of the latter). Hence, there might be cases where the required spectral resources for the backup path will be more than twice the number used for the working transmission (and therefore the number of transponders would also increase for the transmission of the same capacity), as depicted in the example of Fig. 11.

5.4. Algorithms for shared path protection (SP)

In *SP*, the backup resources are pre-computed and selected but not cross-connected, as explained in Section 2.3. In contrast to *DP* schemes, *SP* is a failure-dependent protection scheme as multiple backup paths are associated to each primary path. Thus, pre-computed backup routes are provided for each lightpath and, in the case of failure, the selection of one backup path or another depends on the particular link that has failed. As described in the heuristics for *SP* in Fig. 12, spectral resources are first assigned to the demands on their working paths according to the network approach (i.e., WDM SLR, WDM MLR, or EON). Then, the remaining resources that were not used for the working traffic can be shared and used by any backup path. In order to check whether there would be enough resources available for the recovery of each lightpath, the failure of each link in the network is emulated consecutively. For each link failure, the Shared Risk Link Group (SRLG) -the lightpaths traversing the failed link- are listed, and the routing and resource allocation procedures are performed again for the SRLG in a modified network graph (i.e., a network in which the failed link has been pruned). If a new route can be provided for the affected lightpath, it is stored on the list of backup routes, otherwise it is considered as blocked because it cannot be protected against failure of this link.

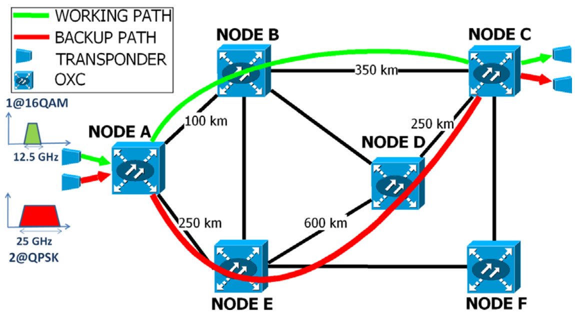

Fig. 11. Example of working and protection paths with different modulation format in EON for a demand of 40 Gb/s: (1) Working path with 1×16 QAM subcarrier over 450 km. (2) Backup path with two $2\times$QPSK subcarrier over 1100km).

```
if protection scheme==DP 1+1
    ▶TotalPConsumption= PCTranspWork+PCTransBU +PCOXCWork+PCOXCBU+PCAmplifiers
end
if protection scheme==DP 1:1
    ▶TotalPConsumption= PCTranspWork +PCOXCWork +PCAmplifiers
end
if protection scheme==DP TAPA
    ▶TotalPeakPconsumption=PCTranspWork+PCTransBU+PCOXCWork+PCOXCBU+PCAmplifiers
    for each hourly traffic variation value during the day
        for each active lightpath
            ▶currentTrafficDemand=trafficVariationFactor*peakTrafficDemand
            ▶Adapt backup path transmission to current traffic demand (according to the technology)
            ▶Compute power savings with respect to TotalPeakPConsumption (check whether switching off some transponders,
             or changing the modulation format for EON is possible)
        end
    end
    ▶TotalPConsumption= TotalPeakPconsumption*(1-(Average power savings over a week/100))
end
```

Fig. 10. Computation of power consumption in DP schemes.

```
▶Sort the connection requests from the traffic matrix in descending order of its demand value (highest demand first)
while list is not empty
   ▶Evaluate resource allocation in the working path (RWA in WDM SLR, RWA in WDM MLR, and RMLSA in EON)
end
for each link of the links in the network
   ▶Fail link and list lightpaths traversing that link (SRLG)
   ▶De-allocate resources in those affected lightpaths in the SRLG list
   ▶Prune failed link from the network graph
   for each affected lightpath from the SRLG (sorted in descending order of traffic demand value)
      ▶Evaluate resource allocation (RWA in WDM SLR, RWA in WDM MLR, and RMLSA in EON) in the modified
       network graph
      if allocation possible
         ▶Allocate corresponding spectral resources
         ▶Save allocation information corresponding on the list of possible backup paths
      else
         ▶Include demand in the list of unprotected demands in the network (if not included before)
      end
   end
   ▶Restore original resource allocation state in the network (all links set as active)
end
if no unprotected path (i.e. list of unprotected demands is empty)
   ▶Compute total power consumption: TotalPConsumption= PCOXCWork +PCAmplifiers+PCTranspWork
   ▶Calculate final measures (total power consumption, spectrum occupancy, energy efficiency)
else
   ▶Calculate service blocking ratio (total unprotected traffic/total traffic demand)
end
```

Fig. 12. Heuristic algorithm for routing and resource allocation with *SP*.

