Energy Minimization Design of Fixed- and Flex-Grid Optical Networks

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***Abstract*— Core networks offer high capacities by harvesting the high bandwidth-distance product of optical technologies. However they consume a non-negligible amount of power, while their traffic volume is forecasted to grow at very high rates for the 10 or 15 coming years. Thus, energy-efficiency in core and metro networks is mandatory for the sustainability of the future Internet. In this context, in this work we used Mantis, our network planning and operation tool, to design and carry out a comparative study of energy efficiency of current and next generation optical networks. In particular, we examined the cases of fixed-grid single-line-rate (SLR) Wavelength Division Multiplexing (WDM) optical networks, which are now deployed in the core, and next-generatoin mixed-line-rates (MLR) WDM and flex-grid networks. Under realistic network scenarios we profiled the total energy consumption of the optical layer and showed that through energy-aware algorithms we can achieve significant power savings.**

Keywords*— *WDM, fixed-grid, flex-grid, cost efficiency, energy efficiency, flexible spectrum allocation

I. Introduction

The Internet is continuously transforming our reality, increasing productivity, and supporting economic developments across the world. Between 1993 and 2013 the size of the data traffic increased by 113 GB/day to 13888 GB/second. It is estimated that power consumption of the Internet is around 4% of the total energy consumption in broadband-enabled countries, and backbone network infrastructures (i.e., routers, transmission systems, optical switches, etc.) consume approximately 12% of total Internet energy consumption (estimated to increase to 20% in 2020). It seems that an energy-aware approach is increasingly needed during the design, implementation, and operation of optical networks, which carry more than 80% of the world's long-distance traffic.

The current optical transport networks are based on wavelength division multiplexing (WDM). The recent advances in transmission technologies and coherent reception have made possible the use of more than one type of transponders simultaneously, that operate at different rates, thus exploiting trade-offs between reach and cost available in the different devices to improve the efficiency and decrease the total network cost. Such networks are referred to as mixed-line-rate (MLR) WDM networks, as opposed to currently deployed sinlge line rate (SLR) WDM technology.

As the next step, flex-grid architectures appear to be a promising technology for meeting the requirements of next generation networks that will span across both the core and the metro segments. A flex-grid network migrates from the fixed 50GHz grid that traditional WDM networks utilize, and has granularity of 12.5 GHz. These networks are built using bandwidth variable switches that are configured to create appropriately sized end-to-end optical paths (lightpaths) of sufficient spectrum slots. Bandwidth variable switches operate in a transparent manner for transit (bypassing) traffic that is switched while remaining in the optical domain. The use of variable spectrum connections increases spectral efficiency, supports future transmission rates, and reduces capital costs. Flexible transceivers envisioned for flex-grid networks, also referred to as bandwidth variable transponders (BVTs), allow multiple choices when serving a demand: they can decide the modulation format, baud-rate, spectrum or even the FEC, and choose those that give sufficient performance to reach the required distance.

Connection establishment in flex-grid networks is more complicated: first, in contrast to WDM networks and the Routing and Wavelength Assignment (RWA) problem where each connection is assigned a single wavelength, in flex-grid networks spectrum slots can be combined to form variable width channels, leading to the so-called Routing and Spectrum Allocation (RSA) problem. Secondly, the transponders' (BVTs') adaptability yields many transmission options, each with different transmission reach and spectrum used, complicating further the connection establishment problem as it increases the number of options available.

Typically optical networks are designed with the objective to minimize their capital expenditure (CAPEX) cost, using appropriate RWA/RSA algorithms. However a key parameter in the network operation expenditure (OPEX) cost is the energy consumption. Although the CAPEX cost and the energy consumption are correlated metrics, their relation is not linear. So Energy-Aware (EA) optical network design has started to receive more attention recently.

