D3.5 Final report for the IRA "Energy-efficient protection schemes"

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Abstract:
This deliverable presents the activities within IRA 3.2 of the TREND NoE. The document describes the different activities and main results on the context of energy-efficiency protection schemes in core networks. Results are presented in terms of technical achievement and collaboration.

Keyword list:
core networks, cost efficiency, differentiated quality of protection, elastic optical networks, energy-efficiency, flexible-grid, IP-over-WDM, optical transport networks, protection schemes, routing and wavelength assignment, sleep-mode, survivability, traffic variation, VLAN, WDM networks.

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1. Executive Summary

Internet traffic is increasing at annual rates between 30% and 50%, forcing operators to continuously upgrade their networks to cope with this exponential traffic growth. As traffic grows, the energy consumption of core networks becomes a more significant issue for operators. Therefore, several energy-aware approaches are being proposed towards energy-efficient networks. Furthermore, guaranteeing a high resilience will also be a must for operators due to the importance of telecommunication networks for the availability of indispensable services in our society. For this purpose, many protection schemes have been proposed in the network so far, e.g. 1+1, 1:1, 1:n, m:n, etc. However, energy consumption issues related to protection schemes have not been seriously considered so far.

The aim of the Integrated Research Action (IRA) 3.2 of the TREND FP7 Network of Excellence (NoE) is to investigate energy-efficient protection schemes for core networks. An important contribution of TREND on this unexplored topic is the joint cooperation among different types of IRA partners (vendor, operator, and academia). This deliverable aims at introducing the main achievements within this IRA, which are presented in Section 3.

Firstly, in Section 3.1, some of the most common protection schemes (i.e., dedicated protection 1+1 (DP 1+1), dedicated protection 1:1 (DP 1:1), and shared protection (SP) schemes) have been evaluated in terms of energy efficiency. DP 1+1 was shown as the least energy efficiency scheme, but it is still the most widely deployed and secure option to fulfill any service level agreement (SLA) thanks to its fast recovery.

Consequently, in addition to evaluating the already existing protection schemes, significant efforts have been devoted in this IRA to propose novel mechanisms that allow for an improvement in energy efficiency while maintaining sufficient reliability as required by the end users. For instance, in Section 3.2, a variation of DP 1+1 that exploits the daily traffic patterns has been proposed to reduce the energy consumption of the protection resources in both current fixed-grid wavelength division multiplexing (WDM) and flexible-grid networks. This scheme allows maintaining the same level of reliability as DP 1+1 scheme with reduced power consumption.

However, in many cases clients may not require such a high level of reliability for their service. Accordingly, the heterogeneity of protection requirements requested by the clients could be exploited to enhance the energy efficiency. In this sense, a differentiated quality of protection (QoP) scheme based on different traffic classes has been proposed and evaluated for current fixed-grid WDM and flexible-grid or elastic optical networks (EON), see Section 3.3.

Finally, apart from the potential energy savings in the optical layer, additional improvements can be obtained when considering IP-over-WDM by setting protection resources into a sleep-mode, as discussed in Section 3.4.

Cost advantages are also a key driver for a Telecom operator to adopt a new technology or technique. In this sense, providing sufficient reliability entails additional economic efforts by the operators due to the higher CapEx (capital expenditures) and OpEx (operational expenditures) resulting from, for instance, the need for new telecommunication infrastructure deployments and higher electrical power consumption. Consequently, the impact on cost of several protection schemes has been investigated by performing a cost evaluation which considers not only the cost of network equipment, but also the electricity expenses in a given time-frame for both fixed- and flexible-grid networks.

The main conclusions from this work and some of remaining challenges related to energy efficiency on protection schemes are identified in concluding Section 4 of this deliverable.

The studies presented in this document have already resulted in several publications and mobility actions, which are summarized in Section 5. In fact, 10 joint articles have already been presented/submitted (8 accepted and 2 under submission), three invited presentations at conferences, and three mobility actions have taken place. Additionally, three joint papers have already been planned.

2. Introduction

This deliverable presents the outcomes of the IRA3.2 “Energy-efficient protection schemes” of the TREND FP7 NoE. All the activities presented in this deliverable have been performed through joint activities by different types of partners (vendors, operators, and academia).

This deliverable is organized as follows. Section 3 provides an overview and evaluation in terms of energy consumption of different protection schemes, and proposes some innovative solutions to improve the energy efficiency of survivable optical transport networks. Both the optical and the data network layers have been considered. Furthermore, an overall cost evaluation including the network energy expenses has been carried out in order to compare the efficiency of the different protection schemes. Each activity is presented with a short "ID card" indicating the topic, factual results (mobility actions and papers) and involved partners. Papers issued from the activities are indicated by the referenced numbers and are attached to this deliverable in a single compressed zip file. Papers that have been submitted and pending for publication are also indicated in references (and marked as submitted), but are not included in the compressed file.

Section 4 contains the main conclusions obtained in this IRA, and mentions the remaining challenges on energy-efficient protection schemes. All the activities within this IRA such as papers and mobility actions are summarized in Section 5.

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3. Energy-efficient Protection Schemes in Core Optical networks.

3.1 Comparison in energy efficiency of the conventional protection schemes for fixed-grid WDM and flexible-grid OFDM-based network

Summary: An energy efficiency comparison of conventional path protection schemes for fixed-grid WDM and flexible-grid OFDM-based networks has been carried out. The survivable elastic network with SP scheme was found to offer the best energy efficiency per GHz at any traffic load value.

Results: This work is published in the proceedings of the European Conference on Optical Communications (ECOC) 2012 with the title "On the Energy Efficiency of Survivable Optical Transport Networks with Flexible-grid" [1]. This work was extended in a chapter of a Green Communications book entitled "Energy Efficiency Improvement with the Innovative Flexible-grid Optical Transport Network" [8]. These results have also been partially presented in two other joint publications [11] [12].

Contributing partner(s): HWDU, TID

3.1.1 Introduction

This activity aims at evaluating the energy efficiency of three common path protection schemes for optical transport networks: dedicated protection 1+1 (DP 1+1), dedicated protection 1:1 (DP 1:1), and shared protection (SP). In particular, the energy efficiency of flexible-grid networks based on orthogonal frequency division multiplexing (OFDM) have been compared with the conventional fixed-grid WDM networks operating with single line rate (SLR) of 10, 40 or 100 Gb/s, and a mixed line rate (MLR) mode (10/40/100 Gb/s). The simulation results will show which protection scheme and technology is more favorable in terms of energy efficiency in a long-haul network with different traffic load conditions.

3.1.2 Network model

In our WDM model, a maximum per-link capacity of 80 wavelengths within the 50 GHz ITU-T grid is assumed. Line rates of 10 Gb/s, 40 Gb/s, and 100 Gb/s, have been included in the analysis. Two types of operation are considered:

- *Single Line Rate (SLR)*: Transmissions of 10, 40, or 100 Gb/s with reaches of 3200, 2200, and 1880 km [18], respectively.
- *Mixed Line Rate (MLR):* Possible transmission of the three mentioned line rates (10, 40 and 100 Gb/s) in the same fiber. In order to minimize the inter-channel nonlinearities between adjacent signals of different transmission technologies, the C-band has been divided into two independent wavebands, as proposed in [19], separated by a guard band of 200 GHz (4 channel spacing). The first one is used for 10 Gb/s (On-off keying) transmission, and the second one for both 40 and 100 Gab/s transmissions, which are based on a "compatible" modulation format (with no intensity variations over time), and thus can be placed on adjacent frequency slots

without significantly affecting the signal quality of each other. Consequently, reach values similar to the SLR case can be considered.

For EON, a frequency slot of 12.5 GHz has been considered, so the transmission rate of a single subcarrier can be 12.5, 25, 37.5, 50, 62.5 and 75 Gb/s for BPSK, QPSK, 8QAM, 16QAM, 32QAM, and 64QAM respectively. Several subcarriers can be combined to create super-channels with higher transmission rate. A guard band of two subcarriers (25 GHz) is used to separate adjacent channels. A transmission reach of 4000, 2000, 1000, 500, 250 and 125 km has 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 [13]. The OFDM variation that has been considered for EON in this study assumes transmission on a single polarization with coherent detection where both optical and electrical synthesis are used, i.e. different optical orthogonal subcarriers are generated, being each of them composed of several electrical subcarriers like the experience described in [20].

The evaluation has been carried out in one of the reference network models from TREND, the Spanish core network of Telefónica, shown in Figure 1 (composed of 30 nodes and 96 bidirectional links). Single fiber pair per link and transparent connectivity have been considered in the analyses. The realistic traffic matrix for 2012 (3.22 Tb/s) has been adopted as a traffic reference and scaled up to different factors to emulate different traffic load conditions (i.e. scaled up to a factor of 20 to obtain a total traffic ranging from 3.22 to 64.48 Tb/s).

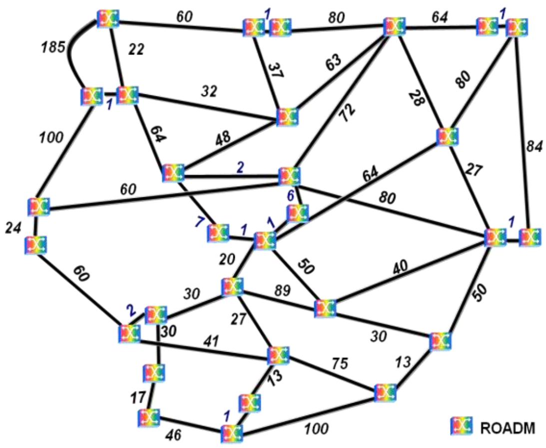


Figure 1. Spanish core network model from TID.

3.1.3 Power consumption model

Three main energy consuming devices are considered in this evaluation: Transponders, optical cross connects (OXC) and optical amplifiers (OA).

a) Transponders

34, 98 and 351 W [14] have been assumed for WDM transponders of 10, 40 and 100 Gb/s transponders respectively. Due to the commercial unavailability of CO-OFDM transponders, some assumptions have been made to estimate realistic values of power consumption [13]. The presence of DSP (Digital Signal Processing) at the transmitter part is assumed to be the main distinction between a CO-OFDM transponder and a coherent WDM one, and therefore the comparison could be based on the DSP complexity. Since this complexity is similar at the same bit rate [15], the power consumption has been assumed to be the same for both types of transponders. Accordingly, based on the values of the dual polarization coherent transponders of 250 and 351 W for 40 and 100 Gb/s respectively (125 and 175.5 W for single polarization) [14]; and assuming that the DSP scales linearly with the bit rate, the power consumption of a single polarization CO-OFDM transponder can be interpolated as a function of its transmission rate (1). Tab. 1 presents the power consumption (PC) values for the different modulation formats. An additional 20% of PC is considered as the overhead contribution for each transponder type.

$$PC_{OFDM}(W) = 1.683 \cdot TR(Gb/s) + 91.333 \qquad (1)$$

b) *Optical Cross Connects (OXC)*

A flexible-grid OXC was assumed to consume similar power as the fixed-grid variant: dependent on the node degree N and the add/drop degree α as in (2) [14].

$$PC_{OXC}(\mathrm{W}) = N \cdot 85 + \alpha \cdot 100 + 150 \qquad (2)$$

c) *Optical Amplifiers (OA)*

An EDFA (erbium doped fiber amplifier) consuming 30 W [14] per direction, and an overhead contribution of 140 W per amplifier location, has been considered.