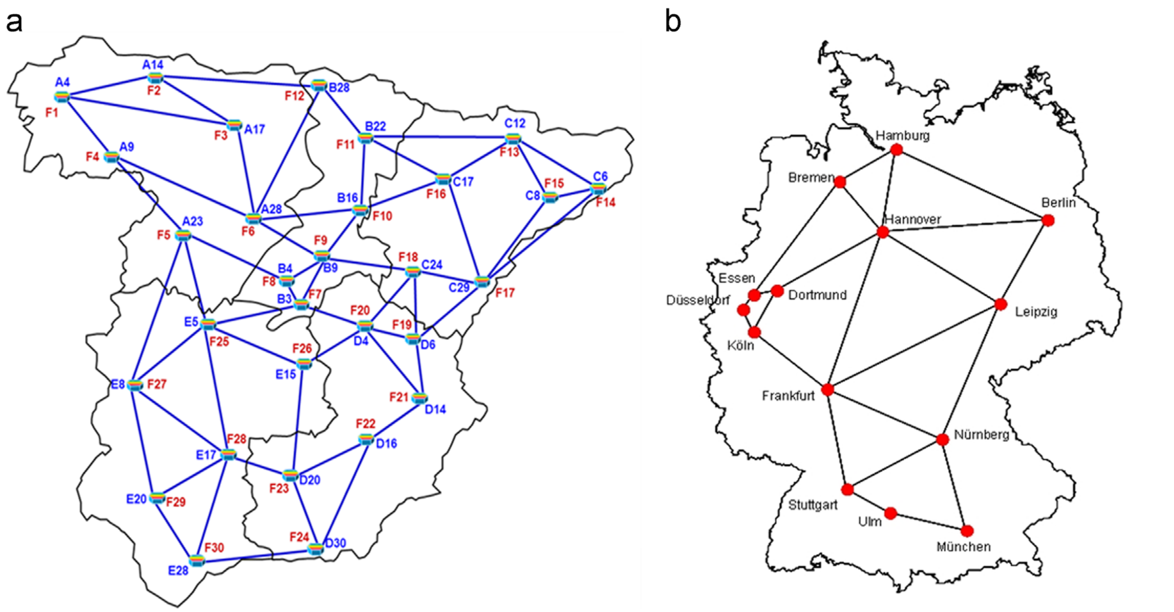

Fig. 13. (a) Telefónica I+D's Spanish core network model. (b) DT German core network [32].

6. Network topologies

Two different long-haul network topologies have been considered to evaluate the energy and cost efficiency in different scenarios. The first one is the Spanish core network model depicted in Fig. 13(a) (used by Telefónica I+D for its traffic studies), and the second one is the German core network model from Deutsche Telekom (DT) in Fig. 13 (b). Both network topologies present significant differences which are summarized in Table 2. In our model, a single fiber pair has been considered per link, and no electrical regeneration is provisioned at any of the nodes, as transparent reach is feasible for all the possible source-destination connections being analyzed.

7. Simulation results

7.1. Energy evaluation

The results on *EnergyEffPerGHz* for the different protection schemes (*DP* 1+1, *DP* 1:1, *DP TAPA* and *SP*) and network technologies (SLR 40G, SLR 100G, MLR and EON) are shown in Fig. 14a and Fig. 14b for the Spanish and German networks, respectively. Note that only the results under non-blocking conditions are shown in the figures (i.e. for those traffic values at which it is possible to fulfill all the traffic demands with the protection requirements).

The results obtained for both network topologies show that *SP* is more energy efficient per GHz than any of the *DP* schemes. This is explained by the fact that the backup transmissions only consume energy in case of failure. As mentioned before, the network blocking gives an indication about the total traffic that can be carried by a single-fiber network. Thus, the lower blocking ratio of *SP* may also have an impact on energy efficiency, as the deployment of additional fibers and energy-consuming devices will result in higher power consumption. The differences on the maximum traffic that can be carried with *SP* compared to *DP* schemes in the different network approaches are presented in Table 3 and Table 4 for the Spanish and German networks, respectively.

Regarding the *DP* schemes, the three possibilities obviously present the same spectrum occupancy as the same amount of spectral resources is reserved (network is dimensioned according to the peak traffic value). However, they differ in *EnergyEffPerGHz*, due to the different power consumption of the backup transmission. Among the *DP* schemes, *DP* 1:1 is clearly the most energy efficient because no additional power will be consumed for the backup transmission, but it is less reliable than the other

Table 2
Description of network topologies

Network parameter	DT German network model	Telefonica's I+D Spanish network model
Diameter (km)	800	1000
Number of nodes	14	30
Number of bi-directional links	23	48
Number of bi-directional traffic demands	91	48
Overall traffic (Tb/s)	2.8	3.22

Table 3
Spanish network-Maximum traffic supported by the different network technologies without blocking with DP and SP schemes.

Network Type	Max. Traffic with DP (Tbps)	Max. Traffic with SP (Tbps)
EON	54.808	61.256
SLR 40 G	12.896	16.12
SLR 100 G	32.24	41.912
MLR	32.24	45.136

Table 4
German network-Maximum traffic supported by the different network technologies without blocking with DP and SP schemes.

Network Type	Max. Traffic with DP (Tbps)	Max. Traffic with SP (Tbps)
EON	39.10	78.19
SLR 40G	8.38	19.54
SLR 100G	25.13	50.27
MLR	22.34	25.13

