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Energy efficiency of elastic frequency grids in multilayer IP/MPLS-over-flexgrid networks

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ABSTRACT

Flexgrid Optical Networks provide higher spectrum efficiency and flexibility in comparison to traditional wavelength switched optical networks (WSON) due to the finer granularity in managing communication channels at the WDM layer, thus allowing beyond 100 Gbps transmission capabilities. They also promise allocating part of the traffic aggregation function to the optical layer, thus reducing the use of energy-hungry electronic devices. Accordingly, in this work, we analyzed these architectures from the power consumption perspective by evaluating the energy efficiency derived from introducing the Flexgrid technology in order to allow the shift of grooming and bandwidth aggregation functions at the optical layer, by envisioning a next generation of IP/MPLS-over-flexgrid transport architectures.

1. Introduction

Optical infrastructures are the silver bullet in modern wide area communication arena. In a few decades optical transport technologies evolved from low speed PDH to SDH and WDM, up to 100 Gbps or 1 Tbps OTN solutions, also bringing an increasing degree of automation in network management and bandwidth resources provisioning. However, energy costs account for an important and ever-increasing part of the operational costs (OPEX) in today's transport networks. Consequently, energy efficiency has become a major concern for network operators (Hou et al., 2013). In multilayer IP/MPLS-over-Wavelength-Switched Optical Networks, power consumption is associated with electronic processing, and hence, great research attention is focused on the costly, power-consuming IP/MPLS nodes (Aleksić, 2009). In WSONs, low bit rate demands, e.g., 1 Gbps or 2.5 Gbps are groomed together by exploiting the full wavelength capacity. However, there is large consensus that the optical transmission speeds will far exceed the 100 Gbps over the next decade, reaching bit-rates of several Tbps (Tkach, 2010). Indeed, operators will have to satisfy higher bit-rate demands, for example, ranging from 40 Gbps to 400 Gbps. In this scenario, highly flexible, spectrum efficient flexgrid optical networks, supporting an elastic behavior in the provisioning of transmission channels over the available optical resources, are attracting an increasing interest due to the technological maturity of the devices enabling their development (Jinno et al., 2009, 2010). These networks essentially relax the fixed grid-space constraint (usually 50 GHz according to G.694.1) in WDM connections, allowing the partitioning of the available optical spectrum into combinable frequency slots (sub-carriers) of smaller fixed width (e.g., 25 GHz, 12.5 GHz or even 6.25 GHz) in order to provide an improved control granularity at the wavelength management layer. The spectrum in each slot is occupied symmetrically around a central frequency, and often two guard bands on both the sides are used to separate the spectra in adjacent sub-carriers associated to different connections. In such a way, multiple slots may fit into a single wavelength space, each characterized by a different symbol-rate, modulation format, Forward Error Correction code and spectrum width, depending on the bit rate of the signal to be transmitted and the distance to be covered by the optical signal. Analogously, it is possible to pack multiple adjacent slots in order to create arbitrary sized channels (superchannels) managed/operated as single entity, eventually spanning multiple wavelengths in the entire C-band, by allowing beyond 100 Gbps transmission. In other words, since the optical channel width is no more rigidly defined, for each connection request it can be perfectly tailored to the actual width of the transmitted signal, by combining multiple optical carriers in order to create a channel of desired capacity and minimize transmission capacity waste. The fundamental components characterizing modern flexgrid architectures arebandwidth-variable transponders (BV-T) and bandwidth-variable wavelength selective switches (BV-WSS), providing the fundamental functions of bandwidth-variable wavelength cross-connects (BV-WXCs). The

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former devices adapt the signal to be transmitted or received through the optical network on a flexibly allocated channel characterized by specific connection parameters (modulation, etc.) and enough available spectrum width. On the other hand, the BV-WSSs provide elastic spectrum allocation, typically based on broadcast-and-select arrangements into BV-WXCs architectures that in turn allow the establishment of optical paths throughout the network by switching the transmitted input signals within their frequency bandwidth to the appropriate output ports. Once the needed frequencies are reserved on each physical link on the optical path, the connection can be used for transporting single-carrier (k-PSK, k-QAM) or multi-carrier (O-OFDM) modulated signals. When flexgrid is used in multilayer networks, the clear picture of IP/MPLS for aggregation and optical layer for transport is distorted since an important part of the aggregation function is shifted onto the optical layer, thereby leading to a reduction in the power consumed at the IP/MPLS layer. At the same time, however, additional functionalities required in flexgrids such as digital signal processing (DSP) in BV-Ts and enhanced control of BV-WSS capabilities in BV-OXCs, might also increase power consumption at the optical layer. To the best of our knowledge, no figures of power consumption for BV-OXC integrating BV-WSSs or IP/MPLS nodes enhanced with BV-Ts are currently available in the literature. Thus, in this work we explored a new dimension in optical flexgrid architectures by evaluating the power consumption savings that can be achieved from the shift of part of the grooming operations from the IP/MPLS to the optical layer. For this purpose we developed a novel energy model, explicitly considering the power consumption of each fundamental component characterizing flexgrid networks, and formulated a specific optimization problem that has been solved in an heuristic way by using a greedy randomized adaptive search procedure (GRASP) (Resende and Ribeiro, 2011) for effectively exploring the solution space. According to our experimental analysis performed through simulation on different real world carrier topologies, significant energy savings should be directly originated from the additional flexibility and elastic behavior provided by flexgrid technology. Such a reduction in overall power demand represents the upper bound for the affordable increments at the optical layer in the future IP/MPLS-over-flexgrid networks.

