Traffic and Power-Aware Protection Scheme in Elastic Optical Networks

(Invited Paper)

Jorge López*‡, Yabin Ye*, Víctor López†, Felipe Jimenez†, Raúl Duque†, Peter M. Krummrich‡,
Francesco Musumeci§, Massimo Tornatore§, Achille Pattavina§
*Huawei Technologies Duesseldorf, Riesstr. 25, 80992 Munich, Germany
†Telefónica I+D, c/ Don Ramón de la Cruz 84, 28006 Madrid, Spain
‡TU Dortmund, High Frequency Institute, Friedrich-Wohler-Weg 4, 44227 Dortmund, Germany
§CNIT, Italy and Dept. of Electronics and Information, Politecnico di Milano, via Ponzio 34/5, 20131, Milan, Italy
E-mail: *jorge.vizcaino; yeyabin@huawei.com; †vlopez; felipej; e.pt1@tid.es; ‡peter.krummrich@tu-dortmund.de;
§fmusumeci; tornator; pattavina@elet.polimi.it

***Abstract*—Currently, the need for "greener" telecommunication networks is stimulating research efforts to find new solutions to cope with power consumption and sustainability issues. Exploiting the potential of optical Wavelength Division Multiplexed (WDM) networks for this purpose has been identified as an attractive approach. However, the traditional WDM fixed-grid, where 50 GHz-spaced optical carriers are used with Single Line Rates (SLR), may result in lower efficiency from both the spectral occupation and power consumption perspectives. Higher flexibility can be provided by adopting Mixed Line Rates (MLR) and, especially, the so-called Elastic Optical Network (EON) paradigm, which is enabled by the Orthogonal Frequency Division Multiplexing combined with Coherent Detection (CO-OFDM). In this scenario a finer channel spacing is considered so the spectrum can be best fitted to actual traffic needs. Another critical issue is the network robustness to failures, accomplished by reserving additional resources as a backup for *protection*. 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 paper, 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 SLR, MLR and 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.**

***Index Terms*—Elastic Optical Network; Protection; Traffic fluctuation; Energy efficiency.**

I. INTRODUCTION

The deep penetration of Information and Communication Technology (ICT) services, such as Video on Demand (VoD), high-definition Internet Protocol (IP) TV and teleconferencing, in everyday life is leading telecommunication networks operators to substantially increase network capacity and look for new solutions to efficiently exploit resources and to cope with this traffic growth. It is envisioned [1] that the Internet traffic increase will be around 40% in the coming years, corresponding to a growth factor of 1000 in approximately 20 years. Correspondingly, an increase in the power consumption of the Internet will be experienced so that power requirements will represent one of the major constraints when performing network design and operation. Therefore, new power efficient solutions need to be investigated in order to jointly reduce the impact of network Operational Expenditures (OpEx), mainly affected by the power requirements, and Capital Expenditures (CapEx), i.e., network devices.

In this scenario, optical technology exploiting the Wavelength Division Multiplexing (WDM) technique is commonly recognized as an efficient solution to reduce power consumption within the network. However, in the conventional optical transport based on a fixed frequency grid the typical optical carriers spacing is 50 GHz, as standardized by International Telecommunication Union (ITU) [2], and operates with a single line rate (SLR). This dictates a rigid spectrum allocation scheme for the provisioning of new traffic demands and may lead to inefficient use of spectral resources, since low capacity demands need to be served by an entire WDM channel. Several alternatives have been proposed to address this issue. One example is the adoption of mixed line rate (MLR) in WDM networks, where using transponders operating at different line rates (e.g., 10, 40 and 100 Gbit/s) provides higher flexibility to manage heterogeneous traffic demands. This solution has also been demonstrated to be efficient from the power consumption perspective [3]. Furthermore, additional flexibility can be obtained by adopting finer channel spacing and introducing elastic bandwidth provisioning by allocating a variable number of lower bit-rate subcarriers, according to the actual demands requirement. The optical Orthogonal Frequency Division Multiplexing (OFDM) technique, combined with coherent detection (CO-OFDM) and the possibility of exploiting multiple modulation formats for the different subcarriers are two powerful technologies which make the Elastic Optical Network (EON) a promising solution for future networks from both the cost and power consumption point of view, so that it is currently being studied by ITU committees

978-1-4673-1391-9/12/$31.00

for standardization. In the EON context, when establishing traffic demands, rather than the classical Routing and Wavelength Assignment (RWA) done in WDM networks, a more complex Routing, Modulation Level and Spectrum Allocation (RMLSA) is performed. In the literature, the EON paradigm is also referred to as Spectrum-sLICed Elastic optical path network (SLICE) [4] and its strength in terms of energy efficiency has been investigated and compared to SLR and MLR WDM networks in [5].