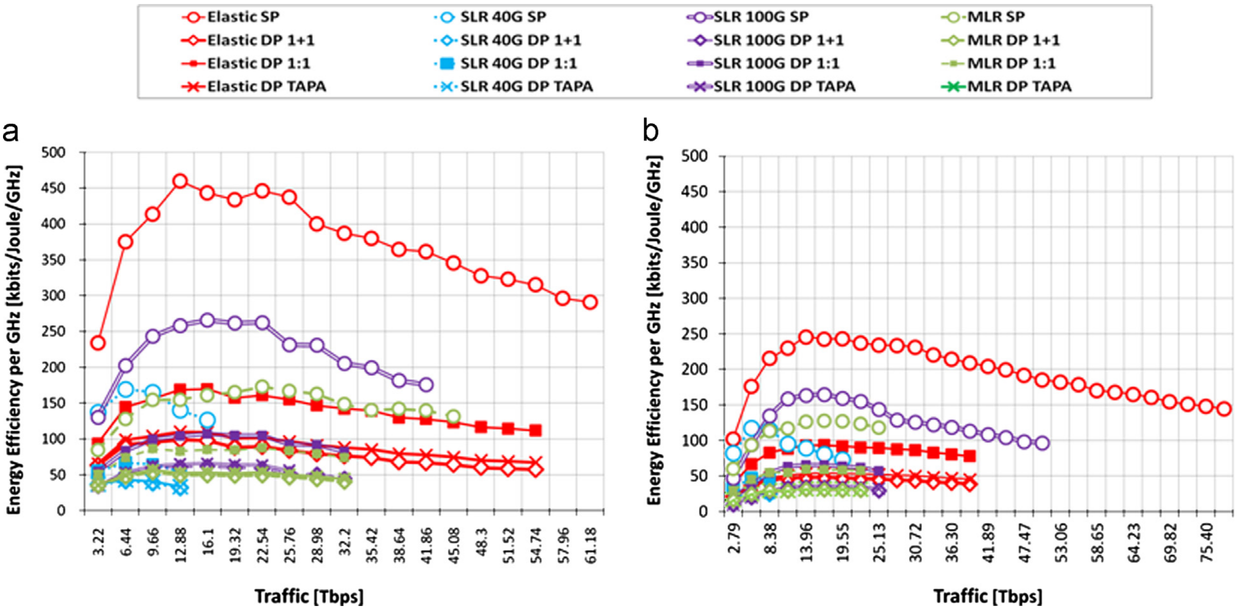

Fig. 14. Energy Efficiency per GHz for the different network technologies and protection schemes:(a) Spanish network and (b) German Network.

DP schemes. On the other hand, *DP* 1+1 scheme is the least energy-efficient as it requires duplicated transmission on working and backup paths with the consequent higher power consumption.

DP TAPA was proposed as a variation of *DP 1+1* to maintain similar reliability level with reduced power consumption. The daily traffic variations and the energy savings that can be achieved by *DP TAPA* with respect to *DP* 1+1 are presented in Fig. 15 and Fig. 16 for the Spanish and German core network, respectively. As shown, EON is the technology that can benefit the most from this innovative scheme thanks to the enhanced flexibility given by the elastic bandwidth transmission and the possible modification of modulation format in the backup path when traffic is low (i.e. up to 20.29% and 22.76% of energy can be saved at low-traffic hours of the weekend for the Spanish and German network, respectively). As indicated in Fig. 14, *DP TAPA* improves the energy efficiency per GHz of *DP* 1+1 and can be adopted in those cases where the high availability of *DP* 1+1 is required.

EON shows superior performance in *EnergyEffPer*GHz than any other network approach for all the evaluated protection schemes. As shown, EON improves its performance when traffic increases thanks to its better spectral efficiency (i.e. high traffic demands occupy considerably higher spectrum in fixed grid SLR/MLR WDM networks). Furthermore, the lower blocking provided by EON would enable to transmit more traffic in a single-fiber network (see Table 3 and Table 4), which, as mentioned before, also affects the energy efficiency of the network.

Similar patterns can be observed in the two network topologies. However, there are some differences due to the different dimensions of the networks, and, especially, to the different number of links and nodes. Therefore, the values of *EnergyEffPerGHz* are considerably higher for the Spanish network than for the German one, which is explained by the lower average spectrum usage of the former (i.e. similar amount of traffic is then scattered across a bigger number of links, which results in a lower average spectral occupancy).

The network topology and the geographical distribution of the traffic also have an impact on the network blocking. As shown in Tables 3 and 4, the *SP* scheme generally presents higher blocking in the Spanish network due to the high concentration of traffic in the central region, which results in highly loaded links avoiding reallocation of all the lightpaths when one of those links fails. However, the *DP* schemes offer lower blocking in the Spanish network, due to the larger dimensions and bigger

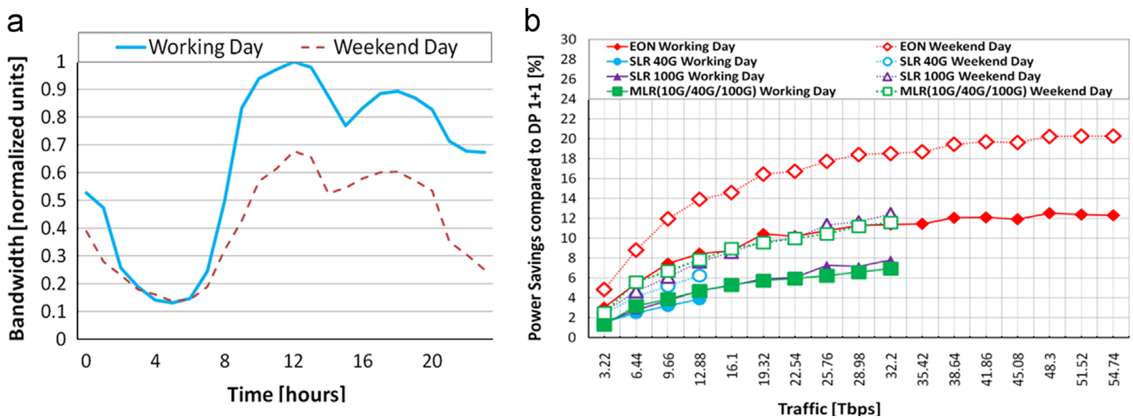

Fig. 15. Spanish network- (a) Traffic variation in the Telefónica's network model on working and weekend-days. (b) Average energy savings on a weekday/ weekend day with respect to *DP* 1+1 for the different network technologies and traffic load conditions.