Table 1. Power Consumption of a CO-OFDM transponder for different modulation formats

Modulation format	**Subcarrier Capacity [Gb/s]**	**Power Consumption [W]**
BPSK	12.5	112.374
QPSK	25	133.416
8QAM	37.5	154.457
16QAM	50	175.498
32QAM	62.5	196.539
64QAM	75	217.581

3.1.4 Protection strategies

The following path protection 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, two DP schemes have been assumed: (1) DP 1+1, and (2) DP 1:1. The first one, DP 1+1 transmits on both working and backup paths, thus requiring the deployment of duplicated transponders (Figure 2). Transmission based on DP 1:1 (Figure 3) 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).
- *Shared protection (SP) (*Figure 4): 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 the recovery might be unsuccessful if sufficient spectral resources are not available for the establishing of a new backup path. 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.

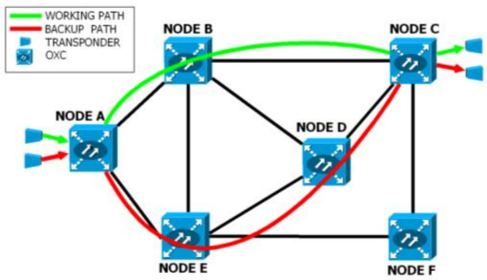


Figure 2. Example of operation of the DP 1+1 scheme.

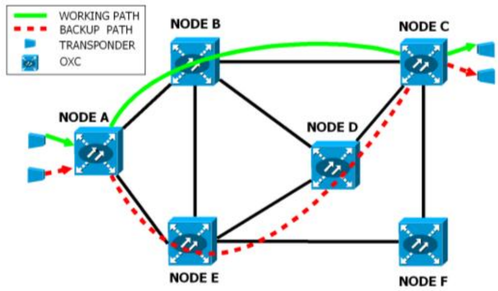


Figure 3. Example of operation of the DP 1:1 scheme.

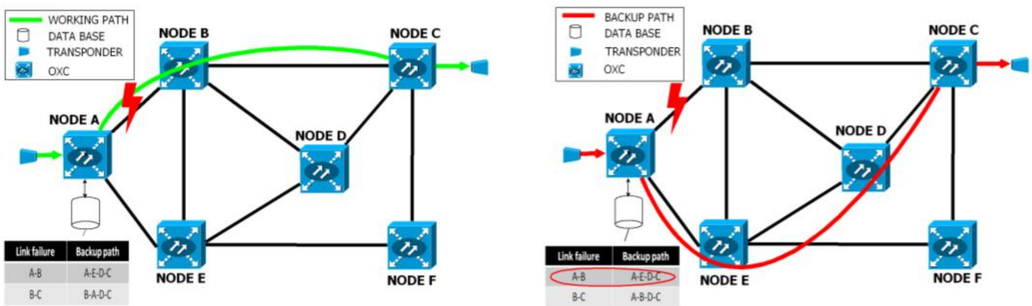


Figure 4. Example of operation of a SP scheme: (left) before failure, (right) after failure.

3.1.5 Survivable-resource allocation algorithms

We studied the resource allocation for a set of static demands that is resilient to any single-link failure, the dominating form of failure in optical networks. In these algorithms, the demands from the traffic demand matrix are firstly sorted in descending order with the highest demand first (similar results were obtained by ordering the product of the traffic demand value and the shortest path length). Then, the resource allocation for each demand from the list is evaluated according to the protection scheme:

a) *Dedicated path protection (1+1 and 1:1)*

The allocation is jointly evaluated for the possible combinations of candidate working path (k shortest paths), and their corresponding candidate backup paths (its k link-disjoint paths). For the feasible path-pair combinations, a metric based on the power consumption is calculated, allowing for the selection of the most energy efficient path-pair for the resource allocation (wavelengths or subcarriers). For both the 1+1 and 1:1 schemes, the spectral resources for the working and backup paths are reserved and pre-cross connected. The difference lies in the computation of the total power consumption, as in the 1+1 scheme the transmission is simultaneous in both working and backup paths, whereas in the 1:1 scheme the transmission occurs only in the working path.

b) *Shared path protection*

Once the resource allocation is evaluated for all the traffic demands in their working paths, the remaining spectral resources can be shared by any backup path. The failure of each link in the network is then analyzed consecutively.

Besides the energy efficiency measure (traffic transported/power consumption), the spectral efficiency is also a relevant parameter that must be taken into account. Therefore, we adopt a new measure from wireless, *Energy efficiency per GHz* (bits/Joule/GHz), to account for both parameters as in (3):

$$\text{Energy efficiency per GHz} = \frac{EnergyEfficiency(\text{bits/Joule})}{AvgSpectrumOccupancy * \text{BandwidthCBand(GHz)}}. \qquad (3)$$

3.1.6 Results

Among the different network types of operation, the SLR 40G is generally the most energy efficient at low traffic load, due to its lower energy per bit at the transponder (2.45 Gb/Joule compared to 3.4, 3.51 and 9 for 10G, 100G and BPSK in the OFDM, respectively). However, when the traffic increases, the spectrum occupancy in the links becomes considerably high, resulting in some blocked demands, either due to the unavailability of spectral resources or to the impossibility of transparent communication. As the traffic grows, the energy efficiency of the SLR 100G, MLR, and especially of EON is improved. Moreover, at high traffic load, the spectral efficiency also starts to become relevant, since it affects the maximum capacity that the network is able to handle with a single fiber pair (shown in Table 2). This fact is also important from the energy efficiency point of view, since deploying additional network elements not only implies an increase in cost, but also in power consumption. The Elastic network clearly shows the lowest spectrum occupancy and blocking ratio thanks to its distance adaptive modulation and its flexible grid operation. Regarding the different protection schemes, SP and DP 1:1 show better energy efficiency than DP 1+1, as the backup paths only consume energy in case of failure. However, the SP scheme offers lower spectrum occupancy and blocking ratio than the DP 1:1 one as the spectral resources are shared by different backup paths.

Figure 5 shows the results concerning Energy Efficiency per GHz for the different types of network operation and protection schemes, at different traffic load conditions with no blocking conditions (all the traffic demands are protected against any single link failure). Therefore, it presents an overview of the energy efficiency, spectrum occupancy and blocking ratio measures. As shown, a survivable Elastic network with SP scheme offers the best results in energy efficiency per GHz at any traffic load value. Simulations were carried out in another country-sized network, the Deutsche Telekom network, leading to similar results (presented in [9]).

Table 2. Maximum traffic supported with no blocking with DP and SP with the different transmission technologies.

Transmission technology	***Maximum traffic with DP (Tb/s)***	***Maximum traffic with SP (Tb/s)***
EON	54.808	61.256
SLR 10 Gb/s	3.224	3.224
SLR 40 Gb/s	12.896	16.12
SLR 100 Gb/s	32.24	41.912
MLR	32.24	45.136

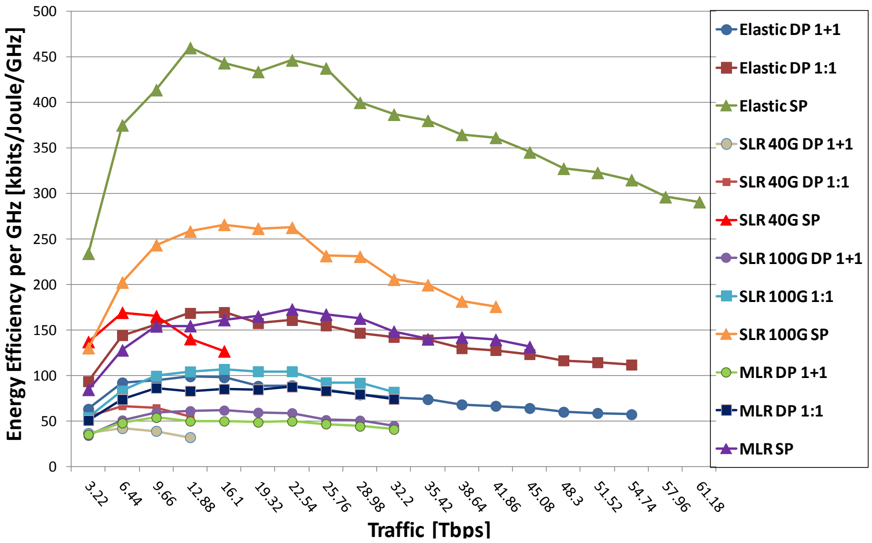


Figure 5. Energy Efficiency per GHz [kb/J/GHz] for the different network technologies and protection schemes in TID's Spanish network model.

3.1.7 Conclusions

The Elastic OFDM-based network is proposed as a promising candidate for the operation of future optical transport networks, and survivability is certainly a parameter that needs to be considered. The resource allocation flexibility of the Elastic network can be beneficial in energy efficiency for a realistic network scenario with different protection schemes. In fact, 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).

Among the different 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.

3.2 Traffic and power-aware protection scheme exploiting daily traffic variations

Summary:	Traditional approaches allocate dedicated (1+1) resources for protection and the peak-rate capacity is reserved in both working and protection paths for every traffic demand. Thus, the power consumed in resilient network is substantially increased compared to the unprotected case. In this work, we evaluate the impact of the hourly network traffic variation to reduce the power consumed by backup resources, by adapting their rate to the current required bandwidth. We apply this paradigm to the single line rate (SLR), mixed line rate (MLR) and elastic optical networks (EON) scenarios and find that, especially in the EON case and for high traffic load conditions, substantial energy savings (up to 27%) can be obtained by exploiting the information on hourly traffic variation.
Results:	This work is published in the proceedings of Networks 2012 (15th International Telecommunications Network Strategy and Planning Symposium) with the title "Traffic and Power-Aware Protection Scheme in Elastic Optical Networks" [3] (extended in [9]). These results have also been partially presented in two other joint publications [11] [12]. This activity is one of the outcomes of a 3-weeks mobility action of Jorge López Vizcaíno (HWDU) to TID.
Contributing partner(s):	HWDU, TID, CNIT-PoliMi

3.2.1 Introduction

Even though many innovative protection schemes have been proposed so far, the traditional DP 1+1 scheme is still the most widely used as it guarantees high resilience and high availability (i.e., short recovery time). However the actual power consumption is substantially increased compared to the case without protection. In this activity, we adopt a different approach, taking advantage since the overall network load during off-peak hours (e.g., at night or in the early morning) is a small percentage of the maximum value. Therefore, we proposed a novel protection scheme to exploit these traffic fluctuations to improve the energy efficiency of a DP 1+1 scheme. This scheme focuses on the protection path, that is, no action will be performed over the working path. On the contrary, the transmission over the protection path is adapted to the current hourly bandwidth requirement. By doing so, the proposed protection scheme allows for a reduction of power consumption while maintaining, at the same time, a high level of availability.