Another critical issue from the service-provider point of view is the fault tolerance, as a single point of failure, e.g., in a network link, may cause the drop of several already established demands, with negative impact on the Quality of Service (QoS) offered to the end-user. Thus, Telco operators, besides the principal resources allocated along the so-called *working* path, reserve some redundant resources over a secondary route, called *protection* (or, alternatively, *backup*) path.

Even though many innovative protection schemes have been proposed so far, the traditional dedicated 1+1 protection scheme is still the most widely used as it guarantees high resilience and high availability (i.e., short recovery time), but it is also the least energy efficient. Indeed, it consists of a simultaneous signal transmission over both working and protection paths, therefore the actual power consumption is substantially increased compared to the case without protection.

In this paper we adopt a different approach, taking advantage of the daily dynamic traffic fluctuations 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. We will focus 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 in power consumption while maintaining, at the same time, a high level of availability.

Only a very limited set of papers in the literature has dealt with power-aware protection schemes and to the best of our knowledge this issue has never been addressed within the MLR and EON contexts. In [6] a power-aware SLR WDM network design with dedicated protection is provided through an integer linear program (ILP) formulation. In such context, the opportunity for power saving is provided by the possibility of switching backup resources into a low-power stand-by mode. Moreover, this issue is extended in [7] where the authors propose a faster heuristic to solve the same problem. Power consumption minimization in the case of shared protection is studied in [8]. Finally, authors of [9] investigate the energy efficiency of traffic grooming in protected IP-over-WDM networks, combined with the possibility of sleep-mode operation for dedicated backup resources.

In this paper, we evaluate the benefits in terms of power consumption of a traffic-aware dedicated 1+1 protection approach where realistic hourly traffic fluctuations are considered to reduce the power consumed by backup resources. Thus, power savings can be obtained by dynamically adapting the bandwidth reserved for protection. This approach is applied to the elastic OFDM-based scenario and to the conventional WDM one, operating in both MLR and SLR cases, and is compared to the traditional 1+1 protection scheme which does not take traffic variations into account. We find that the proposed protection scheme can be significantly beneficial for the elastic network paradigm thanks to its fine granularity and high flexibility provided by the elastic bandwidth provisioning and by the modulation format selection. We show that relevant energy savings are obtained, especially in the EON case and for high traffic load conditions, where 27% of energy can be saved with respect to the conventional 1+1 dedicated protection scheme by exploiting the information on hourly traffic fluctuations.

The remainder of this paper is organized as follows. In Section II the features of the network model will be described in detail for the cases of SLR and MLR WDM networks and for the elastic OFDM scenario. The power consumption values of the various networks elements are discussed in Section III, whereas in Section IV we describe the algorithms used to carry out the RWA and RMLSA in the WDM and elastic OFDM cases, respectively. The simulation results are shown and discussed in Section V, and in Section VI we draw the concluding remarks of the paper.

II. NETWORK MODEL

A. WDM Network

In the WDM network case we consider a 4 THz wide spectrum containing 80 wavelengths (i.e., optical carriers) with channel spacing of 50 GHz. Three different line rates have been assumed, that is, 10, 40 and 100 Gbit/s, with modulation formats Non-Return to Zero with On-Off Keying (NRZ-OOK), Differential Quadrature Phase Shift Keying (DQPSK) and Polarization-Division Multiplexed with Quadrature Phase-Shift Keying and coherent detection (PDM-QPSK), respectively. Such modulation formats provide different maximum transparent reach[1] for the three line rates, i.e., 3200 km (10 Gbit/s), 2200 km (40 Gbit/s), and 1880 km (100 Gbit/s) [10].

Two types of operation are considered: SLR with 10, 40 or 100 Gbit/s transmitters/receivers and MLR with 10, 40, and 100 Gbit/s simultaneously deployed in the network. In this latter approach, the overall spectrum is divided into two wavebands, separated by a guard band of 200 GHz, in order to minimize the cross-talk effect between adjacent channels of different technologies: the first one is used for 10 Gbit/s channels and the second one is exploited for both 40 and 100 Gbit/s channels.