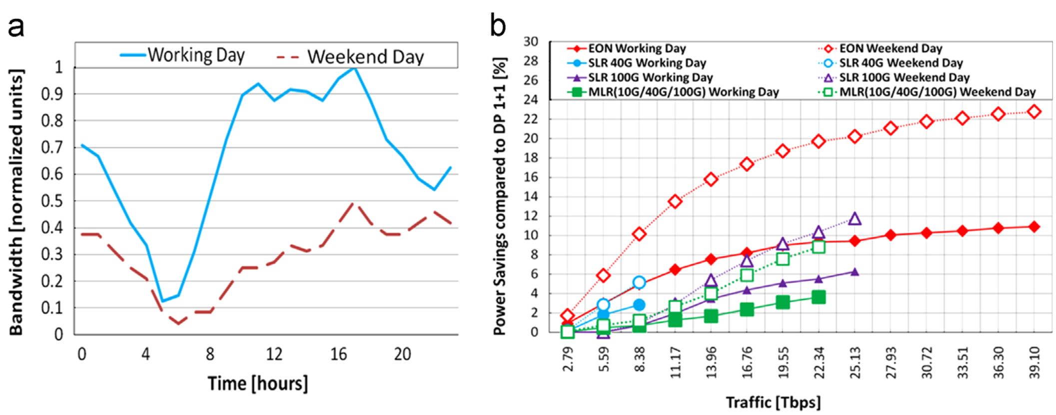

Fig. 16. German network (a) Traffic variation in the DT network model on the working and weekend-days, based on [33]. (b) Average energy savings on a weekday and weekend day with respect to the conventional *DP* 1+1 for the different network technologies and traffic load conditions.

number of links, which increases the chances of finding a feasible link–disjoint backup path (i.e. possible to evaluate more k shortest link–disjoint paths).

7.2. Cost evaluation

7.2.1. Energy cost

The energy costs over a 10-year time frame are presented in Fig. 17(a) and (b) for the Spanish and German core networks, respectively. Similar conclusions can be drawn from the results obtained for both networks. The curves in the upper part of the figures present the energy cost for *DP* 1+1, which obviously consumes more energy than any other scheme due to the simultaneous transmission in the working and protection paths. Then, *DP TAPA* shows lower energy cost than *DP* 1+1 thanks to the reduction in power consumption of the backup resources. The curves in the lower part identify the energy costs of *SP* and *DP* 1:1 for the different technologies. Both schemes provide similar energy cost (i.e. only working transmission consumes energy), but *SP* shows significantly lower blocking than *DP* 1:1.

Among the different network approaches, EON consumes less energy than any other WDM approaches. This difference becomes more noticeable as the total traffic increases thanks to the great adaptability of the transmission to the service demand, and the lower energy per bit of the high order modulation formats with respect to the WDM approaches (i.e., 3.14 J/Gb/s and 2.90 J/Gb, for 32QAM and 64QAM modulation formats in EON, respectively, compared to the 3.51 J/Gb provided by a 100 Gb/s WDM transponder). Comparing the results on the two network topologies, the energy costs of the Spanish core network are generally higher than those of the German one for all the network approaches and protection schemes, which is explained by the bigger number of energy consuming devices that have to be deployed due to its larger dimensions.

7.2.2. Overall cost

This section considers the total cost of the network including CapEx (equipment expenses), as well as OpEx (energy cost) in the different scenarios. For the overall cost study, a TSC BVT has been considered. The results in *CostEffPerGHz* over a 10-year term are presented in Fig. 18(a) and (b) for the Spanish and German network models, respectively. As previously, only the values for which all the demands can be satisfied with the required protection level are presented (zero blocking).

Analogous conclusions can be drawn from the results obtained for both network topologies. EON provides the best performance and clearly outperforms WDM networks at any traffic load condition and for all the protection schemes. The difference in *CostEffPerGHz* between EON and the other network approaches becomes more significant as traffic increases, due to its improved spectral efficiency. Besides, the low blocking ratio of this technology also implies an advantage in terms of cost, as more traffic can be carried by a single fiber-network, thus reducing the number of devices.

Among the protection schemes, *SP* is the most beneficial in *CostEffPerGHz* due to its lower cost (i.e. requires the deployment of fewer transponders than *DP* and low energy cost) and the lower spectrum occupancy (i.e. backup spectral resources are shared). Note that, for the sake of simplicity, the results on *CostEffPerGHz* of *DP TAPA* are not shown in the figures, but they would lie in between the curves for *DP* 1:1 and *DP* 1+1 (i.e. *DP TAPA* offers intermediate energy costs between *DP* 1+1 and *DP* 1:1, but CapEx, the main cost contributor, is the same).

The *CostEffPerGHz* results for the Spanish network are slightly higher than those for the German one, which is explained by the lower average spectral occupancy of the former (i.e. traffic is spread over a bigger number of links) and also to its higher cost (i.e. bigger number of network elements).