3.2.2 Network model

This evaluation is carried out for the same network technologies described in Section 3.1.2 (i.e. analysis takes into account both EON and current WDM networks). The network scenario described in Section 3.1.2, the Spanish core network model from TID, has been considered. The traffic matrix of 2012 (overall traffic demand of 3.22 Tb/s) is also used as a reference and scaled up. The hourly traffic variations on working and weekend days (Figure 6) are considered to perform the rate adaptation on the protection paths.

The power consumption values presented in Section 3.1.3 are adopted for this study (i.e. power consumption is calculated considering transponders, OXCs and OAs).

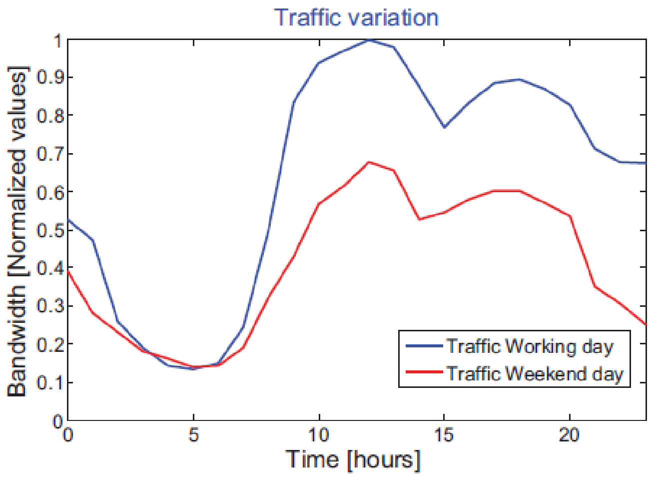


Figure 6. Typical hourly traffic variation in working and weekend days in TID's network model.

3.2.3 Traffic- and Power-Aware routing and resource allocation for protected networks

The main idea consists of adapting the rate of the transponders in the protection paths to the current traffic load of the network on an hourly basis in order to have lower consumption due to backup resources while still maintaining high reliability. We start from a peak-rate traffic matrix where demands between source/destination nodes require bandwidth which varies during the day. Then, we accommodate the demands in descending order with the required bandwidth. The route and resource allocation for the different scenarios (WDM with SLR or MLR and Elastic Optical Network (EON)) is accomplished in a power-aware fashion, according to the peak-rate traffic value for both the working and the link-disjoint protection paths, and the transmission is considered to be simultaneously active.

Algorithm 1 Description of the proposed protection scheme.

STEP 1: Resource allocation for 1+1 protection (peak-rate):
Arrange the demands list DL in decreasing order of required bandwidth
while $DL \neq \emptyset$ **do**
  Evaluate resource allocation in the working and protection path for each demand (RWA for WDM SLR, RWA for WDM MLR, and RMLSA for Elastic Network) for its peak value;
end while
$TotalPeakPowerConsumption = PC_{OXC} + PC_{OA} + PC_{TW} + PC_{TB}$;
STEP 2: Protection path rate adaptation to hourly traffic conditions:
for all hourly traffic variation value during the day **do**
  for all active demand **do**
    Adapt protection path transponders rate to current traffic demand;
    Compute energy savings compared to $TotalPeakPowerConsumption$;
  end for
end for

As shown in Algorithm 1, once the working and backup paths have been selected for all the traffic demands and the total peak power consumption has been computed as the sum of power consumption of OXCs, OAs working and backup transponders contributions (PC_{OXC}, PC_{OA}, PC_{TW} and PC_{TB}, respectively). It has been assumed that the transmission on the working path remains fully active (i.e., at the peak-rate value). On the other hand, on the protection path, the spectral resources previously assigned remain reserved, but the transmission is adapted to the hourly traffic situation, i.e., it is studied whether it is possible to deactivate any transponder or to reduce number of subcarriers/change modulation format in the EON case.

3.2.4 Results

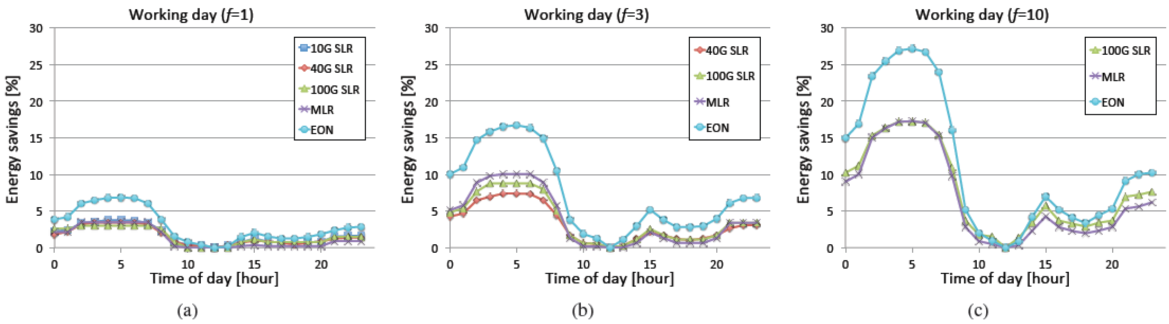


Figure 7. Energy savings (%), with respect to conventional DP 1+1 scheme, for working days in the different network approaches and for different values of traffic matrix scaling factor: (a) f = 1; (b) f = 3; (c) f = 10.

In Figure 7, we show the percentage of energy savings obtained in comparison to the conventional DP 1+1 scheme, for a working day (similar results hold for the weekend day case) in the different network scenarios and for increasing values of the traffic matrix scaling factor, i.e., f =1, 3 and 10. Note that, as for the peak-rate power consumption values, we show here the results in the cases where all the demands are supported by the network, i.e., no blocking occurs (the 10G SLR is only shown in Figure 7(a) and the 40G SLR is only shown in Figure 7(a) and (b)). It can be seen that for all the traffic load conditions, the EON scenario provides the highest energy savings, especially in off-peak hours (i.e., around 5 AM), when up to 27% of savings can be obtained at high load conditions (f = 10). This is due to its efficient adaptability to different traffic conditions, i.e., thanks to its bandwidth expansion/contraction possibility and the modulation format variation.

In Figure 8, the average energy savings that could be achieved with the different approaches on a working and weekend day are presented. As can be noticed, EON is the technology that could benefit the most from such an innovative protection scheme (i.e. energy savings up to 11% and 18% can achieved on a working and a weekend day, respectively).

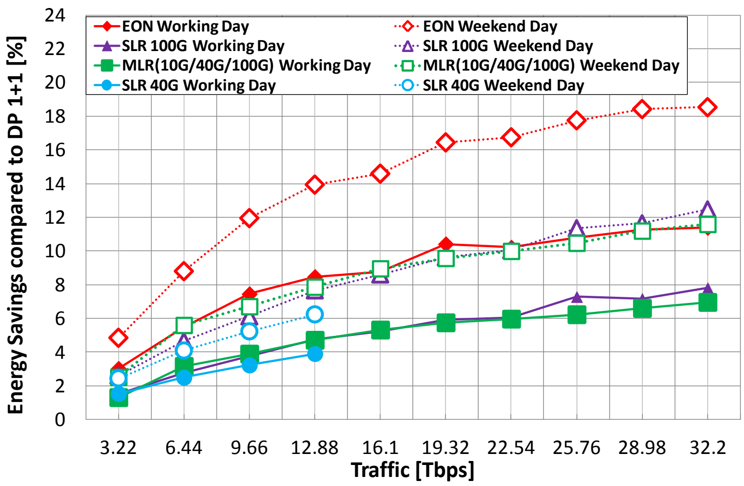


Figure 8. Average energy savings of different architectures on a working and a weekend day with respect to the conventional 1+1 dedicated protection (DP 1+1) scheme for different traffic load conditions for the Telefónica I+D's network model.

3.2.5 Conclusion

Protection is traditionally accomplished by allocating dedicated (1+1) resources which are maintained active independently of the actual traffic requirements of the network, thus “unnecessary” power is consumed. A novel protection scheme which exploits the traffic fluctuations during the day has been proposed to hourly adapt the rate of the backup transponders to the actual bandwidth requirements. We apply this protection scheme to WDM (both SLR and MLR) and to elastic OFDM-based network and find that significant energy savings can be obtained with respect to the conventional protection scheme, especially in the elastic network scenario and for high load conditions, where an average power consumption reduction up to 18% can be achieved on a weekend day.

3.3 Energy-efficient protection by differentiated quality of protection schemes

Summary:	A differentiated quality of protection scheme (QoP) is evaluated in terms of energy efficiency for fixed-grid WDM and flexible-grid OFDM-based networks. Different levels of flexibility, both in the digital and optical domains, are considered for simulations over a nation-wide reference network model. Increasing power savings are achieved as long as the flexibility levels become higher, demonstrating the benefits of QoP deployments to accomplish power consumption reduction. Significant energy savings can be achieved by exploiting the heterogeneous protection requirements.
Results:	This work resulted in two publications: "Differentiated Quality of Protection to Improve Energy Efficiency of Survivable Optical Transport Networks" published in the proceedings of the Optical Fiber Communication (OFC) 2013 [7], and "Quality of protection schemes with extended flexibility for improved energy efficiency in transport networks" published in 9th International Conference on Design of Reliable Communication Networks - DRCN 2013 [6]. Some of the work presented in this work is an outcome of a 2-weeks mobility action of Jorge López Vizcaíno (HWDU) to CNIT-PoliMi.
Contributing partner(s):	HWDU, TID, CNIT-PoliMi

3.3.1 Introduction

In long-haul optical networks, the most common and secure strategy to provide resilience is implementation of a dedicated protection 1+1 (DP 1+1) scheme, where the data are duplicated and transmitted on two link-disjoint paths. DP 1+1 requires the reservation of twice the spectral resources for working and protection paths, and the deployment of redundant transponders, which are simultaneously active and consuming power. Thus, the operation of DP 1+1 results in inefficient utilization of spectral resources, and high energy consumption and capital expenditures (CapEx). Other protection schemes such as shared protection (SP) are more energy-and cost-efficient [1] [4], but might be inadequate for some critical services requiring high availability due to their longer recovery time. Since not all the services used by clients need the same availability, exploiting the heterogeneity of protection requirements requested by the clients can be a smart strategy to achieve a more efficient utilization of resources (e.g. reduce cost and energy consumption). Following this approach, Telecom operators would be able to offer a differentiated quality of protection (Diff QoP) to their customers depending on their service quality requirements and the cost they are willing to pay for it.