B. Elastic Optical Network

In this case we assume that the 4 THz wide spectrum contains 320 frequency slots (FS) with a width of 12.5 GHz each. We also assume that each subcarrier can be used by exploiting different modulation formats, i.e., Binary Phase Shift Keying (BPSK), Quadrature-PSK (QPSK) and

---

[1] The transparent reach is the maximum distance that can be traveled by an optical signal, with an acceptable quality level at the receiver, with no need for signal regeneration.

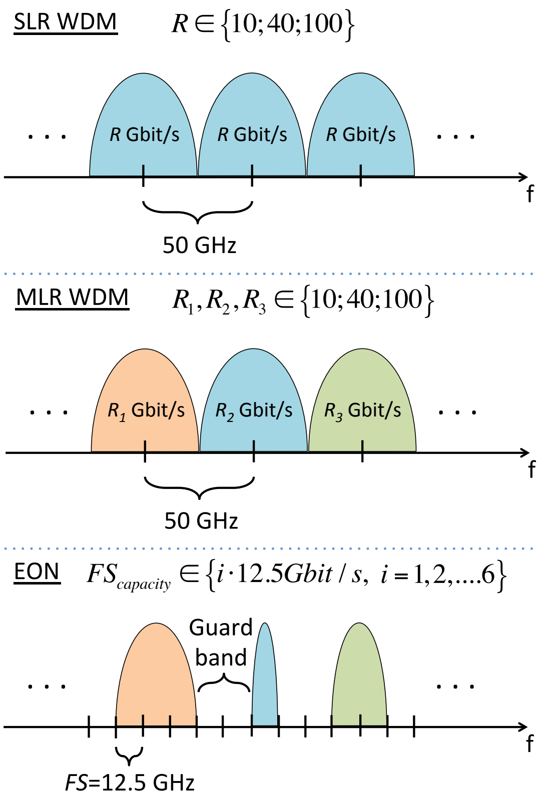


Fig. 1. Example of resource allocation in SLR and MLR WDM and in the EON scenarios.

M-ary Quadrature Amplitude Modulation (M-QAM), where M=8, 16, 32 or 64 symbols can be used. Each of these modulation formats provides a different spectral efficiency (bit/Hz), therefore, the transmission rate of a single subcarrier at 12.5 GHz can be 12.5, 25, 37.5, 50, 62.5 and 75 Gbit/s for BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM, and 64-QAM respectively. Several subcarriers can be combined to create super-channels with higher transmission rate. Note that a guard band consisting of two subcarriers (25 GHz total) is assumed to separate adjacent channels. The maximum transparent reach of each subcarrier is considered dependent on the actual modulation format it uses. Specifically, it is equal to 4000, 2000, 1000, 500, 250 and 125 km for BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM, and 64-QAM respectively [5].

The different spectral requirements of the SLR and MLR WDM and of the EON scenarios are summarized in Fig. 1, where we show how the spectral resources are allocated in the three different scenarios.

III. POWER CONSUMPTION OF NETWORK ELEMENTS

Several components contribute to the overall network power consumption. In this paper we consider the contributions of the devices used in the optical layer, i.e., *Transponders*, *Reconfigurable Optical ADD-DROP Multiplexer / Optical Cross Connects* (*ROADMs/OXCs*) and *Optical Amplifiers* (*OAs*).

- *Transponders*. The power consumption of the devices used in the traditional WDM scenarios (both SLR and MLR) is assumed to be 34, 98 and 351 W for transponders operating at 10, 40 and 100 Gbit/s, respectively [11].

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

Modulation Format	Subcarrier capacity [Gbit/s]	Transparent reach [km]	Power consumption [W]
BPSK	12.5	4000	112.374
QPSK	25	2000	133.416
8-QAM	37.5	1000	154.457
16-QAM	50	500	175.498
32-QAM	62.5	250	196.539
64-QAM	75	125	217.581