In this paper we use Mantis [1], an optical network planning and operation tool that we have implemented in the previous several years, to compare the energy consumption of the different types of optical networks (fixed and flex-grid), using appropriate planning algorithms for each type. In particular, we included in Mantis appropriate energy consumption modules and integrated Energy Aware RWA and RSA algorithms for planning: (i) single-, (ii) mixed-line-rate WDM and (iii) flex-grid networks with tunable BVTs. We use realistic network topologies, traffic matrices, and energy and cost parameters of the used components in an attempt to calculate with high precision the energy consumption of actual cases. Our results show that, depending on the specific characteristics of the physical network topologies, both flex-grid and MLR are far more energy-efficient solutions than currently deployed SLR.

The rest of the paper is organized as follows. In Section 2 we report on the related work. In Section 3 we give a short description of Mantis and the model used to calculate the energy consumption of the different types of optical networks examined. In Section 4 we outline the energy aware algorithm that we used. In Section 5 we present our comparison results. Our conclusions follow in Section 6.

II. RELATED WORK

The energy efficiency of WDM networks has been a relevant research subject in the last few years. More and more research efforts focus on the design of energy aware algorithms that aim at providing the same QoS with the lowest possible energy consumption and the lowest capital expenditure. We classify these algorithms into two subcategories: algorithms for (i) WDM networks [2]-[5] and for (ii) flexible networks [6]-[7].

A detailed survey of energy-aware network design and networking equipment is presented in [2], where the IP/grooming level and the WDM network are both considered. In [3] the authors provide a perspective on how the capital costs and energy consumption of optical WDM networks scale with increasing network capacity. They conclude that using traffic grooming to maximize the utilization of lightpaths and optical bypass to minimize the number of grooming ports is the most cost-effective technique

The authors in [4] exploit the trade-offs between spectral efficiency, power consumption and optical reach in MLR WDM networks taking under consideration the used transponders and regenerators. They recommend the 100 Gb/s DP-QPSK as the most suitable transmission option for next generation optical networks, since it achieves acceptable optical reach and power consumption. In [5] the authors evaluate the energy efficiency of the MLR networks compared to the SLR networks. For the energy evaluation they consider the consumption of the transponders, the amplifiers and the energy required for the electronic processing.

The authors in [6] propose heuristic algorithms to evaluate the energy consumption of flexible OFDM networks with respect to the MLR and SLR networks. The developed heuristic algorithms serve the demand in a sequential order selecting each time the most energy efficient choice. In [7] the authors examine the use of traffic grooming based on adaptive modulation format and elastic spectrum allocation with the objective of minimizing the total consumed energy. Towards this aim, they formulate this minimization problem as an ILP and also develop a heuristic algorithm.

The main contributions that distinguish our present work from that of other researchers are the following. Firstly, we have developed detailed energy and cost models to assess the energy and cost of the various components employed at fixed and flexible grid WDM networks and integrate that to Mantis, our netrowrk planning and operation tool. Secondly, we have integratred into Mantis new energy aware algorithms. Especially the energy-aware RSA algorithm used for flex-grid networks accounts for various transmission parameters of the transponders, harvesting their tunability to improve the energy efficiency of the network. Moreover, the network topologies and the traffic matrices used in our simulations are quite realistic, so we argue that the drawn conclusions are more accurate than those of most previous works.

III. MANTIS AND ENERGY MODEL

We have developed a network planning and operation tool, called Mantis [1], for designing the next generation optical networks, supporting both flex-grid, MLR and SLR WDM networks. Through Mantis, the user is able to define the network topology, the traffic matrix, the CAPEX/OPEX parameters, setup basic configuration parameters, and use a library of algorithms to evaluate the planning, or operation of an optical network of interest.

