Minimizing Energy and Cost in Fixed-Grid and Flex-Grid Networks

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***Abstract*—Core networks offer high capacities, thanks mainly to the optical technologies they utilize, but they consume a non-negligible amount of energy. The traffic volume in metro and core networks is forecast to grow at very high rates, exceeding 30% per year for the next five years, and if the corresponding energy requirements grow analogously, they will sooner rather than later form a bottleneck for network communications. Thus, energy efficiency in optical networks is mandatory for the sustainability of the future Internet. The objectives of the current work are to identify the main causes of energy consumption for current fixed-grid wavelength division multiplexing and future flex-grid optical networks, and to propose and compare techniques for improving their energy efficiency. Toward this end, we carried out a comparative study of energy efficiency of flex-grid networks and fixed-grid single-line-rate and mixed-line-rate networks. Under realistic network scenarios, we calculated the energy consumption of the different components of the optical layer and demonstrated that by using energy-aware techniques in planning such networks, we can achieve significant power savings. Since energy prices are location dependent, especially in large networks, e.g., over continents, we show that accounting for such information can increase the cost savings.**

***Index Terms*—CAPEX/OPEX; Cost; Energy efficiency; Fixed- and flex-grid optical networks; Mixed line rate (MLR); Routing and spectrum assignment; Routing and wavelength assignment; Single line rate (SLR); Spectrum.**

I. INTRODUCTION

A. Motivation

The Internet is continuously transforming our daily working reality and lifestyle, increasing productivity, and supporting economic development across the world. Between 1993 and 2013 the size of the data traffic increased by 113 GB/day to 13,888 GB/s, while Cisco predicts global IP traffic to nearly triple from 2013 to 2018 [1] (see Fig. 1). The global economic downturn seems unlikely to slow the growth of Internet traffic, which leads to increased energy consumption for the infrastructures and devices needed to operate the Internet.

ICT can of course help save energy through telecommuting, the introduction of smart grids, and many other ways, but the need for ICT to keep its own power consumption growth under control is also becoming increasingly evident [2]. It is estimated that the 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) consume approximately 12% of total Internet energy consumption (estimated to increase to 20% in 2020) [3]. The continuing deployment and upgrade of network infrastructure drive up power consumption in a way that makes telecom operators worry that future power consumption levels may pose constraints on the growth of the Internet. Thus, it seems that an energy-aware approach is increasingly needed during the design, implementation, and operation of networks in general, and optical networks in particular, which carry more than 80% of the world's long-distance traffic. Two different approaches can be explored to reduce power consumption in optical networks: the improvement of the energy efficiency of the equipment and the energy awareness of the algorithms used.

B. Fixed-Grid and Flex-Grid Optical Networks

The current optical transport networks are based on wavelength division multiplexing (WDM) technology to concurrently transport information on different wavelengths. In the past decades, research has focused on increasing network capacity by increasing the individual wavelength's capacity. Hence, WDM-based networks have evolved from 1 to 2.5 to 10 to 40 Gb/s, while 100 Gb/s transceivers are just reaching the market. The next step is 400 Gb/s systems and then even higher rates. However, such transmissions would not fit in the 50 GHz wavelength grid of current WDM systems (initial designs of 400 Gb/s transceivers are for 75 GHz). Going back to the 100 GHz grid that was used in WDM systems in the past is not a viable solution. Moreover, WDM systems present an inefficiency problem due to the coarse granularity of the lightpaths (as optical connections are typically referred to), which are allocated a whole wavelength. Traffic manipulation at lower capacity levels is performed at the electronic

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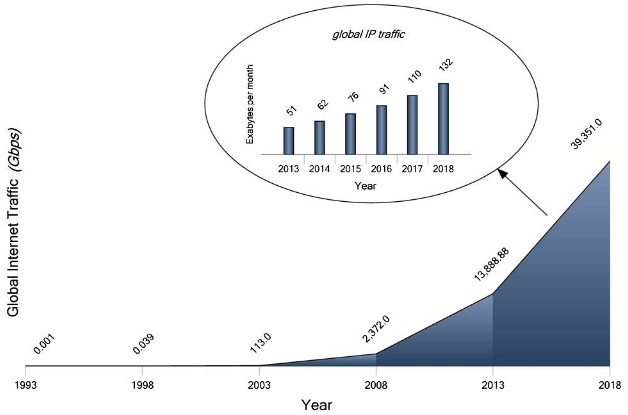


Fig. 1. Global Internet traffic growth and Cisco's VNI Global IP traffic growth forecasts (2013–2018).

aggregation switches at the edges of the optical network and is, in most cases, done independently of and on different timescales than lightpath provisioning of the optical WDM network. Therefore, to support future optical transmissions and improve efficiency, a more flexible optical network with finer granularity is needed.