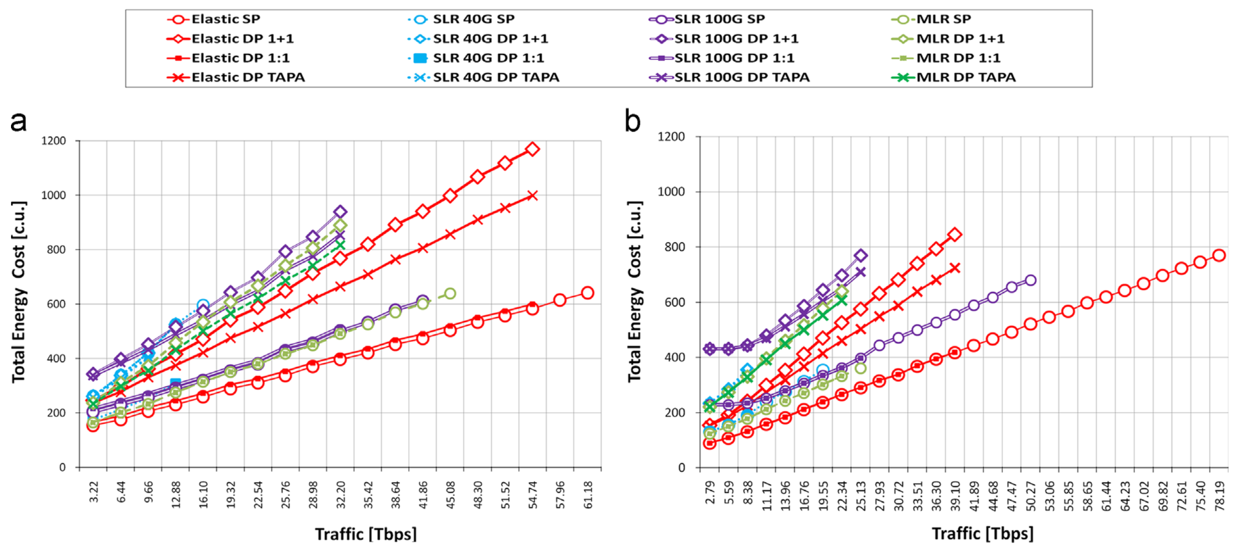

Fig. 17. Total energy cost [c.u.] over a 10-year term for two different network technologies and protection schemes. (a) Spanish network and (b) German network.

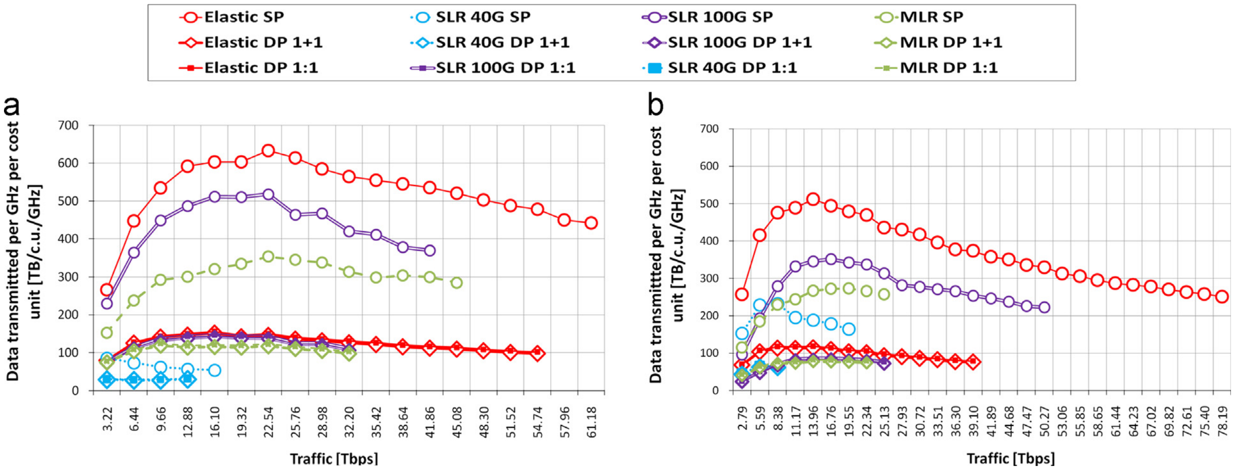

Fig. 18. Cost efficiency per GHz [TB/c.u./GHz] over a 10-year term for the different network technologies and protection schemes with a TSC BVT for the EON approach. (a) Spanish network and (b) German network.

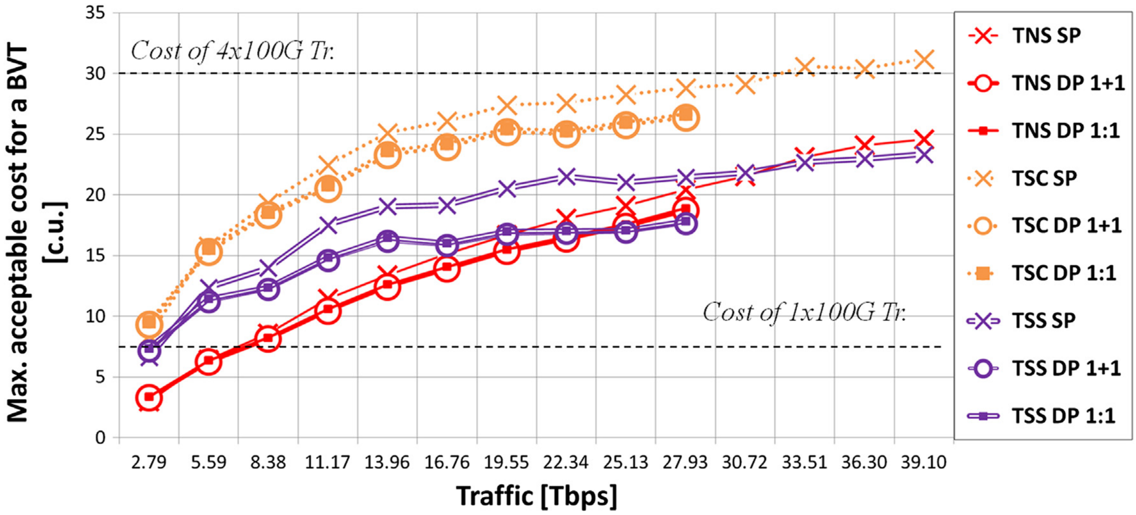

Fig. 19. Spanish network- Maximum acceptable cost (c.u.) for a BVT to turn EON into the most cost-efficient solution, for three cost models and protection schemes.