2. Related work

The energy efficiency of WDM networks has been an "hot" research topic in the last years (Ricciardi et al., 2013), and the analysis of the effects introduced by new flexgrid architectures on the energy consumption of next generation transport networks is recently emerging as a really interesting matter of investigation. The effects of bandwidth allocation on power consumption in fixed-grid and flex-grid networks have been studied in Palkopoulou et al. (2012) showing how the improved efficiency introduced by flexible spectrum management balances the additional expenses that are necessary for migrating to a flexgrid architecture. Also in Angelou et al. (2012), it has been clearly reported that a more efficient spectrum usage together with a finer bit-rate granularity are fundamental prerequisites for achieving both cost and energy efficiency. A further analysis of energy efficiency in optical transport networks, comparing new OFDM-based flexgrid architectures with traditional fixed-grid WDM ones, in the presence of Single and with a Mixed Line Rate operations has been presented in Vizcaíno et al. (2012). The experience presented in Lopez Vizcaino et al. (2012) focuses on energy efficiency of flexgrid networks in the presence of survivability constraints, by comparing dedicated-protection schemes with shared-protection ones. In addition, the work presented in Khodakarami et al. (2014) explores the effects of elastic spectrum allocation, adaptive modulation and traffic grooming, by formulating both an ILP-based minimization problem and an heuristic solution with the goal of minimizing the total energy required. A specific network planning and operation tool, known as Mantis (Soumplis et al., 2014), has been used to analyze the energy efficiency of fixed and mixed line rates next-generation flexgrid networks. Finally, in Papanikolaou et al. (2015) the fundamental causes of energy consumption in future flex-grid networks, have been identified, by proposing and comparing several energy containment techniques.

Instead, in this work we investigated an alternate dimension in flexgrid architectures by explicitly focusing on the energy savings that can be achieved by shifting, as possible, the grooming operations from the electric to the optical layer.

3. Energy demand optimization on multilayer IP/MPLS-over-flexgrid

Given a set of connection demands deployed as multiple groomed LSPs onto an available IP-MPLS over optical network topology (based on a traditional fixed grid architecture) we aim at transposing them at the optical spectrum assignment layer by activating the flexgrid functionality and hence leveraging multilayer IP/MPLS-over-flexgrid network capabilities in order to reduce transmission capacity waste, and simultaneously minimize the operational costs associated to the devices' energy consumption. To do this, we at first need to clearly state the specific optimization problem we are faced with, by formally defining the network model on which our optimization approach operates. Such model, based on a network topology abstraction in which a connection demand matrix defines the end-to-end traffic volumes exchanged between each pair of nodes, specifies the basic energy requirements of each involved network device by considering both electrical and optical technologies, and differentiates the consumption according to the various equipment flavors, communication links and spectrum slices available on them, as well as current traffic load. It also formally defines the optimization objectives and the specific constraints characterizing the above problem. More precisely, given the following prerequisites:

- a physical network topology represented by a graph $G(N, L)$, being N the set of locations and L the set of fiber links (u, v), with $u, v \in N$, connecting two locations;
- a set S of available slots of a given spectral width for each link (u, v) in L;
- a set $D = \{(s_1, d_1), \ldots, (s_{|D|}, d_{|D|})$ (with $s_i, d_j \in N \times N \forall i, j$) of IP/MPLS connection demands, implemented through label switched paths (LSP), to be transported end-to-end on the WSON;
- the virtual (logical) network topology, represented by a graph $G_v(N_v, E)$, being N_v the subset of locations where IP/MPLS nodes terminating the connections in D are placed and E the set of virtual links (lightpaths established over the flexgrid optical layer) realizing the optical connectivity among these IP/MPLS nodes;
- the operational energy cost for every type of IP/MPLS node and BV-T available on the flexgrid network. These costs are characterized by a fixed component depending on the specific device features (mainly related to its energy efficiency) and a variable cost that grows proportionally with the number of individual connections (LSPs) traversing them, together with their transmission capacity and modulation type;
- the operational energy cost of the involved BV-OXC nodes, which include a fixed component for the base system (also depending on its architecture and energy efficiency), and a variable one that is function of both its nodal degree (the number of aggregated input/output fiber strands) and number of optical sub-carriers involved;

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- the operational energy cost associated to optical amplification devices to be deployed in the fiber links, depending on the type of amplification technology used, and growing with the length of the fiber strand and with the frequencies associated to the transported channels;

We need to determine the optimal configuration parameters of the optical devices within the flexgrid (BV-Ts and BV-WXC), in terms of channel spacing (slot width)/number of channels, modulation and bit-rate necessary for transporting the complete set of connection demands D over the virtual topology $G_v(N_v, E)$, by minimizing the total energy cost associated to network operations over time.