Recent research efforts on optical networks have focused on architectures that support variable spectrum connections as a way to increase spectral efficiency, support future transmission rates, and reduce capital costs. Flex-grid (elastic or flexible are also terms used in the literature and will be used in this paper interchangeably) optical networks 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 50 GHz grid that traditional WDM networks utilize [4], and has granularity of 12.5 GHz, as standardized by the International Telecommunication Union (ITU-T) [5]. Moreover, flex-grid can also combine spectrum units, referred to as slots, to create wider channels on an as-needed basis (Fig. 2). This technology enables a fine-granular, cost- and power- efficient network able to carry traffic that may vary in time, direction, and magnitude. Flex-grid networks [6] are built using bandwidth variable switches that are configured to create appropriately sized end-to-end optical paths 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.

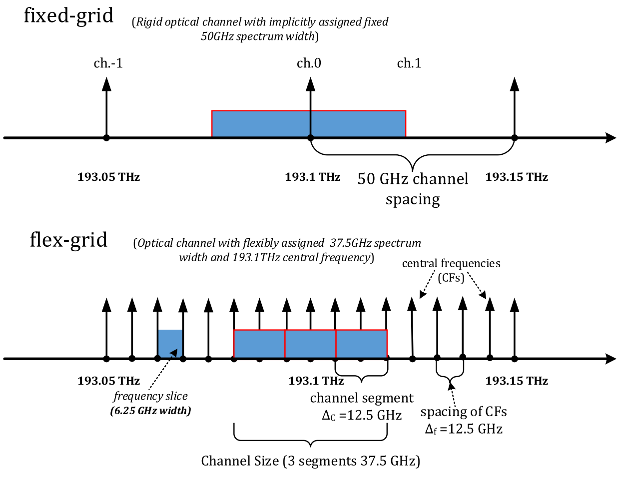


Fig. 2. Fixed WDM grid (with 50 GHz channel spacing) and flexible grid (with 12.5 GHz).

In fixed-grid WDM networks and assuming a specific type of transceiver, there is one way of serving a demand: the bit rate is fixed, the optical reach is fixed, and the occupied spectrum is fixed (a single wavelength). 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 some or all of the following: the modulation format, baud rate, spectrum, or even the forward error correction (FEC), and choose those that give sufficient performance to reach the required distance.

The problem of establishing connections in fixed-grid WDM networks is typically referred to as the routing and wavelength assignment (RWA) problem, which is known to be an NP-hard problem. In the past, WDM systems were designed to use a single type of transponder, that is, they utilized a single-line rate (SLR). Recent advances in transmission technologies and coherent reception have made possible the use of more than one type of transponder simultaneously, 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 typically referred to as mixed-line rate (MLR), as opposed to the SLR case discussed above. The RWA problem for MLR WDM networks is more complicated than for SLR, since it involves making decisions for the type of transponder to use for each connection.

Connection establishment in flex-grid networks is more complicated for several reasons. First, in contrast to WDM networks 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. Additionally, the transponders' (BVTs') adaptability yields many transmission options, each with different transmission reach and spectrum used, complicating the connection establishment optimization problem.

Both RWA and RSA include as a sub-problem the placement of regenerators in the network. WDM transceivers have specific transmission reach (the physical layer introduces various types of impairments: noise, interference, dispersion, etc.), and regenerators are used to establish lengthy connections. However, in contrast to WDM networks, in flex-grid networks the transmission reach depends on the transmission configuration of the tunable BVTs and of the regenerators and can be controlled. Thus, regenerator placement in flex-grid networks also involves choosing the BVTs' configurations, making it more complicated than in fixed-grid networks.