For the design of Mantis, we adopted an architecture that provides fast execution, efficient computation resources' usage and basic fault tolerance, and enables the deployment of the tool both as a cloud service and as a desktop application. Mantis components are organized in three layers: the access layer, the application layer and the execution layer. Furthermore, there are two common interfaces whose primary purpose is to provide loose coupling between the application layer and the other two layers. By using these interfaces we can use the same access and execution layers for both versions of the tool while we can extend their functionality without breaking the implementation of the other components. The access layer handles the interaction with the users through a web-based user interface and its exposed RESTful API. The execution layer consists of the execution engine and the library of available algorithms. The execution engine receives requests, for starting or terminating algorithm executions, prepares the execution environment, monitors the execution progress and handles the results or possible failures. The algorithms are written either in Cython or C++ and are accessed from the execution engine through a custom plug-in mechanism. This mechanism enables new algorithms to be added in the tool without any modification of the application layer and the execution engine. The application layer orchestrates the execution of user requests. It is the only layer that differs between desktop application and cloud service deployment as there are different requirements and operations that should be performed.

A. Network Architecture and Energy and Cost Model

We have integrated in Mantis an energy and cost model for fixed WDM and flex-grid networks. The network architecture and the cost model is based on the model developed in [8], while the energy model is made from various sources.

The network architecture is based on fiber links, optical nodes and transponders. The link is divided into spans, e.g. every 80 km, which consist of a Standard Single Mode Fiber (SSMF) segment. Due to fiber attenuation at the end of each span an amplifier is installed to compensate for the losses of the preceding fiber span.

The components that build the nodes are the wavelength selective switches (WSS), the amplifiers (EDFAs), combiners and splitter. These components are combined to create the network interfaces (NIs) that connect the nodes to the fiber links and the add/drop terminals that interface with the transponders and the clients.

The node architecture evaluated here, shown in Fig. 1, is directionless (any client port can be connected to any outgoing fiber and the opposite) and colourless (the client port can be tuned to any wavelength and any wavelength can be terminated from any incoming fiber to a client port). However, this node architecture may cause wavelength blocking due to the contention feature. Each add/drop terminal allows a specific wavelength to be added/dropped only once, and additional terminals are required to add/drop a specific wavelength more than once (contentionless feature). Since the problem is solved by adding more add-drop terminals, this architecture is referred to as *incrementally contentionless*.

B. Energy and CAPEX model

The cost model we have developed consists of two types of expenditures: energy consumption and CAPEX. The latter refers to the costs of ownership of the network equipment. Following IDEALIST CAPEX model [8] the reference cost unit (c.u.) that we use in our model is the 100 Gb/s coherent transponder. The energy consumption cost includes the cost arising due to the energy consumed by the components which comprise the WDM network. We used various sources for defining the energy consumed by the various optical components. The following resources are considered in the energy and CAPEX models for the WDM fixed-grid: transponders, regenerators, optical cross-connects (OXCs), consisting of WSSs and amplifiers.

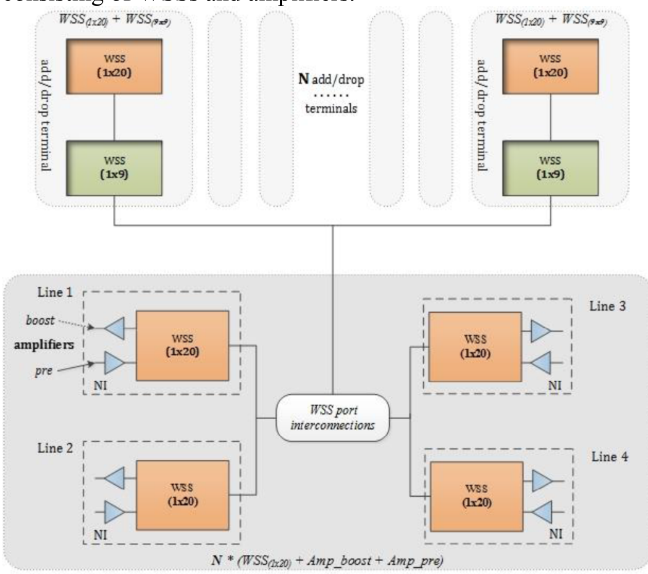

Fig. 1. Colourless, directionless, and incrementally contentionless node architecture.