The above problem, concerns network planning in the presence of routing and spectrum allocation (RSA) constraints where a contiguous fraction of frequency spectrum has to be assigned to connection requests (spectrum contiguity) to be routed on the virtual topology Gv(Nv, E) with no frequency overlapping on physical fiber links. It is known to be NP-hard (Klinkowski and Walkowiak, 2011; Christodoulopoulos et al., 2010; Wang et al., 2011) and more complex than the traditional routing and wavelength assignment (RWA) problem due to the existence of the additional contiguity constraint in spectrum allocation. For this reason, its exact solution becomes impractical when real-sized network and traffic instances are considered. Hence, for solving it we use a GRASP-based heuristic algorithm formulated according to the schema presented in Castro et al. (2012) and Pedrola et al., 2012, where the operational costs of the different flexgrid network components have been determined according to a properly crafted power consumption model. The GRASP heuristic framework has been chosen since it provides, also in the case of very complex models to be solved, an excellent trade-off between optimality and computation time by ensuring rapid convergence to high quality solutions through a thorough exploration of the solutions space. In fact it has been used to cope with a wide range of complex optimization problems in communication networks (Höller et al., 2008; Pedrola et al., 2013; Palmieri et al., 2010; Resende and Ribeiro, 2003).

4. Power consumption model

In most of the flexgrid-specific network devices such as BV-Ts and BV-WSS/BV-OXC the fundamental part of power demand is associated to the electronic processing activities performed by the internal ASIC and/or FPGA components, mainly belonging to the framing, Forward Error Correction, codec and DSP units. However, not all these components are characterized by a power consumption that depends on the actual data rate. For example, according to the results presented in Vacondio et al. (2013) the power drained is strongly dependent by the symbol-rate but is almost unaffected by the modulation used (Morea et al., 2013). Anyway, as in energy models used in traditional WSONs, we can model the power demand as the linear combination of a static and a dynamic component, where the static one, accounting for about the 50% of the total power, is associated to both the logical electronic levels and to the various leakage currents. The dynamic component is strongly depending on the operating frequency and hence is directly proportional to the square of the voltage and to the clock frequency. Let us consider the generic WSON architecture consisting of several IP/MPLS nodes located on the network edge coupled with some BV-OXCs giving them access to the optical core, as illustrated in Fig. 1.

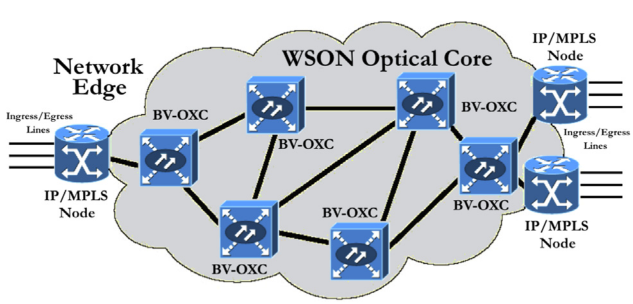

Fig. 1. IP/MPLS/WSON reference architecture.

State-of-the-art fully flexible colorless, directionless and contention-less OXC architectures (sketched in Fig. 2) are implemented by using liquid-crystal on silicon (LCoS)-based WSSs both at the input and output, allowing arbitrary spectrum demarcation and maximum switching flexibility within the so-called route and select architecture (Collings, 2013). More precisely, an add/drop chain is needed for each network degree requiring the use of several WSS modules for each degree, usually 2 modules for the input line, together with 2 modules for the output line, plus a certain number of WSS modules on each add/drop chain, depending on channels to be added and dropped. Optical carrier multiplexing is usually accomplished by using low-cost power couplers, whose power consumption is negligible. Furthermore, some BV-Ts are needed to provide add/drop functions, depending on the specific note configuration. Finally, a couple of post-amplification (booster) and pre-amplification devices are required for each degree, in order to increase the signal level after transmission and before photo-detection takes place, respectively.

Therefore, the power consumption of a BV-OXC will be given by the sum of the power consumption of its components, whose number is associated with the number of degrees and add/drop chains/optical sub-carriers involved:

$$P_{OXC} = (2N_d + N_k)P_{BV-WSS} + N_t P_{BV-T} + N_d(P_{Boost} + P_{Amp}) \quad (1)$$

where P_{BV-WSS}, P_{BV-T}, P_{Boost} and P_{Amp} are respectively the power consumptions characterizing the involved BV-WSS, BV-T, Booster and Pre-Amplification devices, assuming, for simplicity of the resulting model, that we use a single type of each device in the BV-OXC architecture. In addition, N_d, N_t, and N_k, are respectively the nodal degree, the number of BVTs and add-drop chains characterizing the OXC configuration.