The potential of Diff QoP architectures in terms of overall power efficiency has been demonstrated in [7], whereas in [6] this analysis is extended to consider the inclusion of intelligent packet-to-circuit mapping capabilities (e.g., through the ODU-Flex (optical channel data unit flexible) technology) into the optical network nodes. Significant energy savings can be achieved by the combination of both strategies.

3.3.2 Network model

The study is focused on corporate service deployments exclusively involving optical transport infrastructure. This means that Optical VPN (virtual private network) services will be offered to enterprise customers, connecting their sites and headquarters locations. In this context, a Diff QoP scheme is proposed to provide different protection levels for each VPN connection, according to the client protection requirements.

The provisioning of Differentiated QoP is based on the definition of Different QoP traffic classes. These traffic classes can be offered to the customers according to their protection requirements. More specifically, four different classes have been defined, as presented in Table 3, ranging from maximum protection (C1 with maximum protection) to unprotected services (C4 with best-effort protection).

Table 3. Definition of QoP classes.

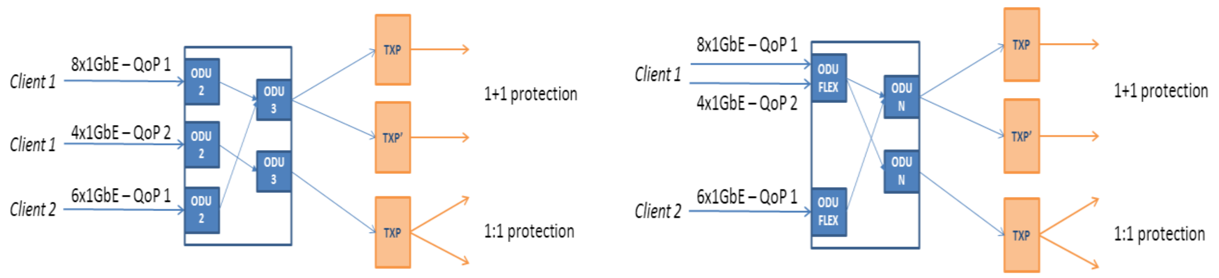
QoP Class	***Description***
C1-Maximum Protection	*DP 1+1*, duplicate transponder(s), fastest recovery.
C2-High protection	*DP 1:1*, single transponder(s) for working path.
C3-Medium protection	*SP*, single transponder(s) for working path.
C4-Unprotected	Best-effort (*BE*).

In such scenario, the deployment of a Diff QoP scheme involves the realization of three main tasks at the optical add/drop nodes to map a client traffic demand into an optical connection with a certain QoP level:

1) *Mapping of electronic traffic demands generated by physical logical ports (e.g., Ethernet ports) into low-hierarchy ODU containers:*

   In a potential implementation of Diff QoP, if the mapping of client traffic demands is performed by traditional fixed ODU containers, each physical port, corresponding to a client or QoP class, will be assigned a dedicated ODU card, thus limiting the flexibility of this scheme (Figure 9a). The introduction of ODU-Flex (optical channel data unit flexible) capabilities at the OXC provides adequate levels of flexibility in the mapping process (i.e. ODU-Flex containers with 1.25 Gb/s capacity, which permits to fit any client rate into any higher level ODUk of OTN (optical transport network)). As shown in Figure 9b, the ODU cards are no longer rigidly assigned to a QoP level. Actually we obtain some flexibility in the digital domain when mapping low to high hierarchy ODU containers, but we would still employ different ports for each client signal according to its destination and QoP class.

   In order to further improve the flexibility in the traffic mapping process at the OXC, we also consider the introduction of some basic "packet intelligence" in the OXC (i.e. packet-to-circuit mapping intelligence that allows performing virtual local area network (VLAN) switching based on VLAN-tagging). In other words, signals generated by one client and having different destination and/or QoP can be combined together and use a single port, as shown in Figure 10. With this scheme, a destination/QoP is no longer tied to a physical port, helping reduce the number of Ethernet ports and ODU cards and making efficient use of lower energy consumption (per transmitted bit) high capacity ports.



(a) (b)

Figure 9. (a) QoP implementation with classical ODU traffic mapping (2 different QoP traffic classes, QoP1 and QoP2), and (b) QoP implementation with ODU-Flex traffic mapping.

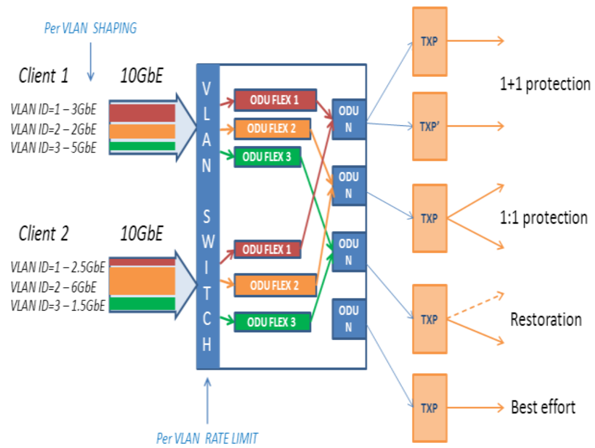


Figure 10. QoP implementation based on an OXC architecture with basic packet intelligence.

2) *Grooming of low hierarchy ODU containers into high hierarchy ODU containers:*

   The low hierarchy ODU containers (fixed-rate ODU containers or an integer number of ODU-Flex ones will be then multiplexed to higher hierarchy ODU containers) as shown in Figure 9 and Figure 10.

3) *Mapping of high hierarchy ODU containers into optical transponders:*

   Tributary signals of some QoP class can be mapped to fixed-rate ODU or ODU-Flex containers, multiplexed into a higher hierarchy ODU structure and switched to optical transponders assigned to this QoP. At the line side, the same transmission technologies described in Section 3.1.2 have been considered for the operation of the network: fixed-grid WDM networks (SLR and MLR) and flexible-grid or EON.

At the line side the power consumption values described in Section 3.1.3 have been adopted for transponders, OAs and OXCs. At the tributary side, the power consumption model for the Ethernet layer in [16] has been used as reference.

The network scenario considered in this work is the Spanish core network model provided by TID for the studies within the ICT STRONGEST project [17]. The network model comprises 5 regional domains interconnected by a national domain, and composed of 150 nodes and 319 bi-directional links as depicted in Figure 11.

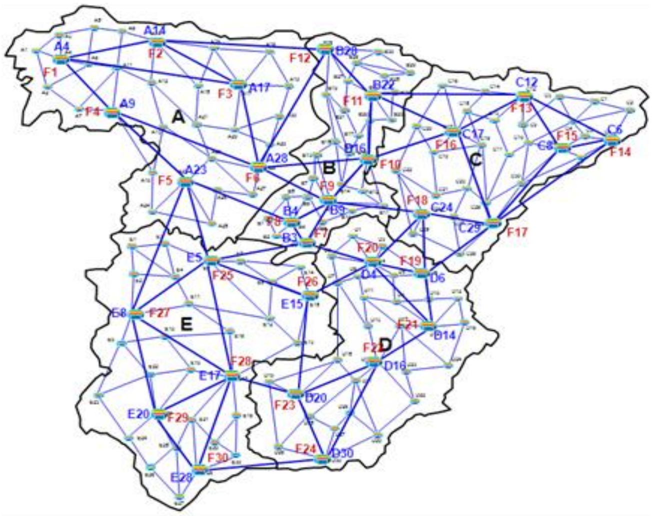


Figure 11. Network Scenario-Spanish core network model from TID [17].

At the line side, a network protected by a DP 1+1 scheme (i.e. the total aggregated demand is protected without traffic differentiation), has been compared with a Diff QoP scheme for both the WDM and the elastic OFDM-based network scenarios. The potential savings at the line side are complemented with the possible reduction on power consumption achieved by using a logical VLAN to destination/QoP strategy at the tributary side (Figure 10), compared to a physical port to destination/QoP strategy (Figure 9b).

The distribution of the traffic classes and the total traffic certainly determines the degree of differentiation that can be finally applied to the network. In this manner, in order to evaluate the possible power consumption savings under different conditions, the study has been carried out for four different traffic loads (i.e. starting from an initial overall traffic of 1.56 Tb/s for 2012 and scaled by factors of 5, 10 and 15), and considering three possible scenarios with different distributions of traffic classes (see Table 4).

Table 4. Traffic scenarios.

Traffic Scenario	***C1 (%)***	***C2 (%)***	***C3 (%)***	***C4 (%)***
S1	41	27	19	13
S2	19	13	41	27
S3	25	25	25	25

3.3.3 Differentiated QoP algorithms

The methodology used in this study is based on an extension of the heuristics algorithms for the routing and resource allocation explained in Section 3.1.5. As an input, a traffic matrix containing the aggregated demand of each class between each pair of nodes is provided.

In the DP 1+1 case, the demands from the traffic matrix are, in a first step, sorted in descending order of aggregate traffic demand value. Then, it is evaluated whether working and protection paths (link-disjoint paths) can be provided for each particular demand from a set of candidate paths (k-shortest paths). In the Diff QoP case, the demands are classified into four independent traffic matrices (one for each QoP Class). Then, the allocation is evaluated consecutively for each of the groups of demands according to their protection scheme, and in descending order of protection requirements (i.e. starting from the ones requiring maximum protection, C1, and finishing with those not requiring any protection, C4). As mentioned before, a demand can be upgraded to a higher QoP class. Thus, for traffic demands different than C1, it is firstly evaluated whether they can be groomed into the remaining spectral resources of the already established lightpaths of higher QoP with the same destination. In this regard, EON offers an additional advantage, as it is possible to increase the capacity of the lightpath by increasing the modulation order. When the required protection requirements cannot be fulfilled for a demand, then it is blocked. As an output, the power consumption of the network with Diff QoP in the different traffic scenarios will be obtained and compared with that of a conventional network implementing DP 1+1 for all its traffic.

On the other hand, at the tributary side, for every customer, the number of physical ports required to deploy its optical VPN infrastructure is computed following both a physical port to destination/QoP strategy (Figure 9b) and a logical VLAN to destination/QoP approach at the tributary side (Figure 10). Once the total number of ports of each type for every of the customers has been obtained, the power consumption share of the tributary interfaces (between customer and optical node port) is calculated.

3.3.4 Results

This section aims at presenting the overall power consumption savings that could be achieved by combining the two strategies (i.e. Diff QoP and VLAN-tagging) with respect to the a conventional network protected by DP 1+1, and in which a port is commonly dedicated to every client at the tributary side.