Fixed-grid transponders & regenerators					OXC *components*		
Type	Capacity *(Gb/s)*	Energy *(Watts)*	Cost *(c.u.)*	Reach *(Km)*	Architecture	Energy *(Watts)*	Cost *(c.u.)*
TSPs	40	170	0.48	2500	WSS (1x20)	28	0.48
	100	240	1	2000	WSS (1x9)	20	0.32
	400	480	1.36	500	EDFA	30	0.06
Regens	40	170	0.77	2500	splitter / combiner	0	0.00
	100	240	1.6	2000			
	400	480	2.18	500			

Table 1. Energy consumption and cost of transpoders, regenerators and OXC for fixed-grid WDM.

We assumed the use of transponders with line rates of 40, 100 and 400 Gb/s, and the maximum transparent reach for each type as shown in *Table 1*. For each transponder, a corresponding regenerator is available.

The energy consumption of the incrementally contentionless OXC architecture is based on its comprising components and is described in the following equation:

$$Incremental\_Contentionless\_OXC = N*(WSS_{(1x20)} + Amp\_boost + Amp\_pre) + WSS_{(1x20)} + Amp\_Drop + Amp\_Add + WSS_{(1x9)}, \quad (1)$$

where N is the node degree, *Amp_Add*, *Amp_Drop, Amp_boost* and *Amp_pre* correspond to the energy consumption of the amplifiers (double stage EDFA), and $WSS_{(1x20)}$ and $WSS_{(1x9)}$ is the energy consumption of the WSS modules (*Table 1*).

As opposed to fixed transponders assumed in WDM networks, the traffic in flex-grid networks is served by BVTs that control the following features: (i) the modulation format (ii) the baud-rate and (iii) the spectrum (in contiguous spectrum slots) that they utilize. By adapting these features, a BVT of cost c can be tuned to transmit r Gb/s using bandwidth of b spectrum slots and a guardband of g spectrum slots from the adjacent spectrum lightpaths resulting in a total energy consumption v, to transmit at reach l km with acceptable Quality of Transmission.

It has been demonstrated in [9] that format-flexible transponders have the same power consumption independent of the chosen modulation format. However the transmission reach depends mainly on the modulation format and the related spectrum efficiency. So the main advantage of format flexible transponders relies on the large scale of transmission distances, hence the possibility of skipping intermediary regenerators.

On the other hand, it stands to reason that the energy consumption depends on the used baud-rate. So baud-rate flexible transponders can trade-off energy consumption for other parameters. According to the corresponding energy consumption, only the subsystems of the transponder that provide electronic processing exhibit power consumption related to the operating baud-rate. Thus, the energy consumption of a flexible transponder is split into two categories (i) static and (ii) dynamic. The first allows the electronic maintenance of logic levels in the device, but also the various leakage currents. The dynamic power consumption of the device depends on the frequency at which it operates. This power is directly proportional to the square of the voltage and to the clock frequency. If only the frequency of the device is tuned, the dynamic power (and the total power) scales linearly and this is the assumption that we have taken here.

The model assumed for the BVT transponders is that of the muxponder that has maximum rate 400 Gb/s. The components that are taken into account for the energy consumption model are divided into the following categories (i) client side, (ii) E/O modulation, (iii) O/E receiver. The first consists of the client cards, the component of framer/deframer and of the Forward Error Correction module. Note that at any time, and depending on the transmission rate of the transponders, not all client cards are active. The E/O modulation consists of the drivers, the laser and the local oscillator. Finally, in the O/E receiver part are included the modules of photodiode, transimpedance amplifier (TIA), ADC and DSP.

From the aforementioned components only the following have energy consumption related to the baud-rate: (i) the framer/deframer, (ii) FEC and (iii) DSP. Table 2 presents the transmission options of the assumed BVT model, including the energy consumption for each option.