Each BV-T, which is made up of a BV-TX and a BV-RX, manages a number of sub-carriers and their modulation formats according to the demand. To perform such a task, it employs a DSP and two DAC (Digital/Analog Converters). The power consumption of the DSP in the BV-T depends on the number of electronic operations implemented as well as on its operating frequency f, and it is given by

$$P_{DSP} = \frac{1}{2}CV^2Af \quad (2)$$

where C and A are constants (the aggregated load capacity and the activity factor, respectively) depending on the DSP fabric (Meisner et al., 2009), V is the operating voltage given by

$$V = V_{\max}\frac{f}{f_{\max}} \quad (3)$$

and $V_{\max}$ and $f_{\max}$ are the maximum operating voltage and frequency, respectively. Therefore, the power consumption of the DSP depends quadratically on the voltage and cubically with the working frequency. On the other hand, the DAC power consumption is strongly dependent on the data sampling (Svensson et al., 2006), which can be approximated with

$$P_{DAC} = 12kTf_s2^{2n} \quad (4)$$

where f_s is the sampling frequency, k and T are respectively the sampling noise parameters related to the accuracy of the sampling and n is the bits resolution. Comparing the Eq. (4) with commercially available off-the-shelf DACs, we obtain similar values for the power consumption of such devices, which is always in the order of tens of mW, negligible with respect to the DSP power consumption

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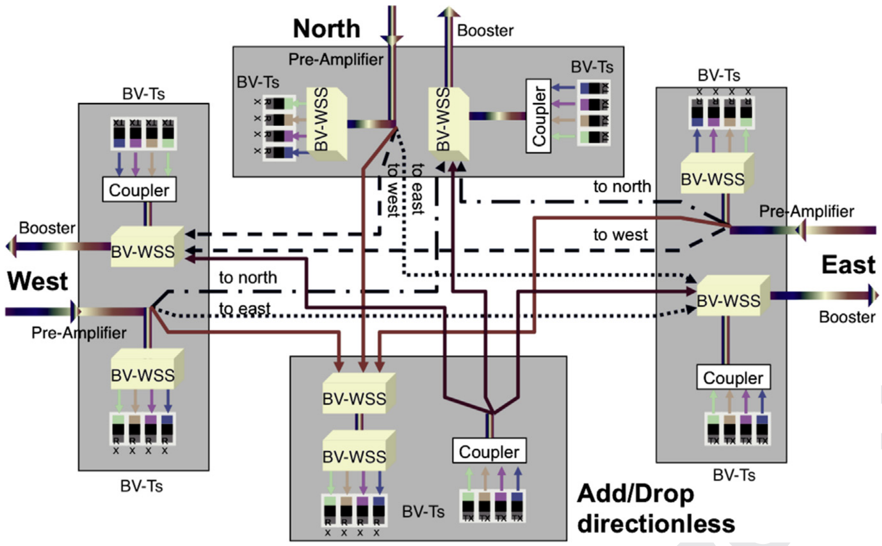

Fig. 2. Schematic architecture of a three-degrees BV-OXC.

Table 1
Modulation formats comparison.

Modulation format	Transmission reaches (km)	Subcarrier capacity (Gbps)
BPSK	4000	12.5
QPSK	2000	25
8 QAM	1000	37.5
16 QAM	500	50
32 QAM	250	62.5
64 QAM	125	75

Table 2
Power scaling factors of IP/MPLS nodes.

Switching matrix (Gbps)	5 (W/Gbps)
400	8
100	9
40	9
10	10

(which is in the order of tens of W). In addition to the power consumption associated to the DSP and DACs, the BV-T power consumption depends linearly on the number of subcarriers, modulation format and transmission rate, resulting in

$$P_{BV-T} = P_{DSP} + 2P_{DAC} + \sum_m N_m \sigma_m(r) \tag{5}$$

where N_m is the number of subcarriers with modulation m (BPSK, QPSK, 8QAM, 16QAM, 32QAM, 64QAM) and $\sigma_m(\cdot)$ is the specific power consumption of the modulation, which depends on the transmission rate r. The modulation format to be used will depend on the transmission reaches and the desired subcarriers capacity, as resumed in Table 1 which reports the reference values for 12.5 GHz frequency slots. On the receiver side subcarriers are managed independently by an equal number of coherent receivers whereas on the transmitter side they can share the same laser source.

The power consumption of each BV-WSS depends on the number of channels N_c to be switched (which are multiples of the selected frequency slot), plus a fixed power consumption φ_{BV-WSS}. Therefore, the power consumption of a BV-WSS can be modeled as

$$P_{BV-WSS} = N_c P_c + \varphi_{BV-WSS} \tag{6}$$

where P_c is the power consumption needed to switch a single channel (frequency slot). Finally, regarding the energy consumption of post-amplification and pre-amplification devices, namely P_{Boost} and P_{Amp}, we can assume for both of them a constant power consumption value, not depending neither on the number of channel nor on the associated transmission rate since in these devices the entire frequency band involved (e.g., C-band) is amplified as a whole.