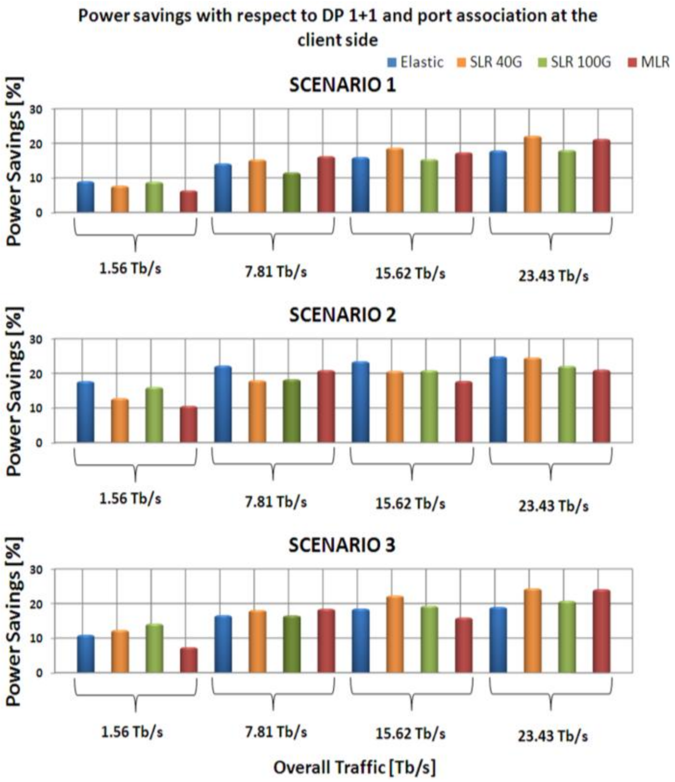


Figure 12 Power savings [%] of a network implementing a QoP scheme and VLAN differentiation with respect to a network with DP 1+1 scheme at the line side and port differentation at the client side. Results are presented for the three possible traffic scenarios (Table 4) and the different traffic load values.

The power savings achieved by these novel strategies are presented in Figure 12. The results show that the degree of power savings will depend on the network technology, total traffic, and distribution of traffic classes. Even though power savings can be obtained for all the different traffic conditions, these can be more significant at high traffic load. This is explained by the fact that, at low traffic load, a bigger number of traffic demands with lower protection requirements (C2, C3 and C4) are “upgraded” to C1 in order to get a better utilization of the resources, thus resulting in an overall power consumption closer to that of the conventional DP 1+1 scheme.

However, as traffic increases further, it would be possible to apply more differentiation to a higher fraction of the total traffic (i.e. more lightpaths will be protected by less power consuming schemes such as DP 1:1, SP, or BE protection). Regarding the different traffic scenarios, higher energy savings can be achieved in S2 and S3, as there are more customers requiring lower protection levels which allows for the application of more energy-efficient protection schemes.

3.3.5 Conclusions

Exploiting the different and heterogeneous protection requirements of the customers by a Differentiated Quality of Protection scheme has been evaluated as a strategy to improve the energy efficiency in optical transport networks. The results show that significant power savings can be obtained by the application of a differentiated QoP scheme at the line side, and the introduction of “packet intelligence” at the node by means of VLAN tagging at the tributary side.

The energy-efficient improvements are applicable to both fixed-grid WDM and elastic OFDM-based networks in a nation-wide network under different traffic conditions. These power savings can be up to 24%.

3.4 Power-aware design of protected IP-over-WDM networks with sleep-mode devices

Summary: Recently, the need for energy-efficient and sustainable capacity growth has become stringent for telecommunication networks and great efforts have been produced to reduce their power consumption. Optical technologies based on Wavelength Division Multiplexing are well-recognized as a promising solution for greening the future Internet. One relevant approach to achieve such power savings consists in aggregating traffic flows in few network links, so that power can be saved by switching-off some unused network devices. However, the need to ensure network resiliency against link and/or node failures imposes that still the resources reserved to protect connections become available immediately after a failure occurs. Therefore, a possible solution is to set some devices into low-power sleep-mode, so that they can be rapidly re-activated and provide fast connection recovery. We focus on the power-efficiency of protected IP-over-WDM networks and provide a comprehensive comparison of four different protection strategies, namely Shared-Link, Shared-Path, Dedicated-Link and Dedicated-Path Protection (SLP, SPP, DLP and DPP respectively) in a sleep-mode scenario. In the proposed design strategies we assume that low-power sleep-mode is enabled for devices used for protection. Mathematical models for a power-aware design with sleep-mode are used for the four protection strategies. We show that relevant power savings (up to about 60%) can be obtained for all the protection strategies by setting protection devices into sleep-mode

Results: This work is published in the proceedings of the IEEE Greencom conference 2012 with the title “Power-Aware Design of Protected IP-over-WDM Networks with Sleep-mode Devices” [2]. This contribution was extended in the publication “Energy-Efficiency of Protected IP-over-WDM Networks with Sleep-Mode Devices” of the Journal of High Speed Networks [5].

Contributing partner(s): CNIT-PoliMi, HWDU

3.4.1 Introduction

Traditionally, in optical IP-over-WDM networks, the redundant devices are powered-on, even though no failure has occurred, i.e., regardless if they are actually used or not. To avoid unnecessary power consumption, some of the network components used for protection can be set in a sleep (or standby) low-power mode, assuming that the idle device can be quickly configured and activated in case of failure. Considering sleep-mode for backup devices, a trade-off between protection and power-efficiency arises, as to maximize the former objective operators might tend to distribute traffic over the network (load balancing), while in the latter case, the operator will tend to aggregate traffic flows in order to set into sleep-mode (or even switch-off) as many devices as possible. Note also that, in the case of power minimization, while traffic grooming is desirable to aggregate more traffic on fewer links, excessive grooming may lead to increase electrical-optical (EO) and optical-electrical (OE) signal conversion operations, i.e., additional power consumption. We use an integer linear programming (ILP) formulation for a power-aware design of IP-over-WDM networks where low-power sleep mode devices are used for backup lightpaths provisioning and compare different protection strategies, i.e., Dedicated-Link, Dedicated-Path, Shared-Link and Shared-Path Protection (DLP, DPP, SLP and SPP, respectively).

3.4.2 Network model

We consider a network architecture where IP routers are interconnected through optical fiber links which optically transmit the signal exploiting the WDM technique. Several network elements are needed to support a connection among the routers within IPoWDM networks (see Figure 13). The electronic signals are generated by the IP routers and then converted into the optical domain by the WDM transponders, thus a wavelength channel (i.e., a lightpath) is initiated. The parallel lightpaths (λs) are then multiplexed into the same optical fiber link (note that in this work we consider single-fiber links) through an optical multiplexer and transmitted towards the next IP router, where wavelengths are first de-multiplexed and then OE converted by WDM transponders. Along the fiber links, signals are optically amplified via EDFAs, which are typically placed with an 80 km span. Two more EDFAs are usually deployed at the edges of the WDM link as booster and pre-amplifier, respectively. Note that in this paper we do not consider optical switching, i.e., network nodes are not equipped with OXCs, since we assume that signal switching is accomplished in the electronic layer through IP routers.

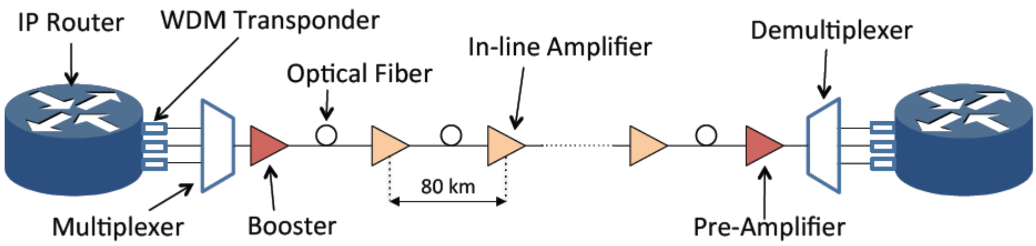


Figure 13. IP-over-WDM network architecture consisting of IP routers connected through optical fiber links.

Based on the network architecture described above, in our study we consider the power consumption of WDM transponders (i.e., transmitter/receivers), WDM links (i.e., optical amplifiers) and the contribution due for electronic traffic processing performed by IP routers. See [5] for the details of the specific power consumption contributions.

The power-aware design strategies for the two different protection scenarios have been tested over the NSFNET network topology with 14 nodes and 22 single-fiber bidirectional links, where 20 wavelengths are assumed for each link. We consider a non-uniform traffic matrix with 180 Gb/s total traffic.

3.4.3 Protection strategies

We compare four different protection strategies from the power consumption point of view, namely Dedicated-Link, Dedicated-Path, Shared-Link and Shared-Path Protection (DLP, DPP, SLP and SPP, respectively). Note that in this work, the protection strategies are intended as performed at the IP-flow level, i.e., we reserve backup resources for protection by considering every connection, generated at the IP layer, separately and independently from the others.

In dedicated protection strategies (DLP and DPP), protection resources are exclusively reserved for the different connections. Therefore, in these cases, a high amount of redundant resources is employed to protect all the connections. Here we assume that dedicated protection is a 1:1 protection, i.e., for each traffic flow transmitted over a working path, we only reserve the capacity in a protection path, which does not carry traffic until the failure occurs.

On the other hand, in shared protection cases (SLP and SPP), redundant capacity reserved for protection can be shared by two or more different connections, as long as the working paths protected through the same resources are link (or node) disjoint. In these cases, redundant resources are efficiently exploited, though shared protection strategies can only be used when a single-link (or node) failure is allowed at the same time. Furthermore, for the link protection cases, every link connecting two nodes A and B is protected reserving the capacity along an alternative route which connects A to B. Instead, in the path protection strategies, the whole end-to-end working path is protected by reserving backup capacity along a node-disjoint (and, consequently, link-disjoint) path.

In Figure 14, we show how two connections are routed over the working paths w_1 and w_2 and how the protection resources p_1 and p_2 are reserved in the four cases.

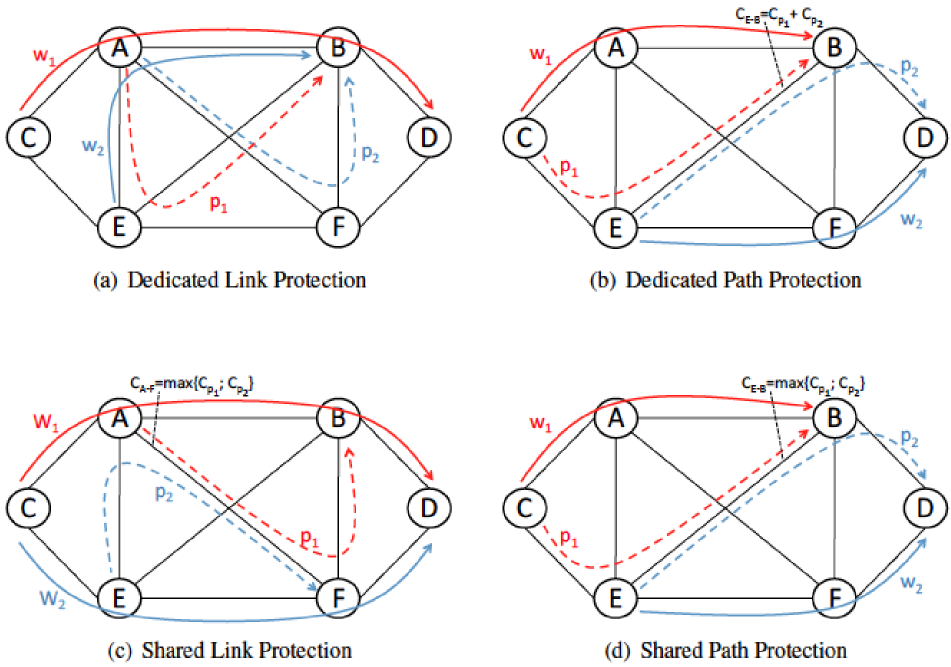


Figure 14. Different protection strategies under analysis. (a) Dedicated link protection, (b) dedicated path protection; (c) shared link protection and (d) shared path protection.