Optical networks are typically 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, which, as argued earlier, is becoming a very important parameter from an environmental, economical, and future growth point of view. Although the CAPEX cost and the energy consumption are correlated metrics, their relation is not always linear [7]. Therefore, energy-aware optical network design has started to receive more attention recently.

In this paper, we compare the energy consumption of different types of optical networks (fixed- and flex-grid), using appropriate planning algorithms for each type. In particular, we use energy-aware (EA-) 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 components used, in an attempt to calculate with high precision the energy consumption of actual cases. Our simulation results show that, depending on the specific characteristics of the physical network topologies, both flex-grid and MLR are by far the most energy-efficient solutions, and are able to successfully serve traffic demands even under heavy load. We also find that the more diverse is the network (in terms of path lengths) and its traffic, the more advantageous will be the use of flex-grid over fixed-grid technologies. We observed that transponders consume the majority of energy in current traffic conditions, and forecast that, in the future, regenerators are going to increase their percentage. We also observed that there is an interesting trade-off between power and spectrum minimization that depends on the specific characteristics of the network. Finally, we showed that accounting for actual location-based electricity prices, which varies especially in continental networks, we can obtain important monetary savings.

The rest of the paper is organized as follows. In Section II we report on the related work. In Section III we present the model used to calculate the energy consumption of the different types of optical networks that we examine. In Section IV we outline the energy-aware algorithms that we use in our studies. In Section V we present our performance comparison results. Our conclusions follow in Section VI.

II. Related Work

The energy efficiency of WDM networks has been a fruitful research subject in the past few years. More and more efforts focus on the design of energy-aware algorithms whose goal is to grant the same quality of service (QoS) with the lowest possible energy consumption and the lowest CAPEX. We classify these algorithms into two subcategories: algorithms for i) WDM networks [8–15] and for ii) flexible networks [16–18].

Approaches for WDM networks include grooming algorithms, optical bypass technologies, and techniques to switch off network elements. Grooming algorithms try to aggregate and route low-rate demands over wavelength-rate lightpaths so as to use a smaller number of transceivers and add/drop equipment. Optical bypassing is used to avoid energy consuming opto–electro–optical (OEO) conversions, that is, receiving and retransmitting the optical signal at intermediate nodes. Switching off elements takes into account time variations in traffic to reduce network overprovisioning and the redundant devices used for fault recovery.

A detailed survey of energy-aware network design and networking equipment is presented in [8], where the IP/grooming level and the WDM network are both considered. In [9] 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. Traffic grooming for energy reduction in WDM networks is also addressed in [10], where the authors show that the number of active components and, hence, total energy consumption in the network, can be reduced by looking further into the modular physical architecture of the network nodes during request allocations.

Another approach to saving energy in core/transport networks relies on switching off network nodes and links. In [11] the authors consider turning off nodes and links under connectivity and maximum link utilization constraints. They show that it is possible to power off some network elements and still guarantee full connectivity among sources and link utilization below a QoS-induced threshold. In [12] the authors propose an algorithm to reduce the power consumed by optical fiber links, considering client flow protection requirements.

The authors in [13] exploit the trade-offs between spectral efficiency, power consumption and optical reach in MLR WDM networks by taking under consideration the diverse capabilities of MLR 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 [14] the authors evaluate the energy efficiency of an MLR network compared to an SLR network. For the energy evaluation they consider the consumption of the transponders and the amplifiers and the energy required for electronic processing.

In [15] the authors develop a mixed integer linear programming (MILP) model to minimize the consumption of the IP over a flexible optical orthogonal frequency division multiplexing (OFDM) network. The power consumption they consider consists of router ports, erbium-doped fiber amplifiers (EDFAs), and OFDM tunable transponders. The authors of [16] propose heuristic algorithms to evaluate the energy consumption of flexible OFDM networks with respect to the MLR and SLR networks for static traffic scenarios. The developed heuristic algorithms serve the demand in a sequential order, selecting each time the most energy efficient choice. The authors of [17] concentrate on the energy efficiency of flexible optical networks with survivability constraints, comparing the dedicated-protection scheme to the shared-protection scheme. In

[18] the authors examine the use of traffic grooming, adaptive modulation format, and elastic spectrum allocation, with the objective of minimizing the total consumed energy. To do so, they formulate this minimization problem as an ILP and also develop a heuristic algorithm.