On the other hand, the total power consumption $P_{IP/MPLS}$ of a more traditional electronic IP/MPLS node is given by the sum of the fixed power consumption of the base system $\varphi_{IP/MPLS}$, which depends on the node capacity, and the variable power consumption, which depends on the traffic load. The static part is the power consumed by the node base system required to keep the device on, which mainly consists of the switching matrix and control circuitry, and accounts for a great part of the total power consumption. The greater the node, the more complex its circuitry is, and hence, its fixed energy needs increase. Moreover, since faster ports require lower energy per bit than slower ones (Ricciardi et al., 2011), we use bit-rate dependent power consumption values for the different considered interfaces. Therefore, the power consumption of an IP/MPLS node is given by

$$P_{IP/MPLS} = \sum_i SF_i(x) + \varphi_{IP/MPLS} \tag{7}$$

where $SF_i(x)$ is the power scaling factor of the interface i supporting a traffic load of x Gbps, as reported in Table 2 (BONE project, 2009).

5. Performance evaluation

Extensive simulation experiments have been performed in order to evaluate performance and effectiveness of the proposal under different operating conditions and scenarios. In order to resemble closest-to-reality scenarios, we made specific assumption on the traffic profiles, the distribution of connection requests and on the network topology and node design.

In detail, we analyzed the power consumption resulting from the introduction of the following set of frequency slots at the optical layer: 50 GHz, 25 GHz, 12.5 GHz, and 6.25 GHz in specific IP-MPLS over WSON topologies. We started from a traditional WDM fixed grid layout including transponders and optical switching equipment that operate according to the standard 50 GHz grid, and then introduce reconfigurable transponders and selective optical switches accepting variable rates in the transmitted signals over single or aggregated sub-carriers characterized by specific spectrum

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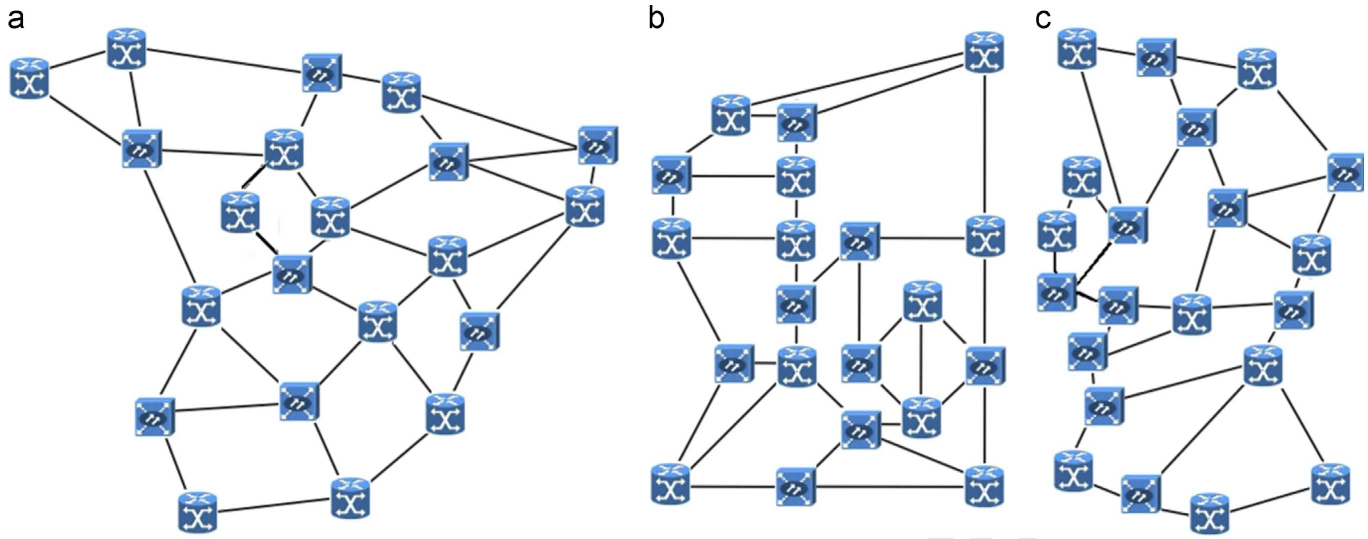

Fig. 3. Sample network topologies used: Spanish Telefonica (a), British Telecom (b), and Deutsche Telecom (c).

widths, in order to progressively vary the grid spacing end hence evaluating the effects of the introduction of grid flexibility into the optical transport network. We tested these varying spectrum widths over the three nationwide optical network topologies shown in Fig. 3, related to Spanish Telefonica, British Telecom and Deutsche Telekom (IDEALIST FP7 Project, 2013). The Telefonica's transport network, based on a hierarchical structure with 5 meshed regional domains resulting into a larger nation-wide one, consists of 21 nodes and 35 fibre links with an average length of 148 km, whereas the British Telecom national core topology consists of 20 nodes connected by 31 fibre connections, with an average length of 147 km. Finally, the 21-nodes Deutsche Telekom backbone network comprises 30 fibre links with an average length of 243 km.