Capacity *(Gb/s)*	Reach *(Km)*	Data slots	Guardband slots	Energy Consumption *(Watts)*	Capacity *(Gb/s)*	Reach *(Km)*	Data slots	Guardband slots	Energy Consumption *(Watts)*
40	4000	4	1	183.6	200	2500	6	1	432
40	3000	3	1	183.6	200	2200	5	1	432
40	2500	2	1	183.6	200	1900	4	1	432
40	1900	1	1	183.6	200	750	3	1	333
40	600	1	1	154.8	200	600	2	1	333
					200	500	1	1	333
100	3500	4	1	270	400	2500	14	1	630
100	3000	3	1	270	400	2200	12	1	630
100	2500	2	1	270	400	1900	10	1	630
100	1900	1	1	270	400	750	8	1	432
100	600	1	1	198	400	600	6	1	432
					400	500	4	1	432

Table 2 Energy consumption of S-BVTs

In the BVT transponder architecture we assume that two lasers are sufficient to transmit the desired rates with the available modulation formats. The energy consumption each time depends on the number of lasers that are active. The equation, based on [8], we used to compute the power consumption of the BVT transponder is the following:

$$P_{BVT}= n*(108+4.8*R)*1.2 \qquad (2)$$

where R is the baud-rate at which the transponder operates and n is the number of active lasers. Finally, the total consumption assumed for a BVT transponder is increased by 20% to capture the power management consumption.

IV. Description of Algorithms

In this section we outline the algorithm we developed and employed in Mantis tool for minimizing the energy consumption when planning SLR and MLR fixed-grid WDM (EA-RWA), and flexgrid optical networks (EA-RSA).

We start by giving a general definition of the network planning problem. We are given an optical network $G = (V,E)$, where V denotes the set of nodes and E denotes the set of (point-to-point) single-fiber links. We are also given the actual (physical) lengths D_l of the links l in E. We assume an a-priori known traffic scenario given in the form of a traffic matrix Λ in Gb/s, where Λ_{sd} denotes the requested capacity for demand (s,d), that is, from source s to destination d. The switch architecture is that presented in Section *3.B*, with the only difference between the fixed- and flex-grid case the use of bandwidth variable WSS in the latter case. The available transponders in the case of fixed- and flex-grid case are those presented in Section *3.B*. We also assume that in the case of the fixed-grid (SLR and MLR) the system supports W wavelengths, while in the flex-grid case it supports S spectrum slots.

The objective is to serve all traffic and minimize the energy consumed in the related fixed-grid WDM and flex-grid optical networks. To do so we reduce the power consuming components such as transponders, regenerators, add/drop terminals and amplifiers, and when we are given the option (MLR or flex-grid) we choose the components/configurations that will lead in the minimization of the energy consumed.

Since the related planning problems are NP-hard and we are considering realistic problem instances with networks of many nodes/links and heavy traffic, we decided to use heuristic algorithms. In particular, the heuristic algorithm we used serves the demands one-by-one on a specific ordering, remembering the choices made for previous served requests in order to avoid wavelength contention and incrementally calculate the energy consumption of the whole network. Note that the energy consumption (but also the spectrum and other network performance metrics) differ, depending on the ordering in which demands are served. This is because choices made for one connection, e.g. to serve it over a specific path that places regenerators at specific nodes so as to avoid adding add-drop terminals over another path, could differ later when the chosen path becomes congested while the avoided path turns to be relatively empty. Since the ordering plays an important role, the used algorithms use Simulating Annealing (SA) meta-heuristic to search among different orderings.