  Due to the commercial unavailability of CO-OFDM transponders, some assumptions have been made to estimate realistic values of power consumption for the elastic OFDM transponders. The requirement for Digital Signal Processing (DSP) at the transmitter side is assumed to be the main distinction between a CO-OFDM transponder and a traditional WDM one, therefore the comparison could be based on the DSP complexity. This complexity is assumed similar for both types of transponders and only depends on the transponder bit rate. Based on the values in [11] for the dual polarization coherent transponders of 250 and 351 W for 40 and 100 Gbit/s, respectively (125 and 175.5 W for single polarization), 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, as shown in eq. 1, where the power consumption of the CO-OFDM transponder (PC_{OFDM}), expressed in Watts, depends on the transmission rate (TR, in Gbit/s) of the transponder itself.

  $$PC_{OFDM} = 1.683 \cdot TR + 91.333 \text{ [W]} \tag{1}$$

  Table I shows the power consumption values of the CO-OFDM transponder according to the different modulation formats. An additional 20% of consumption has been considered as an overhead contribution in each case.

- *ROADMs/OXCs*. The power consumption of flexible-grid OXC has been assumed to be equal to the one of the fixed-grid OXC (PC_{OXC}). We consider OXCs with 80 channels. Their power consumption depends on the node degree N (i.e., the number of fibers connected to the node) and the add/drop degree α (i.e., the number of channels which can be added or dropped locally) on the line of [11], where an overhead consumption of 150 W is assumed, as shown in eq. 2.

  $$PC_{OXC} = N \cdot 85 + \alpha \cdot 100 + 150 \text{ [W]} \tag{2}$$

- *Optical Amplifiers (OAs)*. The OAs which have been considered for both the WDM and EON scenarios are the Erbium Doped Fiber Amplifiers (EDFAs). Such OAs are typically placed within an optical fiber link every 80 km (one EDFA for each fiber direction). A single EDFA module consumes 30 W and an additional 140 W of power per amplifier location is also considered for power supply, fan unit etc. [11].

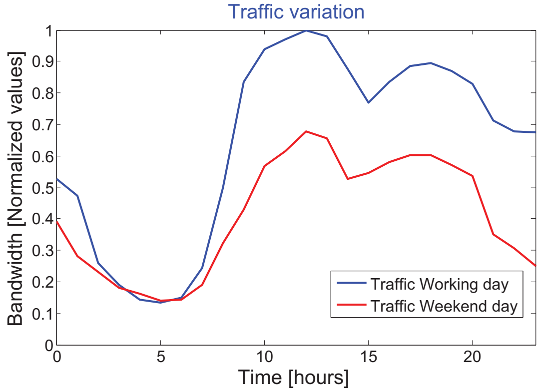


Fig. 2. Typical hourly traffic variation in working and weekend days.

IV. TRAFFIC AND POWER-AWARE ROUTING AND RESOURCE ALLOCATION FOR PROTECTED NETWORKS

In this section we show how the power-aware routing and resource allocation is performed to accommodate protected traffic demands in the WDM and EON scenarios, by also taking into account the hourly traffic fluctuations occurring during the day.

The main idea consists of adapting the rate of the transponders in the protection paths to the current traffic load of the network on a hourly basis in order to have lower consumption due to backup resources while still maintaining high reliability. Indeed, the bandwidth required by the demands varies substantially within the day. For instance, during off-peak hours (typically at night), it is only a small percentage with respect to the maximum value, as shown in Fig. 2, where we draw the typical traffic fluctuations (normalized to unity) for both working and weekend days, corresponding to the Spanish network topology used in our study and within the framework of the *TREND* Network of Exellence. Thus, in order to reduce network power consumption while still maintaining high resilience against failures, we adapt the rate of backup transponders to the actual hourly traffic requirements.

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 EON) is accomplished in a power-aware fashion, according to the peak-rate traffic value for both the working and the link-disjoint protection path, and the transmission is considered to be simultaneously active (1+1 protection).

To do so, for every demand to be accommodated, we evaluate the greener resources allocation for both working and protection paths, i.e., RWA (in WDM network with SLR and MLR) or RMLSA (for the EON case). Note that in the WDM and EON scenarios, we need to take into account the wavelength continuity constraint and spectrum continuity and contiguity constraints, respectively, i.e.: i) in the WDM case, the wavelength(s) used to accommodate each demand must be used in all the links belonging to the end-to-end path of the demand; ii) in the EON case, the subcarriers used for a demand are contiguous (adjacent) in spectrum and are fixed in every link of the path. Moreover, for each demand, in the working and protection paths, the spectral resources are treated separately, i.e., there is no constraint on using the same wavelengths (WDM) or subcarriers (EON) in the working and protection path. See [5] for further details on RWA and RMLSA new lightpath establishment algorithms.