3.4.4 Power-aware design ILP model

The problem of power-aware design of protected IP-over-WDM networks has been formulated as four ILP flow-based formulations for the different protection strategies (see [5] for the details). The objective aims at finding the minimum total power consumed by the IP-over-WDM network, consisting of the electronic processing consumption, which is formed by the basic node consumption and the traffic-dependent consumption due to slot and port cards; power consumed by EDFAs; and finally the consumption due to transmitters/receivers located in the transponders.

3.4.5 *Results*

In Table 5, we show the results obtained for the four different protection strategies, for an increasing factor *f* equal to 1, 2, 5, 10 and 20 and used to scale the bandwidth required by the connections. The proposed Power-Aware (PA) design strategies, where devices can be set into sleep-mode if they are only used for protection, are compared with the scenarios where protection devices are considered as fully powered-on ("all-ON" in the table). Moreover, we consider as benchmark the case of the unprotected network, where routing of non-resilient connections is carried out in a power-aware fashion. We observe that for all the protection strategies, the overall network consumption can be reduced by enabling low-power sleep-mode for protection devices, especially for higher bandwidth requirements (high values of *f*), when power savings ranging from 39% (SPP case) to 59% (DLP case) are obtained. This is due to the high impact of slot and port cards power contribution which increases with traffic. For lower traffic loads, the power advantage obtained with sleep-mode tends to reduce due to the lower amount of electronic processing needed. In any case, for every protection strategy, the power savings obtained using sleep-mode devices are maintained always above the 30% with respect to the corresponding all-ON case. As expected, the shared protection scenarios have a slightly better behavior in terms of power requirements with respect to the dedicated ones, since in the SLP and SPP cases fewer resources need to be reserved for protection paths. Note that in the all-ON scenarios this difference is more evident due to the much higher power contribution provided by protection devices in the dedicated protection scenarios. Considering the SLP and SPP strategies, it can be observed that the results are comparable in terms of power requirements (the difference between the two scenarios is below 1%) and, in general, the SLP scenario slightly outperforms the SPP one. Similar considerations can be drawn for the comparison between the DLP and DPP cases, where 1–2% of difference is observed in the power consumption values; however in this case it is not univocal which one is the best solution. Further results and considerations can be found in [5].

Table 5. Power consumption values (kW) obtained for increasing traffic load in the different cases.

Scaling factor	SLP		SPP		DLP		DPP		Unprotected
	sleep-mode	all-ON	sleep-mode	all-ON	sleep-mode	all-ON	sleep-mode	all-ON	
$f = 1$	73.791	110.297	73.89	108.054	74.008	120.057	73.89	115.321	73.398
$f = 2$	86.469	130.672	86.469	121.974	86.902	148.835	87.301	136.661	85.859
$f = 5$	121.365	185.6	121.954	186.406	122.388	232.027	121.817	203.591	120.381
$f = 10$	172.764	277.409	173.275	274.573	174.579	378.684	173.339	319.265	170.682
$f = 20$	270.23	455.448	270.992	442.877	274.186	662.191	not supported		266.806

3.4.6 *Conclusions*

In this paper we investigate the power consumption of protected IP-over-WDM networks by comparing four different protection strategies, namely Shared-Link, Shared-Path, Dedicated-Link and Dedicated-Path Protection. We show that for all the protection strategies relevant power savings, up to about 60%, can be obtained by setting protection devices into sleep-mode, and consistent savings can be also reached (up to about 18%, according to the protection strategy and traffic load) with respect to power unaware design strategies where the cost, intended as number of used wavelengths, is minimized. Moreover, we show that, by employing sleep-mode for protection devices, it is possible to guarantee network resilience for a small (1–2%) additional power expenditure compared to the unprotected network scenario.

In most cases, the differences among the four protection strategies are negligible (below 1%), since the most relevant contribution to the total power consumption is due to the electronic traffic processing performed at the IP layer, which is almost independent of the adopted protection strategy and takes the highest advantage from setting backup resources into sleep-mode, especially for higher traffic. Moreover, also the power consumed at the WDM layer can be significantly reduced when enabling sleep-mode for protection devices.

3.5 Cost evaluation of protection schemes on fixed-grid WDM and flexible-grid OFDM-based networks

Summary: We have compared the total cost of an innovative elastic network with respect to the conventional WDM ones operating in realistic network scenarios. The results give an insight of the cost benefits that can be obtained with an elastic OFDM-based network for the operation of future optical transport networks with different protection schemes. Both the cost of network equipment and the energy expenses are considered in the evaluation.

Results: This work is published in the proceedings of the IEEE Global Telecommunications Conference (GLOBECOM) 2012 workshop on Flexible Optical Networks [4]. This activity is one of the outcomes of a 3-weeks mobility action of Jorge López Vizcaíno (HWDU) to TID.

Contributing partner(s): HWDU, TID

3.5.1 Introduction

A network upgrade usually implies additional economic efforts by the operators due to the higher CapEx and OpEx resulting from, for instance the need for new telecommunication infrastructure deployments and higher electrical power consumption. Furthermore, guaranteeing a high resilience will also be a must for operators due to the importance of telecommunication networks for the availability of indispensable services in our society. Therefore, protection schemes have to be taken into account in the performance evaluation. This contribution aims at evaluating not only energy efficiency, but also the cost of three common protection schemes. Firstly, the cost efficiency of an elastic OFDM-based network is compared to the WDM counterpart, including both CapEx and energy cost, in realistic network scenarios using different protection schemes: DP 1+1, DP 1:1, and SP. Besides, the target cost of a bit-rate variable transponder (BVT) to make the elastic approach result in lower total network cost than the current WDM approaches for different traffic load conditions has been determined for the three mentioned protection schemes.

3.5.2 Network model

This evaluation is carried out for the same network technologies described in Section 3.1.2 (i.e. analysis takes into account both EON and current WDM networks). The network scenario described in Section 3.1.2, the Spanish core network model from TID, has been considered. The traffic matrix of 2012 (overall traffic demand of 3.22 Tb/s) is also used as a reference and scaled up to emulate different traffic load conditions.

3.5.3 Cost model

The relative cost values for current WDM equipment are based on a model used by Telefónica in similar studies; whereas several assumptions have been made to estimate realistic values for the elastic network.

a) Transponders

For the WDM transponders, normalized cost values of 1, 3 and 7.5 have been considered for the transponders with bit rates of 10, 40 and 100 Gb/s respectively.

For the elastic OFDM-based network, a BVT, more specifically a CO-OFDM transponder allowing for modification of the signal properties (i.e. number of subcarriers and modulation format) by means of software is necessary. The high-level architecture of the transmitter part of such a transponder will probably consist of several low speed modulators in parallel, together with a digital signal processing (DSP) module and high-speed DACs (Digital-to-Analog Converters). The receiver part will also be composed of multiple coherent receivers at low speed. In this study, two main assumptions have been made in order to estimate the cost of a CO-OFDM transponder:

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

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

Accordingly, based on the previous assumptions, and considering 400 Gb/s as the maximum transmission rate that the transponder is capable to achieve, the cost of a flexible transponder has been chosen to be 36 cost units, i.e. 20% higher than 4 times the cost of a 100 Gb/s WDM transponder (1.2*4*7.5).

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 [22], and, if not considered in our analysis, it would be difficult to economically justify the investment in such a high-speed transponder 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.

Figure 15 presents an example of the allocation of two traffic demands of 100 Gb/s and 200 Gb/s with the three approaches described above.

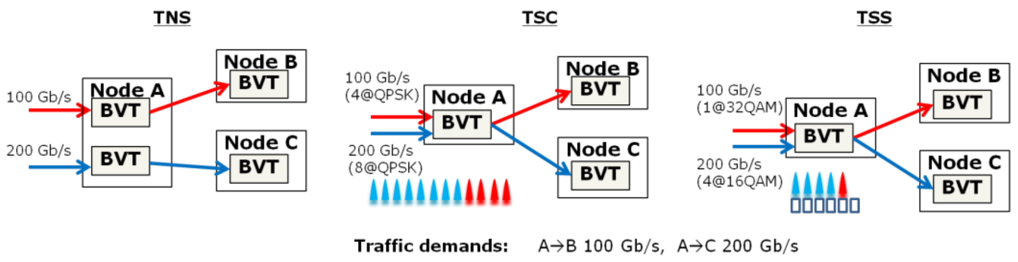


Figure 15. Representation of the allocation of transponders for two traffic demands of 100 Gb/s and 200 Gb/s with the BVT cost models for TNS, TSC, and TSS.

b) OXC

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

$$Cost_{OXC}[\text{c.u.}] = \left(N + 2 + 2 \cdot \left\lceil \left(\frac{x-9}{8} \right) \right\rceil \right) \cdot Cost_{WSS} \qquad \begin{cases} x=9 & 0<\alpha<=9 \\ x=\alpha & \alpha>9 \end{cases} \qquad (4)$$

c) Optical Line Amplifiers

The cost of each EDFA per direction has been assumed to be 1 cost unit.

d) Energy Cost

The power consumption values included in section 3.1.3 have been considered to calculate the power consumption of the network. Once the power consumption has been obtained, it is possible to calculate the energy expenses by considering the energy cost for industrial customers in Spain for 2011 [21]. The normalized cost value is $2.086{\times}10^{-5}$ /kWh.

3.5.4 Survivable-resource allocation algorithms

The methodology of survivable-resource allocation algorithms presented in section 3.1.5 has been extended to consider the cost computation. Provided that the analysis was limited to a single fiber pair per link, it is also necessary to consider the performance with respect to spectral efficiency and the blocking ratio, as the maximum traffic accommodated on a single fiber definitely affects the final network cost. Thus, we have defined a measure (*Cost*

Efficiency per GHz) to account for the number of bits that is transmitted with a single cost unit (c.u.) per GHz (bits /c.u./GHz) as presented in equation (5). The term *TransmitedData* is the total amount of data transmitted in the considered time frame: *TotalCost* contains both the equipment and the energy cost during the specified time frame, and *AvgSpectrumOccupancy* is the average of the spectrum occupancy in the links of the network.