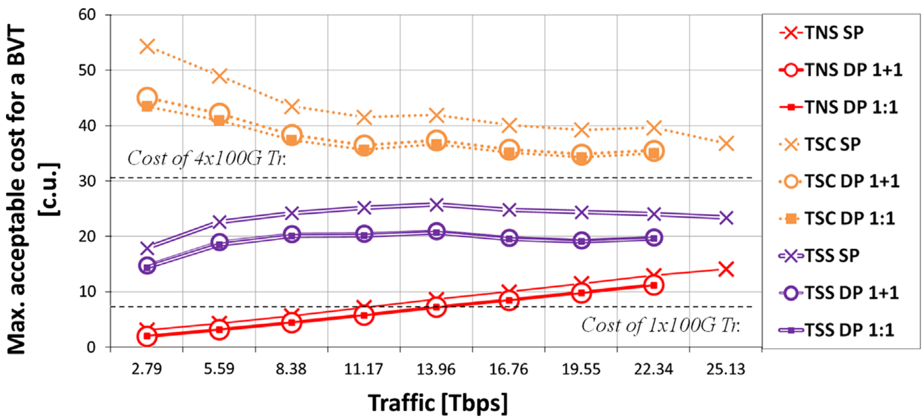

Fig. 20. German network- Maximum acceptable cost (c.u.) for a BVT to turn EON into the most cost-efficient solution, for three cost models and protection schemes.

7.2.3. *Maximum acceptable cost for BVT in EON*

BVTs are the main cost contributors of EON, and therefore their cost will be key to determining whether the migration to this novel network approach makes economic sense for operators. This section aims at giving an insight into the maximum acceptable cost of a BVT to make EON the most economic approach under different traffic conditions and protection schemes.

Fig. 19 and Fig. 20 present the maximum acceptable cost of a BVT in the Spanish and German networks, respectively. Any potential cost lower than the values presented in those figures would make EON more cost-efficient than any other WDM approach. From the three cost models, the *TNS* is considerably penalized by the need to dedicate a 400 Gb/s transponder to a single demand, especially when traffic is low. As traffic increases, the average demand gets closer to 400 Gb/s and its cost efficiency is notably improved. The *TSC* can be identified as being the most beneficial from an economic point of view, and the *TSS* provides intermediate results.

A higher cost for a BVT can be tolerated with the *SP* scheme, as nodes are only equipped with transponders for the working transmission, whereas the *DP* schemes require to purchase transponders for both working and backup paths. The results of *DP TAPA* (not shown in the figures for simplicity) would lie in between the ones for *DP* 1+1 and *DP* 1:1 (similar element cost as DP1+1 but lower energy cost).

The maximum acceptable cost of a BVT strongly depends on the traffic conditions (i.e. number of traffic demands and overall traffic load) and also on some aspects of the network topology such as the number of nodes. Therefore, the results in both networks present some significant differences. In the Spanish network (Fig. 19), at low traffic load conditions, a big number of BVT transponders are necessary, but their capacity is not efficiently used. Thus, even a sliceable BVT should approximately cost the same as a 100-Gb/s WDM transponder (7.5 c.u.) to obtain economic advantages with respect to current WDM networks. As traffic increases, the capacity usage improves, so a higher cost can be tolerated for a BVT. Still, for the majority of the traffic values in Fig. 19, the cost per bit of the BVT has to be lower than those of conventional coherent WDM transponders to make EON the most cost-efficient approach.

On the other hand, in the German network, the results are significantly different due to the smaller number of nodes. TSC shows very promising results since, at low traffic load, EON would be beneficial even with a cost per bit higher than that of a current WDM coherent transponder. This is explained by the possibility of serving all the traffic by deploying a single TSC BVT per node (i.e. if the overall traffic generated in a particular node is lower than 400 G, the full capacity of the transponder can be shared by all the traffic demands). Using a single transponder per node can bring significant cost benefits as, otherwise, dedicating a transponder to every traffic demand would result in higher capital and energy expenses. As an example, for the German network with *SP* and an overall traffic of 2.79 Tb/s, the MLR approach needs 24 G × 10 G and 68 G × 40 G transponders, whereas EON with a BVT TSC would only require 14 transponders, one per node. This behavior is in clear contrast with the results achieved in the Spanish network topology, where it would be necessary to purchase more BVT transponders due to the higher number of nodes. The lower energy cost presented by EON, and the smaller number of WSS ports at the OXCs, also help to increase the cost efficiency. As shown in Fig. 20, at low traffic load, cost benefits could be obtained even with a BVT of higher cost per bit than a 100-Gb/s coherent WDM transponder. However, as traffic increases, a single transponder per node is not enough, making it necessary to add new BVT transponders, whose capacity may not be efficiently filled (i.e. curves tend to decrease in maximum acceptable cost when traffic increases).

It is worth mentioning that the results are only shown for those traffic values for which blocking does not occur for the MLR network, but EON allows accommodating more traffic in a single fiber network (see Table 3 and Table 4). Therefore, as traffic increases further than the values presented in the figures, it might be possible to accept an even higher cost for a BVT since, as mentioned above, deploying additional fibers and/or network elements, would certainly entail a higher cost.