We extended the heuristic algorithm presented in [10] to make it energy aware. Note that the used flex-grid RSA algorithm is general and was also used to minimize the energy consumption of the SLR and MLR cases if we define the transmission tuples appropriately. The different configurations of the transponders are passed as feasible transmission configuration tuples $t=(l_t,r_t,b_t,g_t,c_t,v_t)$ as shown in *Tables 1-2*. The algorithm is extended to include in its weighted multi-objective cost the energy consumption of a connection. The algorithm calculates k-shortest paths for each demand, and then for each of these paths and for each feasible transmission tuple it calculates the regeneration points. Since the solution options for each demand can be vast, slowing the execution of the algorithm, the algorithm employes an additional phase where we prune the dominated candidate solutions. These are tuples over the same path that consume more energy and use more spectrum than other [10]. Then the algorithm calculates the network incremental energy consumption of each option, taking into account the demands served up to that point and the current state of the network. It chooses the path-tuple pair that minimizes a weighted combination of the incremental energy and the incremental spectrum utilized. In the experiments presented here the weight of energy minimization was set so as to solely minimize the energy, neglecting the spectrum used.

V. Illustrative Results

We now present the energy consumption and the CAPEX cost of two realistic networks under the network model presented in Section 3. In particular, we assume that the networks under study are deployed using fixed-grid WDM (both in the form of SLR and MLR) or flex-grid technology. To serve the demands in these networks we use the energy aware heuristic algorithms outlined in Section 4. As discussed in Section 3, the results presented focus on the energy consumption and the cost of the optical layer, neglecting the electronic aggregation of traffic at the edges of the optical network.

In our WDM model, a maximum per-link capacity of 80 wavelengths with the 50 GHz ITU-T grid is assumed. We consider transponders with the transmission capabilities presented in *Table 1*. Two types of WDM networks are considered, SLR where all the transponders are of the same type, one of those presented previously, and MLR where all the transponders of *Table 1* are available. For the flexible network, the width of the spectrum slot is considered to be 12.5 GHz, 320 slots are available, and the transmission configuration of the BVTs are those presented in *Table 2*.

The topologies used in our simulations are (i) the Deutsche Telekom (DT) and (ii) the GEANT topology. For these networks we also used realistic traffic matrices. We assumed that traffic increases by 35% per year, and graph results for 12 years with a step of 2 years. Note that at each year we plan the whole network from zero, meaning that we do not take the previous solution as existing and incrementally add more equipment. We do this in an attempt to locate the point that each of the examined technologies is more efficient and would make sense for the network to switch to that technology.

A. Total power consumption

Fig. 2 presents the energy consumption of the SLR, MLR and flexible networks, for the two reference networks. In both networks the flex-grid network (EA-RSA algorithm) is shown to exhibit the lowest power consumption, at heavy load. At medium load the flex-grid network is quite close with the MLR, the MLR being slightly more efficient at light load. So as the load increases the MLR network becomes less efficient, giving an advantage to the flexible network that exploits the higher number of its transmission options. The point that this happens is year 2018, with small variations between the different networks. The performance of the SLR case for the three different transmission rates is inferior to that of the MLR and the