These reference networks have been selected with the goal of having a quite exhaustive set of real network scenarios, defined at least in terms of nodes, each with its specific type and role, and communication links, each with its length and transmission features (fiber type, number of spans etc.). For all the network layouts we assume that only some locations (depending on the specific network topology as reported in IDEALIST FP7 Project, 2013) can be source or destination of the IP/MPLS demands. The remaining locations can be either an empty location if no demand traverses such location, a bandwidth-variable wavelength cross-connect (BV-WXC) with or without IP/MPLS equipment, or a patch-panel connecting optical fibers if neither IP/MPLS nor BV-WXC functionality is needed, according to the problem solution obtained by the GRASP-based heuristic. In order to analyze the effects of traffic load, three different traffic demand profiles (TPs) are considered. The average amount of Tbps offered to the network is equal for all TPs, and individual demands bit-rate are 10, 40, 100, or 400 Gbps. TPs are differentiated by the average demand bit-rates, which range from a scenario with a high number of lightly loaded demands (only 24.1 Gbps on average in TP-1) to a scenario with fewer demands but with a higher bit-rate (80 Gbps on average in TP-3), being TP-2 (52 Gbps on average) in between. Additionally, we consider both a highly loaded scenario (4.5 Tbps are injected into the network) and a medium one (3.5 Tbps). In all the simulations experiments, enough spectrum resources are provided by the sample network topologies so that for all the traffic demands and profiles at least a feasible solution is always available. Figure 4 reports the overall power consumption of the designed IP/MPLS over WSON networks for the three topologies respectively referring to traffic profiles TP1, TP2 and TP3, by considering the different frequency slot widths and under the two different load scenarios. Each of the points in the plots corresponds to an average value over 10 independent runs of each experiment.

As illustrated, the power consumption of the designed networks decreases as soon as the considered slot width is reduced. Note that a finer frequency slot granularity improves the efficiency of the optical layer to manage the optical spectrum; optical connections can be allocated into a number of slots that almost perfectly fit the required frequency bandwidth. As a result, the aggregation function, which is of critical importance when the slot width is wide (50 GHz), can be relaxed using narrower slot widths at the optical layer, thereby reducing the power consumption at the electrical layer. Results also show that power consumption savings in the order of 30% can be achieved by implementing the narrowest slot width. It is worth highlighting that power consumption is significantly reduced when the on-average requested bit-rate increases from TP1 to TP2 and TP3. This is a consequence of the fact that higher bit-rate BV-Ts capabilities are exploited in networks under the latter TPs. Note that higher bit-rate BV-Ts consume lower power per Gbps, in line with Ricciardi et al. (2011). Only apparently the use of a more fine-grained frequency spacing requires a higher number of BV-Ts due to the additional fragmentation of the available spectrum, eventually affecting the demands' grooming into lightpaths. Indeed, as the flexibility is improved, by reducing the slot size and hence incrementing the control granularity at the optical carrier layer, the number of needed transponders should be reduced by creating the properly fitting super-channels and avoiding the need of inverse multiplexing in the presence of large bandwidth demands (for splitting the total bandwidth into smaller units), with obvious effects on the overall energy consumption. Interestingly, the gap between power consumption savings achieved by introducing finer slot widths is significantly reduced from TP1 to TP2, until it is almost negligible in TP-3. This is the result of a more efficient spectrum utilization obtained under TP1, which in turn is gradually reduced as the on-average requested bit-rate is increased.

6. Conclusions

The benefits of flexgrid architectures in optimizing the optical spectrum efficiency are well-known, but no results are available on the effects of the associated spectrum elasticity and aggregation features on the overall network energy consumption. Accordingly, in this work, we have evaluated, for a multilayer IP/MPLS-over-flexgrid network, the energy savings that can be achieved at the IP/MPLS layer by introducing