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 OXCs, OAs working and backup transponders contributions (PC_{OXC}, PC_{OA}, PC_{TW} and PC_{TB}, respectively), it is assumed that the transmission in the working path will remain fully active (i.e., at the peak-rate value). On the other hand, in 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.

As an example of how the transponders rate is adapted to the actual hourly traffic requirement to save power, assume that a certain demand between two nodes, at a 350 km distance (so the maximum allowable modulation format is 16-QAM), requires a maximum rate of 135 Gbit/s. The working path will be configured in a way (subcarriers, modulation format etc.) that this capacity is always ensured. If, as in Fig. 2, the peak occurs at 12 PM, enough spectral resources will be assigned and reserved in working and protection paths to support this peak-rate value. Moreover, at a certain hour of the day, say 5 AM, the traffic is considerably lower than the peak traffic demand ($\sim$13% of the maximum peak value according to the diagram in Fig. 2), so the transmission in the protection path can be adapted in order to transmit only 17.6 Gbit/s. In this example, depending on the network scenario, different power savings can be obtained with respect to the conventional 1+1 protection scheme where backup resources are maintained active at the peak-rate, as shown in Tab. II.

Note that in the MLR WDM network case the transponders for the protection path are already deployed in the network and the only possibility to reduce power consumption is to turn off those which are not needed, but we can not assign different line rates. The fixed transponder allocation for the protection path

TABLE II
EXAMPLE OF POWER SAVINGS OBTAINED AT OFF-PEAK HOUR (5 AM) FOR BACKUP TRANSPONDERS (PC_{TB}) IN THE CONVENTIONAL AND THE TRAFFIC-AWARE PROTECTION SCHEMES (SINGLE TRAFFIC DEMAND).

Network scenario	Conventional protection scheme (135 Gbit/s)		Traffic-aware protection scheme (17.6 Gbit/s)	
	Backup resources (transponders/subcarriers)	$PC_{TB}(conventional)$	Backup resources (transponders/subcarriers)	$PC_{TB}(traffic-aware)$
10G SLR	14 @10G	$14 \cdot 34$ =476W	2 @10G	$2 \cdot 34$ = 68W
40G SLR	4 @40G	$4 \cdot 98$ =392W	1 @40G	98W
100G SLR	2 @100G	$2 \cdot 351$ =702W	1 @100G	351W
10-40-100 MLR	1 @100G +1 @40G	351+98 =449W	1 @40G	98W
EON	3 @50G (16-QAM)	$3 \cdot 175.498$ =526.495W	1 @25G (QPSK)	133.416W

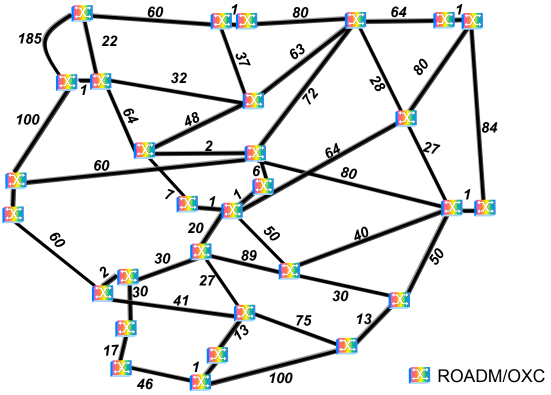


Fig. 3. *Telefónica* Spanish core network topology.

is gathered by the resource reservation carried out according to the peak value (STEP 1 in Alg. 1), so it is possible to turn off only some of the already deployed transponders. Moreover, in the EON scenario, software-defined transponders are used, and it is assumed that they can adapt the transmission rate to the actual bandwidth requirement by varying the number of subcarriers and/or the modulation format.

V. SIMULATION RESULTS

A. Case Study

An application for the traffic and power-aware protection scheme described in Algorithm 1 has been tested for the *Telefónica* Spanish core network model used in *TREND*, consisting of 30 nodes and 96 single-fiber bidirectional links, shown in Fig. 3, where link lengths (in km) are also shown. In the network, no regeneration sites have been considered, i.e., when assigning the working and protection routes to the demands, only the feasible paths are taken into account, according to the bit rate and modulation formats under consideration and the corresponding maximum transparent reaches as previously described. We consider a realistic traffic matrix with total traffic of 3.22 Tbit/s which has been scaled by a factor f ranging from 1 to 10 to obtain different load conditions, up to an overall traffic of 32.2 Tbit/s.