The main contributions that distinguish our present work from earlier works in the field are the following. First, we have developed detailed energy and cost models to assess the energy and cost of the various components employed at fixed- and flex-grid optical networks. Second, we use sophisticated energy-aware algorithms in the sense that they not only consider the full set of available options when trying to minimize energy consumption but also use exact models to calculate the consumed energy. In particular, the EA-RSA algorithm used in flex-grid networks takes into consideration 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 and applicable than those of most previous works. Third, we show that using the actual electricity prices for European countries plays an important role in OPEX minimization, a factor that has not before been considered in network planning algorithms.

III. Models—Network Architecture

The energy and cost model applied in our study takes as the key reference the model developed in the IDEALIST project [19]. The cost model includes equipment for both fixed- and flex-grid cases, and its basic building blocks are presented in Fig. 3. The model distinguishes between the traditional WDM systems, where each wavelength channel fits into the (ITU-T) 50 GHz grid [5], and a flex-grid system where channels can have different bandwidths allocated in a flexible spectrum having 12.5 GHz granularity.

In our model, we consider only the optical layer, and do not consider the grooming-electronic layer encountered before traffic enters the optical network. The reason is that although extra savings can be obtained by optimizing simultaneously both layers, typically telecom operators do this independently. So our focus is on the optical layer and the evaluation of the energy consumption and the savings that can be obtained by using energy-aware techniques at that layer. Moreover, according to [20], including the IP layer to groom the traffic did not show any significant differences between adaptive and MLR networks regarding the power consumption for different topologies and network scenarios.

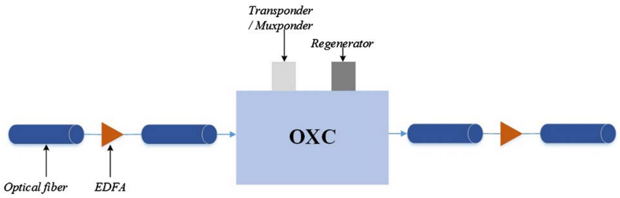


Fig. 3. Building blocks of energy/CAPEX model.

In the first part of this section we present the architecture of a WDM network, focusing on the characteristics of the components it consists of (Fig. 3). In the second part we describe in detail the energy and the CAPEX model of the optical layer, and we consider two types of equipment for WDM fixed grid and for flex-grid networks.

A. Network Architecture

The standard 50 GHz WDM layer is assumed to use coherent transmission exclusively and to have standard single-mode fiber (SSMF) as the reference physical medium. The WDM network consists of the interconnection of WDM nodes (optical switches) by pairs of bidirectional links. Each link consists of one fiber, which supports transmission over multiple wavelengths. The optical transmission starts and terminates at the related nodes at well-defined ports. It can optically bypass intermediate nodes. A transponder (receiver–transmitter pair) is required to receive/transmit the data via an optical wavelength and its main responsibility is to adapt the signal into a form suitable for transmission over the WDM optical network for traffic originating/terminating at a node.

The single fiber link model assumed here is presented in Fig. 4. The link is divided into spans, which consist of a 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. Since we assure coherent reception, no dispersion compensation fiber (DCF) is used.

The components that build the nodes are wavelength selective switches (WSSs), amplifiers (EDFAs in our study), combiners, and splitters, which are passive optical elements. 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. Since the node architectures of our study are based on WSSs, implementing the so-called route-and-select architecture [21], we will describe briefly their functionality. The WSSs are complex multiplexers/demultiplexers that select for the wavelengths the outputs to forward them. They are characterized by the number of WDM channels that they can support (e.g., 40 or 80) and by the number of outputs (e.g., 1×2, 1×4, 1×9, and 1×20). The same WSS can be used in both directions, either for multiplexing or for demultiplexing purposes. Figure 5 illustrates a $1 \times N$ WSS for demultiplexing purposes. Any of the wavelengths that come from the common input port can be forwarded independently of the others to any of the N outputs.