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

3.5.5 Results

This section is subdivided into three subsections: (a) Energy expenses, (b) cost-efficiency evaluation with a TSC, and (c) target cost of a BVT.

a) Energy expenses

The energy expenses in a 10-year term are presented in Figure 16 (energy cost vs. traffic scaling multiplier). Note that the results are only presented under non-blocking conditions, i.e. for those traffic scaling factors at which zero blocking is provided and all the traffic demands are protected against any single link failure. The curves in the upper part present the energy cost for DP 1+1, which obviously consumes more energy than the other options due to the simultaneous transmission in the working and in the protection path. On the other hand, the curves in the lower part identify the energy consumption for SP and DP 1:1 schemes for the different technologies, which are lower than the one for the DP 1+1 scheme. The only difference between the SP and the DP 1:1 schemes in terms of energy usage is the lower blocking provided by the *SP* schemes possibility of accommodating more traffic (i.e. the lower blocking ratio with *SP* scheme).

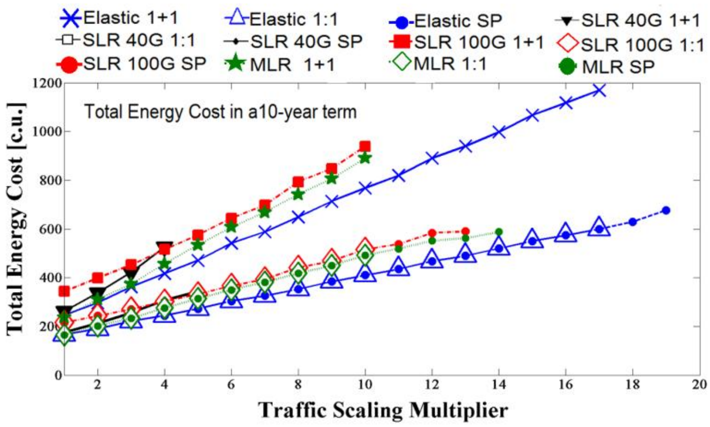


Figure 16. Total energy cost [c.u.] in 10-year term for the different network technologies and protection schemes.

b) Case study with transponders "sliceable" in capacity (TSC)

Figure 16 shows the results concerning the cost efficiency per GHz in a 10-year term. As in the previous figure, only the values in which all the traffic demands can be satisfied are presented. Concerning the evaluated network approaches, the elastic network provides the best performance and clearly outperforms WDM networks at any traffic load conditions. The results show that the difference in cost efficiency per GHz between the elastic network and the other network technologies is becoming more significant as the traffic increases because of its better spectral efficiency. The WDM SLR 100 Gb/s network also increases its performance when the traffic increases, but its spectrum occupancy increases faster. In the same manner, the WDM SLR 40 Gb/s is also penalized by this fact when the traffic increases. In the WDM MLR, the presence of a guard band of 200 GHz to separate the different transmission technologies reduces the available spectrum that can actually be used for transmission, and thus its performance is deteriorated in cost efficiency per GHz. The main reason for the notable cost efficiency per GHz of the elastic network is the fact that the high traffic demands will occupy a considerably higher spectrum in WDM networks due to the operation restricted to ITU-T grid, as there will be many parts of the spectrum unoccupied between the different wavelengths; whereas in an elastic network, the channel bandwidth can be expanded in a contiguous manner, creating super-channels with higher spectral efficiency. Besides, the considerably low blocking ratio of this technology also implies an advantage in terms of cost, as more traffic can be accommodated in a single fiber and thus fewer network devices (such as signal regenerators) would be required in the network to fulfill high traffic demands. Regarding the comparison of the different protection schemes, the *SP* scheme is clearly the one in equipment and energy consumption, and, especially, to its lower spectrum occupancy (i.e. the spectral resources for the protection paths are shared among several working lightpaths).

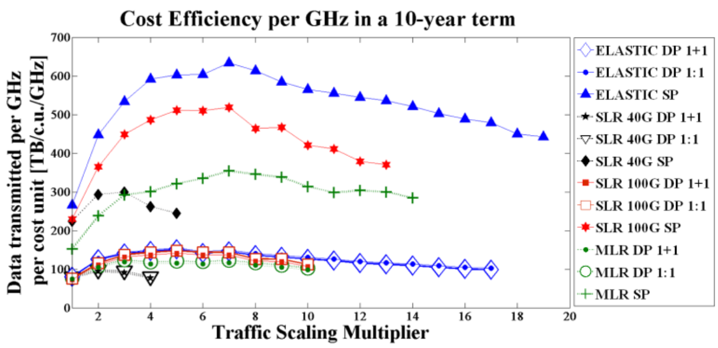


Figure 17. Cost Efficiency per GHz [TB/c.u./GHz] in a 10-year term for the different network technologies and protection schemes.

c) Maximum acceptable cost of a BV-T to minimize total network cost

This subsection is dedicated to the determination of the cost of a BV-T, for which the elastic network will become the most economic approach for the different traffic load conditions. It is worth mentioning that the final cost of the elastic network will depend not only on the cost of the BVT, but also on the manner in which the transmission capacity of the transponder is utilized. Therefore, the three cost models described in Section 3.5.3 (i.e. TSC, TNS, TSS) are evaluated. In order to turn the elastic network into more cost-efficient solution than any of the current WDM approaches, it should provide a lower total cost, considering both CapEx and energy cost. From the simulation results, the WDM approach that provides the lowest cost for both SP and DP schemes is the WDM MLR network. Since transponders are the main contribution to the total cost of the network (more significant than the cost of the OXCs, the EDFAs or energy expenses), the objective is to determine the cost of a BV-T allowing for a lower total cost than the WDM MLR network for the different traffic load conditions and protection schemes.

Figure 18 shows the maximum acceptable cost for a BV-T, meaning that any cost lower than the values presented in that figure will result in more cost-efficient elastic network than any investigated approach. For instance, at low traffic load conditions, it can be seen that the BV-T should approximately cost the same as a 100 Gb/s WDM transponder (7.5 c.u.) in order to obtain benefits in terms of cost with respect to WDM networks, but lower energy cost of the elastic network will be advantageous. Then, when the traffic increases, the elastic approach starts to take advantage of its better performance at high traffic load, so it would be possible to tolerate higher cost for the BV-Ts in order to provide similar cost to that of the MLR network.

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

As far as protection schemes are concerned, it would be possible to accept a higher cost for a BV-T with the SP scheme, as nodes are only equipped with transponders for the working path, whereas the DP schemes require to purchase transponders for both working and backup paths. The results in Figure 18 are only shown for those traffic scaling multipliers providing no blocking for the MLR network, but it is important to note that the elastic network allows for scaling up the traffic matrix by higher factors without blocking (i.e. up to 19 and 17 scaling factors with SP and DP respectively). In these conditions, it might be possible to accept an even higher cost for a BVT since, as abovementioned, deploying additional fibers and/or network elements, such as regenerators, would entail a higher cost.

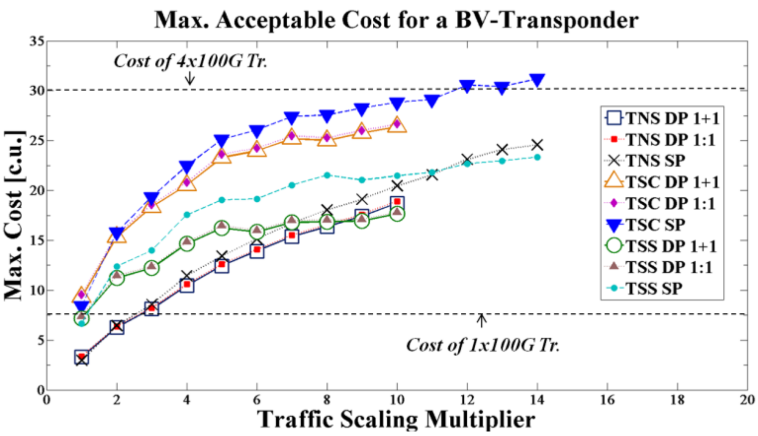


Figure 18. Maximum acceptable cost (c.u.) for a BV-T to turn the elastic network into the most cost-efficient solution, for the three cost models and protection schemes.

3.5.6 Conclusions

Cost is one of the main drivers for the operators when it comes to the decision of deploying a new technology. In a realistic network scenario, allowing service protection, simulations showed that even if the cost per bit of a BVT is initially higher than that of current WDM transponders the elastic network can be a more affordable approach. A significant advantage of the elastic network is given by its lower blocking, which permits to accommodate more traffic in a single fiber. As show in our study, the final cost of such an elastic network strongly depends on the cost of a BVT, and the manner in which its capacity is shared for the transmission of different demands.

Besides the actual expenditures in network elements and the energy cost, the spectral efficiency has also a relevant impact, as it determines the maximum traffic in the network, and therefore the number of fibers and network elements that are necessary for a given traffic load. In addition to the better performance in spectral and energy efficiency, there are some other potential factors that can turn this technology into a more cost-efficient solution, such as the possibility of having a single transponder model in the network (reducing installation complexity, progressive cost reduction due to mass production, etc).

Concerning the cost of different protection schemes, SP schemes are shown as considerably more cost and energy efficient than DP ones.

4. Conclusions

In this deliverable, the TREND partners (vendors, operators and universities) have focused on the energy efficiency of protection schemes. We first analyzed the energy efficiency of the most common protection schemes (DP 1+1, DP 1:1, SP) and showed the superior energy efficiency of shared protection schemes with respect to dedicated protection ones for both current fixed-grid WDM and flexible-grid networks. Despite the superior performance in energy efficiency of shared protection schemes, dedicated protection schemes (in particular DP 1+1) are still the preferred choice for operators since they are the most secure options to fulfill the SLA terms (i.e. it provides the shortest recovery times). Accordingly, great attention has been put in this IRA to propose novel protection schemes that could improve the energy efficiency without sacrificing the reliability levels provided by DP 1+1. By doing this, we can provide more realistic energy-efficient strategies that could eventually be applied by operators on their networks in the future.

As a first step towards an energy-efficient protected network, a novel protection scheme which exploits the daily traffic patterns has been proposed to reduce the energy consumption of the protection resources, while the transmission on the working paths is not modified. Consequently, the same reliability of DP 1+1 can be maintained with reduced power consumption (benefits of such an approach increase with traffic growth). Secondly, differentiated QoP schemes have been evaluated to exploit the heterogeneous protection requirements, assuming not all services and users require the high availability provided by DP 1+1. This scheme can offer energy savings with respect to the conventional DP 1+1, but the degree of these savings will depend on the protection requirements of the clients (i.e. the lower the availability requirements, the higher the savings that can be achieved).