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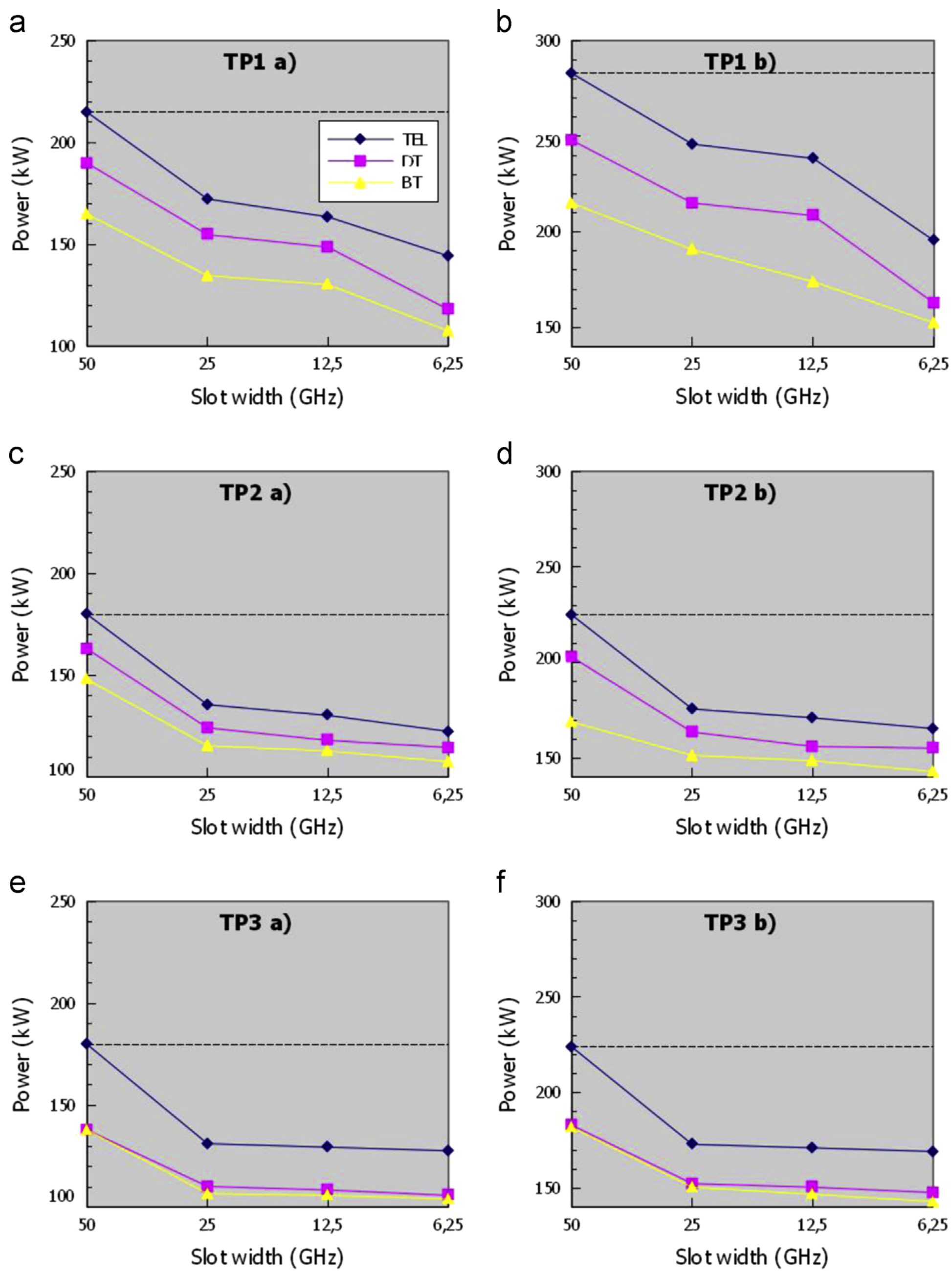

Fig. 4. IP/MPLS power consumption vs. slot width in TEL, BT, and DT networks, for the traffic profiles TP1, TP2 and TP3. (a) Avg. Demand: 24.1 Gbps – Load: 3.5 Tbps. (b) Avg. Demand: 24.1 Gbps – Load: 4.5 Tbps. (c) Avg. Demand: 52 Gbps – Load: 3.5 Tbps. (d) Avg. Demand: 52 Gbps – Load: 4.5 Tbps. (e) Avg. Demand: 80 Gbps – Load: 3.5 Tbps. (f) Avg. Demand: 80 Gbps – Load: 4.5 Tbps.

finer frequency grids at the optical one. Significant savings, in the order of 20%, were found as a result of the more efficient spectrum management performed when finer frequency slots are implemented at the optical layer. In fact, together with an increased control granularity in resources management, flexgrid architectures also allow grooming of traffic demands directly at the optical layer instead of requiring electronic (and power-demanding) activity on IP/MPLS source and destination nodes located on the network edge. However, since electronics will be increasingly important in flexgrid, especially for finer granularities, we have to consider additional energy burden introduced at the optical layer by BV-Ts and BV-WSSs equipment so that the above energy savings at the IP/MPLS layer represent the available margin for possible power consumption increments at the optical layer. Finally, it is worthwhile to highlight that the slot width selection must be made in accordance with the actual traffic conditions under which the network is expected to operate.

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References

Aleksić S. Analysis of power consumption in future high-capacity network nodes. J Optical Commun Netw 2009;1(3):245–58.

Angelou M, Christodoulopoulos K. Klonidis D, Klekamp A, Buchali F, Varvarigos E, Tomkos I. Spectrum, cost and energy efficiency in fixed-grid and flex-grid networks. In: National fiber optic engineers conference, Optical Society of America; 2012. p. NM3F-4.

BONE project, WP 21 TP green optical networks, D21.2b report on Y1 and updated plan for activities; 2009.⟨http://www.ict-bone.eu/portal/landing_pages/bone_deliverables/bone216863_-_d21-2b-report_y1.pdf⟩.

Castro A, Velasco L, Ruiz M, Klinkowski M, Fernández-Palacios JP, Careglio D. Dynamic routing and spectrum (re) allocation in future flexgrid optical networks. Comput Netw 2012;56(12):2869–83.

Christodoulopoulos K, Tomkos I, Varvarigos EA. Routing and spectrum allocation in OFDM-based optical networks with elastic bandwidth allocation. In: Global telecommunications conference (GLOBECOM 2010), 2010 IEEE, IEEE; 2010. p. 1–6.

Collings B. New devices enabling software-defined optical networks. IEEE Commun Mag 2013;51(3):66–71.

Höller H, Melián B, Voß S. Applying the pilot method to improve VNS and GRASP metaheuristics for the design of SDH/WDM networks. Eur J Oper Res 2008;191(3):691–704.