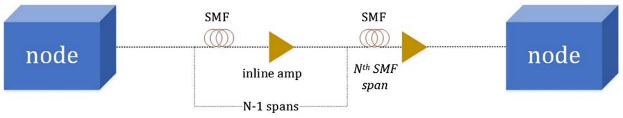


Fig. 4. Link model.

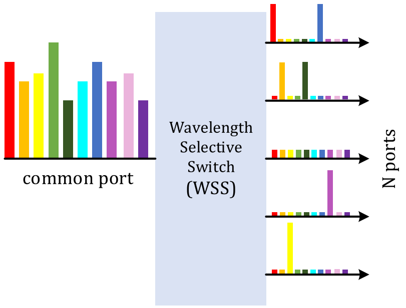


Fig. 5. Wavelength selective switch (WSS).

In our studies we consider two optical node architectures. The different features of these two examined node architectures presented below come from the different implementations of their add–drop terminals.

The node architectures evaluated in our study are both characterized by two basic features: directionless (any client port can be connected to any outgoing fiber and the opposite) and colorless (the client port can be tuned to any wavelength and any wavelength can be terminated from any incoming fiber to a client port). Contention is the characteristic in which these two architectures differ, as described below. Such nodes that are remotely configurable and utilize colorless and directionless add/drop ports are also called optical cross connects (OXCs).

The first OXC architecture (C/D/IC) considered (Fig. 6), even though it offers flexibility as far as the color and direction are concerned, it exhibits 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 given 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* (IC). The energy consumption of the incrementally contentionless OXC architecture is based on its comprising components and is described in the following equation:

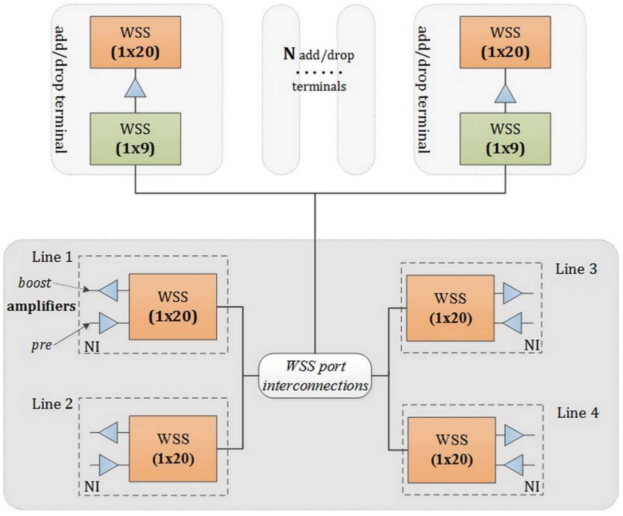


Fig. 6. Colorless, directionless, incrementally contentionless (C/D/IC) node architecture.

$$P_{\text{IC\_OXC}} = N\cdot(\text{WSS}_{(1\times20)} + \text{Amp}_{\text{bst}} + \text{Amp}_{\text{pre}}) + \text{WSS}_{(1\times20)} + \text{Amp}_{\text{drop}} + \text{Amp}_{\text{add}} + \text{WSS}_{(1\times9)}\,, \tag{1}$$

where N is the node degree; Amp_add, Amp_drop, Amp_bst, and Amp_pre correspond to the energy consumption of the amplifiers (double stage EDFAs); and $\text{WSS}_{(1\times20)}$ and $\text{WSS}_{(1\times9)}$ represent the energy consumption of the related WSS modules (see Table II below).

The contentionless feature is fully available in the fully flexible OXC (C/D/C) (Fig. 6), taken from the IDEALIST project and published in [22], allowing connection of any color from any transponder in any fiber direction. C/D/C architectures have the ability to support the dynamic traffic evolution in a flexible and economic manner, since additional transponders can be installed on a node without upgrading the node and without affecting the existing traffic.

The fully flexible colorless, directionless, and contentionless route-and-select node requires one add/drop chain for each network degree (network interface) plus a number of WSS modules on each add/drop chain depending on the number of channels to be added and dropped in the node.

$$P_{C\_\text{OXC}} = N\cdot(2\cdot\text{WSS}_{(1\times20)} + \text{Amp}_{\text{bst}} + \text{Amp}_{\text{pre}}) + 2\cdot N\cdot AD_{(\%)}/20_{(\%)}\cdot\text{WSS}_{(1\times20)} + 2\cdot N\cdot\text{WSS}_{(9\times9)}\,, \tag{2}$$

where N, Amp_bst, Amp_pre, and WSSs are as above, and $AD_{(\%)}$ is the add–drop percentage of the node (evaluated on the whole traffic crossing the node) with granularity of 20%.