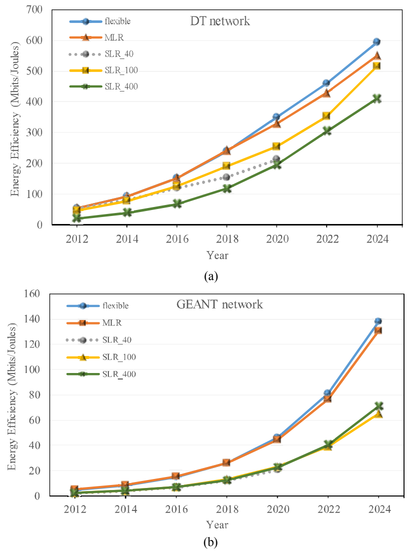

Fig. 2 Power consumed in (a) DT and (b) GEANT

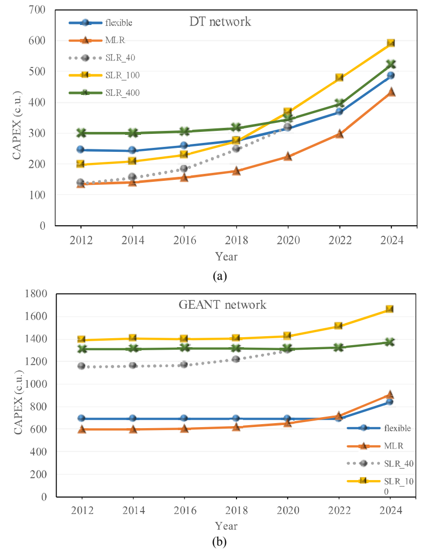

Fig. 3 CAPEX for (a) DT and (b) GEANT

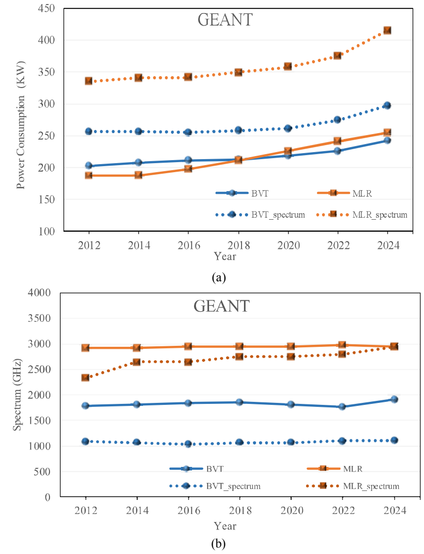

Fig. 4 Power savings vs spectrum occupancy

flexible network in all traffic scenarios examined. This is expected, since the MLR can take the form of any of these and utilize the transponders that are more efficient in each case.

The performance of the SLR networks is substantially affected by the special characteristics of each network and specifically the demanded capacity between each pair of nodes.For light load, SLR 40 Gb/s is more efficient than the other two SLR options. The performance of SLR 40 Gb/s is close to MLR and flex-grid at light load, since most connections are efficiently served by that rate. As the load increases, 100 Gb/s becomes more efficient, and probably at some point after what we have examined 400 Gb/s would be also more efficient. Note that we stop presenting the performance for the SLR 40 Gb/s after the year 2020 since after that we start exhibiting blocking with the 80 provisioned wavelengths. Note also that the performance of the SLR network solutions for the GEANT network are substantially worse than the MLR and flexible cases in that network. This has to do with the versatility of link lengths and paths and the traffic demands in the GEANT network, that make it inefficient to serve traffic with a single type of transponder, as done in the SLR solutions.

B. Capital Expenditure

Similarly to the previous case, the flexible and the MLR algorithms have very close performance, with the flexible algorithm being worse and improving while the offered load increases. It is worth noting that in the above calculations the cost of BVT and that of flex-grid WSS is assumed to be 30% higher than the related cost of the WDM related equipment.

Flex-grid seems more cost efficient than MLR in networks where there is versatility in the path lengths and the demands, so as to make use of the various transponders configurations, as in the case of the GEANT network at heavy load.

C. Trading-off energy for spectrum

In this section we evaluate two different objective functions for the flexgrid optimization algorithm which minimize either the power consumed in the network or the spectrum used. For all cases when our objective is the minimization of power consumed in the network the spectrum occupied is higher because certain energy savings, e.g. in the number of add/drop terminals can be achieved by not using the same slots, or different configurations of the BVTs favour energy to spectrum consumption. Similarly, when the objective is the minimization of spectrum the energy consumed in the network turns out to be significantly higher as seen in Fig. 4. Note that minimizing spectrum utilization is a typical objective used in many planning algorithms. Taking this into account we can consider the spectrum minimization objective as an energy-unaware design. Thus, comparing the performance of the energy aware algorithms with the coresponding energy unaware algorithms we observe the energy savings we can achieve.

VI. Conclusions

We used the Mantis network planning and operation tool to carry out a comparative study of energy efficiency of current and next generation optical networks. Under realistic network scenarios we profiled the total energy consumption of the optical layer and showed that through energy-aware algorithms we can achieve significant power savings.

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