B. Discussion

In Fig. 4 we show the power consumption values obtained at peak-rate hour in the different network scenarios during a working day. These values correspond to those obtained *constantly* during the day if using the conventional 1+1 dedicated protection and without considering the real-life traffic fluctuations for transponders rate adaptation in the protection paths. Note that in the figure we only show the power consumption results under non-blocking conditions, i.e., only for those cases where all the demands are supported by the network. For instance, for the SLR 10G and 40G, the results are only shown for the basic traffic matrix and up to a traffic matrix scaling factor of 4, respectively. As expected, this shows that exploiting higher bit rates transponders, thanks to the possibility of higher modulation formats, may enable the network to support much higher traffic.

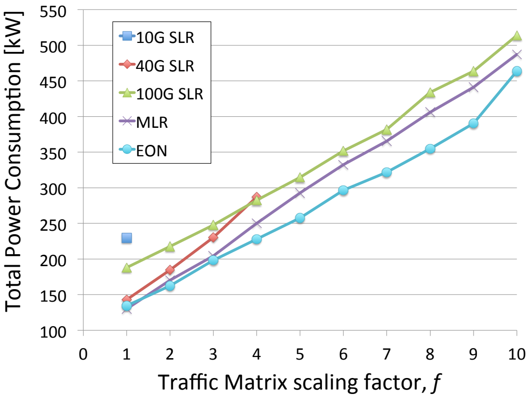
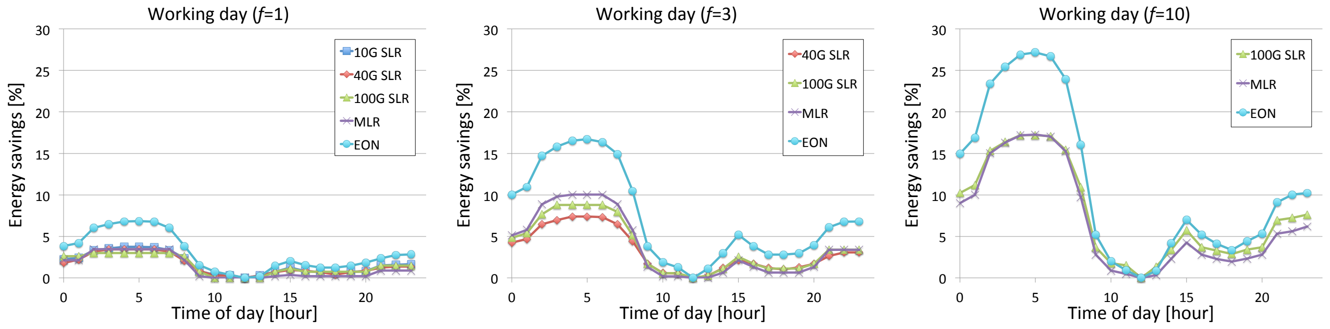


Fig. 4. Total power consumption with conventional dedicated 1+1 protection for the different network approaches and traffic matrix scaling factors f (working day).

It results evidently from Fig. 4 that, even during peak hours, in the EON (and, for lower traffic values, also in the WDM MLR) scenario, substantial power savings can be obtained, especially with respect to the SLR WDM cases, thanks to the flexibility provided by the fine bit-rate subcarriers.

In Fig. 5 we show the percentage of energy savings obtained in comparison to the conventional 1+1 protection 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 Fig. 5(a) and the 40G SLR is only shown in Figs. 5(a) and 5(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, refer to Fig. 2 for the traffic behaviour), when up to 27% of savings can be obtained



(a)
(b)
(c)

Fig. 5. Energy savings (%), with respect to conventional 1+1 protection 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) $f = 10$.

at high load conditions ($f = 10$). This is due to its efficient adaptability to different traffic conditions, i.e., through the bandwidth expansion/contraction and the modulation format variation.

At low traffic loads ($f = 1$), the energy savings are low, due to the limited traffic fluctuations. Thus, the 10G SLR WDM scenario benefits from the fine granularities to save energy, as in this case it is sufficient to turn-off the unused transponders along the protection paths. On the other hand, the 40G and 100G SLR and the MLR scenarios provide very low savings, since in the dimensioning performed according to peak-rate traffic high bit-rate transponders are allocated, thus during off-peak hours many light-loaded backup transponders need to be maintained active to guarantee network resilience.