Hou W, Guo L, Gong X. Survivable power efficiency oriented integrated grooming in green networks. J Netw Comput Appl 2013;36(1):420–8. http://dx.doi.org/10.1016/j.jnca.2012.04.016 ⟨http://www.sciencedirect.com/science/article/pii/S1084804512001099⟩.

IDEALIST FP7 Project, Deliverable D1.1—elastic optical network architecture: reference scenario, cost and planning; 2013. ⟨http://cordis.europa.eu/docs/projects/cnect/9/317999/080/deliverables/001-D11ElasticOpticalNetworkArchitecture.doc⟩.

Jinno M, Takara H, Kozicki B, Tsukishima Y, Sone Y, Matsuoka S. Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies. IEEE Commun Mag 2009;47(11):66–73.

Jinno M, Kozicki B, Takara H, Watanabe A, Sone Y, Tanaka T, et al. Distance-adaptive spectrum resource allocation in spectrum-sliced elastic optical path network [Topics in Optical Communications]. IEEE Commun Mag 2010;48(8):138–45.

Khodakarami H, Pillai BSG, Sedighi B, Shieh W. Flexible optical networks: an energy efficiency perspective. J Lightwave Technol 2014;32(21):3356–67.

Klinkowski M, Walkowiak K. Routing and spectrum assignment in spectrum sliced elastic optical path network. IEEE Commun Lett 2011;15(8):884–6.

Lopez Vizcaino J, Ye Y, López V, Jiménez F, Duque R, Krummrich P. On the energy efficiency of survivable optical transport networks with flexible-grid. In: European conference and exhibition on optical communication, Optical Society of America; 2012. p. P5–05.

Meisner D, Gold BT, Wenisch TF. PowerNap: eliminating server idle power. ACM SIGARCH Comput Archit News 2009;37(1):205–16.

Morea A, Rival O, Brochier N, le Rouzic E. Datarate adaptation for night-time energy savings in core networks. J Lightwave Technol 2013;31(5):779–85.

Palkopoulou E, Angelou M, Klonidis D, Christodoulopoulos K, Klekamp A, Buchali F, et al. Quantifying spectrum, cost, and energy efficiency in fixed-grid and flex-grid networks. J Optical Commun Netw 2012;4(11):B42–51.

Palmieri F, Fiore U, Ricciardi S. A GRASP-based network re-optimization strategy for improving RWA in multi-constrained optical transport infrastructures. Comput Commun 2010;33(15):1809–22.

Papanikolaou P, Soumplis P, Manousakis K, Papadimitriou G, Ellinas G, Christodoulopoulos K, et al. Minimizing energy and cost in fixed-grid and flex-grid networks. J Opt Commun Netw 2015;7(4):337–51.

Pedrola O, Castro A, Velasco L, Ruiz M, Fernández-Palacios J, Careglio D. CAPEX study for a multilayer IP/MPLS-over-flexgrid optical network. J Opt Commun Netw 2012;4(8):639–50.

Pedrola O, Ruiz M, Velasco L, Careglio D, de Dios OG, Comellas J. A GRASP with path-relinking heuristic for the survivable IP/MPLS-over-WSON multi-layer network optimization problem. Comput Oper Res 2013;40(12):3174–87.

Resende MG, Ribeiro CC. A GRASP with path-relinking for private virtual circuit routing. Networks 2003;41(2):104–14.

Resende MG, Ribeiro CC. GRASP: greedy randomized adaptive search procedures. Search methodologies. Springer; 287–312. Q2

Ricciardi S, Careglio D, Fiore U, Palmieri F, Santos-Boada G, Solé-Pareta J. Analyzing local strategies for energy-efficient networking. In: Networking 2011 conference proceedings, Springer; 2011. p. 291-300.

Ricciardi S, Careglio D, Santos-Boada G, Solé-Pareta J, Fiore U, Palmieri F. Towards an energy-aware internet: modeling a cross-layer optimization approach. Telecommun Syst 2013;52(2):1247–68.

Soumplis P, Papanikolaou P, Christodoulopoulos K, Papadimitriou G, Varvarigos E. Energy minimization design of fixed-and flex-grid optical networks. In: 2014 IEEE 19th international workshop on computer aided modeling and design of communication links and networks (CAMAD), IEEE; 2014. p. 125–129. Q3

Svensson C, Andersson S, Bogner P. On the power consumption of analog to digital converters. In: Norchip conference, 2006. 24th, IEEE; 2006. p. 49-52.

Tkach RW. Scaling optical communications for the next decade and beyond. Bell Labs Tech J 2010;14(4):3–9.

Vacondio F, El Falou A, Voicila A, Le Bouëtté C, Tanguy J.-M, Simonneau C, et al. Real-time elastic coherent muxponder enabling energy proportional optical transport. In: Optical fiber communication conference, optical society of America; 2013. p. JTh2A-51.

Vizcaíno JL, Ye Y, Monroy IT. Energy efficiency analysis for flexible-grid OFDM-based optical networks. Comput Netw 2012;56(10):2400–19.

Wang Y, Cao X, Pan Y. A study of the routing and spectrum allocation in spectrum-sliced elastic optical path networks. In: INFOCOM, 2011 proceedings IEEE, IEEE; 2011. p. 1503–1511.