Another strategy to improve the energy efficiency of protected networks consists on setting into sleep-mode some of the devices that are used for protection both in the WDM and IP layer. A power-aware scheme exploiting the sleep-mode functionality can allow for significant reduction on the energy consumed by the network.

Providing protection usually entails the deployment of redundant equipment, increasing the final cost of the network. Since cost is one of the main drivers for operators to adopt a new technology or technique, this matter has also been taken into account. More specifically, a cost evaluation which considers both the cost of the equipment and the energy expenses has been carried out. The results showed that SP schemes can generally offer more cost advantages compared to DP ones. Furthermore, elastic optical networks (EONs) have shown promising cost-and energy-efficiency benefits with respect to current WDM networks with any protection scheme. These outcomes may be of special interest for future network upgrades and deployments.

In summary, several approaches to improve the energy efficiency of protection schemes have been covered within this IRA. The maximum energy savings reported in this IRA are summarized in Table 6. It is worth mentioning that different network scenarios and traffic conditions have been used in some of the studies, which may have an impact on the actual power consumption savings of the energy-efficient protection strategies. Despite the promising energy efficiency improvements presented in these research activities, there are still some remaining tasks that could help improving the energy efficiency of a protected network. This includes a detailed study of the interaction between network layers to reduce the possible redundant protection and the necessity of handling protection on dynamic or adaptive routing solutions, which were not sufficiently covered within this IRA.

Publications and mobility actions performed during this IRA are listed in Section 5

Table 6. Maximum energy savings achieved by the energy-efficient protection strategies presented in IRA 3.2.

Protection Strategy	**Savings with respect to**	**Total power reduction in the network[%]**				**Comments**	**Ref.**
		EON	**SLR 40G**	**SLR 100G**	**MLR (10/40 /100)**		
DP 1:1	DP 1+1	49.31	42.22	45.91	46.69	Less reliable than DP 1+1	[1]
SP	DP 1+1	49.31	42.22	45.91	46.69	Less reliable than DP schemes Lower blocking than DP 1:1	[1]
Traffic-Aware Power-Aware	DP 1+1	18.53	6.23	12.46	11.59	Exploiting traffic variation Same reliability as DP 1+1	[3]
Diff QoP	DP 1+1	24.87	24.60	22.16	24.12	Exploiting heterogeneous protection requirements SLA terms are fulfilled	[6]
Sleep mode devices in IPoWDM	All powered -on network	-	60.00	-	-	IP over WDM Setting IP and WDM devices into a low-power sleep-mode	[2]

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5. Summary of the papers and mobility actions

5.1 Published/submitted papers

Involved partners/Collaborating Institutions	Authors	Title	Conf/journal	Date of presentation / publication
HWDU, TID	J. López Vizcaíno, Y. Ye, V. López, F. Jiménez, R. Duque, P. Krummrich,	On the Energy Efficiency of Survivable Optical Transport Networks with Flexible-grid [1]	38th European Conference and Exhibition on Optical Communication (ECOC) 2012, Amsterdam, The Netherlands	September 2012
CNIT-PoliMi, HWDU	F. Musumeci, M. Tornatore, J. López Vizcaíno, Y. Ye, A. Pattavina	Power-Aware Design of Protected IP-over-WDM Networks with Sleep-mode Devices [2]	IEEE GreenCom2012	September 2012
HWDU, TID, CNIT-PoliMi	J. López Vizcaíno, 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 [3]	Networks 2012, the 15th International Telecommunications Network Strategy and Planning Symposium, Rome, Italy	October 2012
HWDU, TID	J. López Vizcaíno, Y. Ye, V. López, F. Jiménez, R. Duque, P. Krummrich	Cost Evaluation for Flexible-Grid Optical Networks [4]	IEEE Global Telecommunications Conference (GLOBECOM) 2012 workshop on Flexible Optical Networks, Anaheim (CA), USA	December 2012
CNIT-PoliMi, HWDU	F. Musumeci, M. Tornatore, J. López Vizcaíno, Y. Ye, A. Pattavina	Energy-Efficiency of Protected IP-over-WDM Networks with Sleep-Mode Devices [5]	Journal of High Speed Networks, Vol. 19, No. 1, pp. 19-32, January 2013	January 2013
HWDU, TID, CNIT-PoliMi	J. López Vizcaíno, Y. Ye, F. Jiménez, R. Duque, F. Musumeci, M. Tornatore, A. Pattavina, P. Krummrich	Quality of protection schemes with extended flexibility for improved energy efficiency in transport networks[6]	9th International Conference on Design of Reliable Communication Networks - DRCN 2013, Budapest, Hungary	March 2013

HWDU, TID, CNIT-PoliMi	J. López Vizcaíno, Y. Ye, V. López, F. Jiménez, R. Duque, F. Musumeci, A. Pattavina, P. Krummrich	Differentiated Quality of Protection to Improve Energy Efficiency of Survivable Optical Transport Networks [7]	Optical Fiber Communication (OFC) 2013, Anaheim (CA), USA	March 2013
HWDU, TID	J. López Vizcaíno, Y. Ye, V. López, F. Jiménez, R. Duque, I. Tafur, Peter M. Krummrich	Energy Efficiency Improvement with the Innovative Flexible-grid Optical Transport Network [8]	Book chapter in Green Networking and Communications : ICT for Sustainability, Auerbach Publications, CRC Press, Taylor & Francis Group, USA, to be published in 2013	To be published
HWDU, TID, CNIT-PoliMi	J. López Vizcaíno, Y. Ye, V. López, F. Musumeci, M. Tornatore, A. Pattavina, P. Krummrich	Protection in Optical Transport Networks with fixed and flexible grid: Cost and Energy Efficiency Evaluation [9]	Submitted to Optical switching and networking Journal, SI on Optical network architecture and applications in February 2013.	
HWDU, TID	J. López Vizcaíno, Y. Ye, F. Jiménez, P. Krummrich	Energy- and Cost-Efficient Protection in Core Networks by a Differentiated Quality of Protection Scheme [10]	Submitted to European Conference on Optical Communications (ECOC) 2013 in April 2013.	

5.2 Planned papers

Involved partners	**Topic**	**Targeted conf/journal**	**Planned date**
HWDU, TID, CNIT-PoliMi, iMinds, TUB	Joint paper from IRA 3.2	Journal to be decided	2013
HWDU, TID	Evaluation of Differentiated Quality of Protection in a dynamic scenario	Conference to be decided	2013
HWDU, TID	Extended evaluation of Differentiated Quality of Protection	Journal to be decided	2013

5.3 Invited presentations at conferences

Involved partners	**Topic**		**Targeted conf/journal**	**Planned date**
HWDU	Y. Ye	Energy-Aware Protection in Optical Transport Networks	Presentation at the Asia Communications and Photonics (ACP) conference 2012, session on Energy Efficient Optical Communications and Networking	November 2012
HWDU, TID, CNIT-PoliMi, iMinds, TUB	A.Pattavina, J.Elmirghani, F.Idzikowski, F.Jiménez, J.López Vizcaíno, P.Monti, F.Musumeci, W.Van Heddeghem, Y.Ye	Energy Efficient Resilient Optical Transport Networks	Presentation at the TREND/GreenTouch Joint Workshop on Green and Energy Efficient Networking in INFOCOM 2013, Turin, Italy	April 2013
HWDU	J. López Vizcaíno	Differentiated Quality of Protection Schemes for Improved Energy Efficiency in Optical Transport Networks	Presentation at the Future Network and MobileSummit (FUNEMS) 2013 conference, workshop on Future Wired and Wireless Networks: Green, Heterogeneous and Cloud-powered	July 2013

5.4 Mobility actions

Involved partners	Person	Topic	Period
HWDU, TID	Jorge Lopez Vizcaino, Researcher at HWDU, hosted by TID	Energy Efficiency Analysis for Protection/Restoration in Optical Networks	from 07/05/2012 to 25/05/2012
HWDU, CNIT-PoliMi,	Jorge Lopez Vizcaino, Researcher at HWDU, hosted by CNIT-PoliMi	Energy Efficient Differentiated Quality of Protection	from 11/11/2012 to 23/11/2012
HWDU, TID	Jorge Lopez Vizcaino, Researcher at HWDU, hosted by TID	Energy Efficiency Analysis for Protection/Restoration in Optical Networks	from 16/05/2013 to 31/05/2013

5.5 Planned mobility actions

Involved partners	Targeted Topic	Planned period
-	-	-

6. References

[1] J. López Vizcaíno, Y. Ye, V. López, F. Jiménez, R. Duque, P. Krummrich, "On the Energy Efficiency of Survivable Optical Transport Networks with Flexible-grid," ECOC 2012- 38th European Conference and Exhibition on Optical Communication, pp. P5.05, Amsterdam, The Netherlands, September 2012.

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7. List of Acronyms

BE	Best-Effort
BPSK	Binary Phase Shift Keying
BVT	Bit-rate Variable Transponder
CAPEX	Capital Expenditures
CO-OFDM	Coherent Optical OFDM
DLP	Dedicated Link Protection
DP	Dedicated Protection
DPP	Dedicated Path Protection
DSP	Digital Signal Processing
DWDM	Dense WDM
EDFA	Erbium Doped Fiber Amplifier
EO	Electrical to Optical
EON	Elastic Optical Network
GbE	Gigabit Ethernet
ILP	Integer Linear Programming
IP	Internet Protocol
IPoWDM	IP over WDM
IRA	Integrated Research Action
ISP	Internet Service Provider
IT	Information Technology
ITU	International Telecommunication Union
ITU-T	Telecommunication Standardization Sector
MLR	Mixed line rate
NoE	Network of Excellence
OA	Optical Amplifier
OADM	Optical Add Drop Multiplexer
ODU	Optical Data Unit
ODU-Flex	ODU Flexible
OE	Optical to Electrical
OEO	Optical to Electrical to Optical
OFDM	Orthogonal Frequency Division Multiplexing
OOK	On-Off Keying
OPEX	Operational Expenditures
OTN	Optical Transport Network
OXC	Optical Cross-connect
PA	Power-Aware

PC	Power Consumption
QAM	Quadrature Amplitude Modulation
QoP	Quality of Protection
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RMLSA	Routing, Modulation Level, and Spectrum Allocation
ROADM	Reconfigurable Optical Add Drop Multiplexer
RWA	Routing and Wavelength Assignment
SLA	Service Level Agreement
SLP	Shared Link Protection
SLR	Single Line Rate
SP	Shared Protection
SPP	Shared Path Protection
TNS	Transponder Non-Sliceable
TSC	Transponder Sliceable in Capacity
TSS	Transponder Sliceable in Subcarriers
VLAN	Virtual Local Area Network
VPN	Virtual Private Network
WDM	Wavelength Division Multiplexing
WP	Work Package
WSS	Wavelength Selective Switch