As the traffic load increases, the average savings for the different technologies considerably increase because of a higher traffic fluctuation, i.e., the difference between the high and low traffic load conditions becomes more significant. Moreover, the flexibility provided by MLR and especially EON scenarios in selecting the actually required resources allows higher energy savings.

For very high traffic load ($f = 10$), the overall energy savings become significant even for the 100G SLR WDM network, which in general outperforms the MLR network scenario, but the energy benefits obtained in the EON case provide the best performance compared to all the other technology and traffic scenarios, confirming that it is a promising solution not only from the resource utilization, but also (especially) from the power consumption point of view.

VI. CONCLUSION

In this paper we have studied the energy efficiency of protected optical core networks by considering the traffic variation occurring during the day. Protection is traditionally accomplished by allocating dedicated (1+1) resources which are maintained active independently on the actual traffic requirements of the network, thus "unnecessary" power is consumed. Therefore, we exploit the information on traffic fluctuations to hourly adapt the rate of the backup transponders to the actual bandwidth requirements. We apply this protection scheme to WDM single line rate and mixed line rate networks 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 up to 27% of energy can be saved.

ACKNOWLEDGMENT

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n. 257740 (Network of Excellence "TREND"). The authors would also like to acknowledge the valuable datasheet on network elements power consumption from the GreenTouch consortium.

REFERENCES

[1] A. Saleh and J. Simmons, "Technology and architecture to enable the explosive growth of the Internet," *IEEE Communications Magazine, IEEE*, vol. 49, no. 1, pp. 126–132, Jan. 2011.

[2] "Spectral grids for WDM applications: DWDM frequency grid," ITU-T Recommendation G.694.1, available at http://www.itu.int.

[3] P. Chowdhury, M. Tornatore, A. Nag, E. Ip, T. Wang, and B. Mukherjee, "On the Design of Energy-Efficient Mixed-Line-Rate (MLR) Optical Networks," *Journal of Lightwave Technology*, vol. 30, no. 1, pp. 130–139, Jan. 2012.

[4] 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 gb/s to over 400 gb/s," in *European Conference on Optical Communication (ECOC)*, Bruxelles, Belgium, Sep. 2008, pp. 1–2.

[5] J. L. Vizcano, Y. Ye, and I. T. Monroy, "Energy efficiency analysis for flexible-grid OFDM-based optical networks," *Computer Networks*, vol. 56, pp. 2400–2419, July 2012.

[6] A. Muhammad, P. Monti, I. Cerutti, L. Wosinska, P. Castoldi, and A. Tzanakaki, "Energy-Efficient WDM Network Planning with Dedicated Protection Resources in Sleep Mode," in *IEEE Global Telecommunications Conference (GLOBECOM)*, Miami, FL-USA, Dec. 2010, pp. 1–5.

[7] P. Monti, A. Muhammad, I. Cerutti, C. Cavdar, L. Wosinska, P. Castoldi, and A. Tzanakaki, "Energy-Efficient Lightpath Provisioning in a Static WDM Network with Dedicated Path Protection," in *IEEE International Conference on Transparent Optical Networks (ICTON)*, Stockholm, Sweden, June 2011, pp. 1–5.

[8] C. Cavdar, F. Buzluca, and L. Wosinska, "Energy-Efficient Design of Survivable WDM Networks with Shared Backup," in *IEEE Global Telecommunications Conference (GLOBECOM)*, Miami, FL-USA, Dec. 2010, pp. 1–5.

[9] F. Musumeci, M. Tornatore, J. Vizcaino, Y. Ye, and A. Pattavina, "Power-aware design of protected IP-over-WDM networks with sleep-mode devices," in *IEEE Online Conference on Green Communications (GreenCom)*, Sep. 2012.

[10] A. Klekamp, U. Gebhard, and F. Ilchmann, "Efficiency of adaptive and mixed-line-rate IP over DWDM networks regarding CAPEX and power consumption," in *Conference on Optical Fiber Communication (OFC)*, Los Angeles, CA, USA, Mar. 2012.

[11] C. Dorize, W. Van Heddeghem, F. Smyth, E. Le Rouzic, and B. Arzur, "Greentouch draft report on baseline power consumption, version 1.8," Nov. 2011.