7.2.4. *Additional cost implications of EON*

After evaluating the cost efficiency of EON, it is worth mentioning that there are some other cost factors that may also speak in favor of EON:

- *Single type of transponder in the network*: Benefits may come from the economies of scale, reduced inventory of different spare parts, and decrease in installation cost.
- *Simpler capacity upgrade*: Adaptive transmission rate may simplify the capacity upgrade tasks as, in many cases, the operators will not need frequent deployments, but the modification of the BVT behavior by software configuration (e.g. expanding bandwidth or changing modulation order).
- *Adaptive dynamic transmission*: The modification of the signal properties by software allows for the adaptation of the transmission rate to dynamic variations of the traffic, which may result in a better utilization of spectral resources and reduced energy consumption.
- *Reduced overall cost of OXCs*: A super-channel can be treated as a single entity in the network, which may help to reduce the number of ports in the OXC, and so its total cost.
- *Reduced floor space*: A lower number of transponders may reduce the floor space in the operator's premises. Cost advantages are expected from these lower space requirements.
- *Possible leasing of extra capacity to other operators*: Additional revenues can be obtained by leasing the remaining spectral resources to other operators, so that it is possible to monetize the improved spectral efficiency and lower blocking of EON.

8. Conclusions

Increasing the energy and spectral efficiency of optical transport networks has emerged as one of the most challenging tasks for telecom operators and industry. Optical transport networks are required to provide high resilience levels to guarantee an appropriate quality of service. Recently, EON has been presented as a promising solution to enable flexible and high-capacity transmission by means of its elastic bandwidth usage. Simulation results showed EON as an energy and spectral efficient solution, which allows for the transmission of more bits per GHz per Joule (*energy efficiency per* GHz) than any other WDM approach for all the protection schemes (dedicated and shared path ones).

Despite the potential advantages of energy and spectral efficiency showed by EON, cost is one of the main drivers to determine whether EON will be finally adopted by the operators. In this regard, the traffic conditions and the network topology will be decisive for the cost efficiency of EON, which is strongly dependent on its main cost contributor, the BVT. As shown in the presented results, the manner in which the bandwidth of this transponder is utilized has a significant impact on the final cost. Thus, even if the cost per bit of a BVT could be initially higher than that of a current WDM transponder, EON can be a cost-efficient solution if the transponder capacity is shared between multiple demands. Accordingly, in many circumstances, the data that can be transmitted per GHz with a single cost unit (*cost efficiency per* GHz) is higher in EON than in any other WDM network approach.

The higher spectral efficiency of EON results in lower blocking, which permits to accommodate more traffic in a single fiber. This fact has a relevant impact on both cost and energy efficiency, as the number of additional fibers and energy-consuming devices can be reduced for a given traffic load. Furthermore, there are some other potential factors that can turn this technology into a more cost-efficient solution, such as the possibility of deploying a single transponder model in the network.

Among the protection schemes, *SP* was shown as the most energy and cost-efficient, thanks to its lower power consumption and spectrum usage, and *DP* $1+1$ as the least energy- and cost-efficient due to its duplicated transmission, despite offering the highest availability and fastest recovery. In general, migrating from dedicated to shared protection schemes may significantly improve the cost and energy efficiency of the network. In that sense, it would be interesting to investigate the cost benefits that can be obtained by applying a differentiated quality of protection (Diff QoP) strategy. By doing so, the usage of protection resources could be adjusted to the service/client requirements to improve the energy and cost efficiency of the networks.

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References

[1] CISCO Whitepaper, Visual Networking Index (VNI), June 2012.
[2] S. Lambert, W. Van Heddeghem, W. Vereecken, B. Lannoo, D. Colle, M. Pickavet, Worldwide electricity consumption of communication networks, Optics Express 20 (26) (2012) B513–B524.
[3] L.M. Contreras, V. López, O. González de Dios, A. Tovar, F. Muñoz, A. Azañón, J.P. Fernández-Palacios, J. Folgueira, Towards cloud-ready transport networks, IEEE Communications Magazine 50 (9) (2012) 48–55. (September).
[4] J. López, Y. Ye, V. López, F. Jiménez, R. Duque, P. Krummrich, On the Energy Efficiency of Survivable Optical Transport Networks with Flexible-grid, in: Proceedings of the European Conference and Exhibition on Optical Communications (ECOC), Paper P5, 05Septem-ber 2012.
[5] J. López, Y. Ye, V. López, F. Jiménez, R. Duque, P. Krummrich, F. Musumeci, M. Tornatore, A. Pattavina, Traffic and Power-Aware Protection Scheme in Elastic Optical Networks, Networks, October 2012.
[6] J. López, Y. Ye, V. López, F. Jiménez, R. Duque, P. Krummrich, Cost Evaluation for Flexible-Grid Optical Networks, in: Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM),Work-shop on Flexible Optical Networks, December 2012.
[7] J. López Vizcaíno, Y. Ye, V. López, F. Jiménez, R. Duque, I. Tafur, Peter M. Krummrich, Green networking and communications green networking and communications, Chapter on "Energy Efficiency Improvement with the Innovative Flexible-Grid Optical Transport Network, Auerbach Publications, CRC Press, Taylor & Francis Group, USA, 2013, in press.
[8] ITU-T Recommendation G.694.1, Spectral grids for WDM Applications: DWDM Frequency Grid, May 2002.
[9] O. Gerstel, M. Jinno, A. Lord, S.J.B. Yoo, Elastic optical networking: a new dawn for the optical layer? IEEE Communications Magazine 50 (2) (2012) s12–s20. (February).
[10] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, T. Yoshimatsu, T. Kobayashi, Y. Miyamoto, K. Yonenaga, a Takada, O. Ishida, and S. Matsuoka, Demonstration of novel spectrum-efficient elastic optical path network with per-channel variable capacity of 40 Gbps to over 400 Gbps, ECOC 2008, September 2008.
[11] K. Christodoulopoulos, I. Tomkos, E.A. Varvarigos, Elastic bandwidth allocation in flexible OFDM-Based optical networks, Journal of Lightwave Technology 29 (9) (2011) 1354–1366. (May).
[12] L. Gong, X. Zhou, W. Lu, Z. Zhu, A two-population based evolutionary approach for optimizing Routing, Modulation and Spectrum Assignments (RMSA) in O-OFDM networks, IEEE Communications Letters 16 (9) (2012) 1520–1523.
[13] Y. Wang, X. Cao, Q. Hu, Y. Pan, Towards elastic and fine-granular bandwidth allocation in spectrum-sliced optical networks, IEEE/OSA Journal of Optical Communications and Networking 4 (11) (2012) 906–917.
[14] T. Takagi, H. Hasegawa, K. Sato, T. Tanaka, B. Kozicki, Y. Sone, M. Jinno, Algorithms for Maximizing Spectrum Efficiency in Elastic Optical Path Networks that Adopt Distance Adaptive Modulation, ECOC 2010.
[15] B. Kozicki, H. Takara, Y. Sone, A. Watanabe, M. Jinno, Distance-adaptive spectrum allocation in elastic optical path network (SLICE) with bit per symbol adjustment, OFC/NFOEC 2010, Paper OMU3, March 2010.
[16] X. Wan, N. Hua, X. Zheng, Dynamic routing and spectrum assignment in spectrum-flexible transparent optical networks, IEEE/OSA Journal of Optical Communications and Networking 4 (8) (2012) 603–613.
[17] Z. Zhu, W. Lu, L. Zhang, N. Ansari, Dynamic service provisioning in elastic optical networks with hybrid single-/multi-path routing, IEEE/OSA Journal of Lightwave Technology 31 (1) (2013) 15–22.
[18] Y. Sone, A. Watanabe, W. Imajuku, Y. Tsukishima, B. Kozicki, H. Takara, M. Jinno, Bandwidth squeezed restoration in Spectrum-Sliced Elastic Optical Path Networks (SLICE), IEEE/OSA Journal of Optical Communications and Networking vol.3 (no.3) (2011) 223–233.
[19] X. Shao, Y. Yeo, Z. Xu, X. Cheng, L. Zhou, Shared-Path Protection in OFDM-based Optical Networks with Elastic Bandwidth Allocation, OFC/NFOEC, paper OTh4B.4, March 2012.
[20] A.P. Bianzino, C. Chaudet, D. Rossi, J.-L. Rougier, A Survey of Green Networking Research, IEEE Communications Surveys and Tutorials 14 (1) (2012) 3–20.
[21] Y. Zhang, P. Chowdhury, M. Tornatore, B. Mukherjee, Energy efficiency in optical telecom networks, in IEEE Communication Surveys and Tutorials 12 (4) (2010) 441–458.
[22] J. López Vizcaíno, Y. Ye, I. Tafur Monroy, Energy efficiency analysis for flexible-grid OFDM-based optical networks, Computer Networks 56 (2012) 2400–2419.
[23] A. Muhammad, P. Monti, I. Cerutti, L. Wosinska, P. Castoldi, A. Tzanakaki, Energy-efficient WDM network planning with dedicated protection resources in sleep mode, in Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM), December 2010, pp. 1–5.

[24] C. Cavdar, F. Buzluca, and L. Wosinska, Energy-efficient design of survivable WDM networks with shared backup, in Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM), Miami, FL-USA, December 2010, pp. 1–5.
[25] F. Musumeci, M. Tornatore, J.L. Vizcaino, Y. Ye, and A. Pattavina, Power-aware design of protected IP-over-WDM networks with sleep-mode devices, in Proceedings of the IEEE Greencom, 2012.
[26] M. Angelou, K. Christodoulopoulos, D. Klonidis, A. Klekamp, F. Buchali, E. Varvarigos, and I. Tomkos, Spectrum, Cost and Energy Efficiency in Fixed-Grid and Flex-Grid Networks, OFC 2012, Paper NM3F.4, March 2012.
[27] E. Palkopoulou, M. Angelou, D. Klonidis, K. Christodoulopoulos, A. Klekamp, F. Buchali, E. Varvarigos, I. Tomkos, quantifying spectrum, cost, and energy efficiency in fixed-grid and flex-grid networks [invited], IEEE/OSA Journal of Optical Communications and Networking 4 (2012) B42–B51.
[28] A. Bocoi, M. Schuster, F. Rambach, D.A. Schupke, C.-A. Bunge, and B. Spinnler, Cost Comparison of Networks Using Traditional 10 and 40 Gb/s Transponders Versus OFDM OFC/NFOEC 2008, Paper OThB4, February 2008.
[29] C. Dorize, W. Van Heddeghem, F. Smyth, E. Le Rouzic, B. Arzur, GreenTouch Draft Report on Baseline Power Consumption, Version 1.8, November 2011.
[30] A. Klekamp, U. Gebhard, F. Ilchmann, Efficiency of Adaptive and Mixed-Line-Rate IP over DWDM Networks regarding CAPEX and Power Consumption, in: Proceedings the OFC/NFOEC 2012, Paper OTh3B, March 2012.
[31] Europe´s energy portal, http\\www.energy.eu, (accessed December 2012).
[32] DICONET Project Deliverable: D.2.1: Definition of dynamic optical network architectures, Version: 1.00, September 2010.
[33] ARD/ZDF Online Study 2012 internet usage in Germany study, 2012, http://www.ard-zdf-onlinestudie.de/fileadmin/Online12/0708-2012_ Eimeren_Frees.pdf, (accessed 15.01.13).