To conclude, the components that make up the WDM layer and constitute the building blocks of our model (Fig. 3) are the WDM transponders used for optical–electrical (OE) and electrical–optical (EO) signal conversion, i.e., optical signal transmission and reception, the 3R regenerators, employed to compensate optical signal physical impairments at the optical layer, OXCs that are used for optical switching, and the line EDFAs.

The above described architecture is a typical way of building a WDM system. We assume that flex-grid networks, although not yet deployed, would follow the same architecture. The key differences are the use of flex-grid WSSs, also called spectrum selective switches (SSSs), and the use of BVTs. For this reason we will not give more details in this section and list the energy consumption of the different modules in the next section.

B. Energy and CAPEX Model

The cost model used in our studies consists of two types of expenditures: energy consumption cost and CAPEX. CAPEX refers to the costs pertaining to the cost of ownership of the network equipment. Following the IDEALIST CAPEX model [19], the reference cost unit (c.u.) that we use is the 100 Gb/s coherent transponder. As nowadays the state of the art in the transponder technology is now coherent 100 Gb/s, the cost unit is defined as the cost of such a 100 Gb/s device. All other devices are priced with reference to this c.u. The energy consumption cost includes the cost arising due to the energy consumed by the components comprising the optical network. In order to define the energy consumed by the different optical components, we used various sources, such as datasheets of commercially available equipment, project deliverables, and cooperation with telecom operators.

In this section the modeling for a WDM fixed-grid network and for a flex-grid optical network is discussed in detail. Taking the energy consumption study a step further than before, we exploit real data concerning the current electricity prices in European Union countries to translate energy consumption into euros per hour. In this way we connect the energy consumption with monetary OPEX cost and examine whether OPEX savings can be obtained by exploiting the differences in electricity prices among the countries when considering a pan-European network. We will discuss this further in Subsection V.F.

1) WDM Fixed-Grid Optical Network Model: The following resources are considered in the energy and CAPEX models for the WDM fixed-grid: transponders, regenerators, OXCs consisting of WSSs, and amplifiers.

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 I. In our studies we did not consider 10 Gb/s or 1 Tb/s transponders. The former are not compatible with the main WDM model assumptions as they use incoherent reception and need special dispersion compensation link strategies, and the latter are not expected to appear in the near future. For each transponder, a corresponding regenerator is available.

The basic building components for the OXCs are $1 \times 9/9 \times 1$ WSS, 9×9 WSS, $1 \times 20/20 \times 1$ WSS, optical amplifier, and passive optical splitter and combiner. Table II presents the energy consumption and the cost of these components.

The NIs and the add/drop terminals are part of the OXC; hence we consider their contribution in energy consumption and cost through Eqs. (1) and (2) (see Figs. 6 and 7).

TABLE I
Energy Consumption and Cost of Transponders and Regenerators for Fixed-Grid WDM

Fixed-Grid Transponders and Regenerators				
Type	Capacity (Gb/s)	Reach (km)	Energy Consumption (watts)	Cost (c.u.)
TSPs	40	2500	170	0.48
	100	2000	240	1
	400	500	480	1.36
Regens	40	2500	170	0.77
	100	2000	240	1.6
	400	500	480	2.18

TABLE II
Energy Consumption and Cost of OXC Components

OXC Components		
Architecture	Energy Consumption (watts)	Cost (c.u.)
$\mathrm{WSS}_{(1\times20)}$	28	0.48
$\mathrm{WSS}_{(1\times9)}$	20	0.32
$\mathrm{WSS}_{(9\times9)}$	60	3.84
Double stage EDFA	30	0.06
Splitter/combiner	0	0.00

Finally, we assumed the amplification span to be 80 km. We study only the case of EDFAs used after each span, since these are the ones most commonly used. The cost/energy consumption of a double stage EDFA is listed in Table II.

2) Flex-Grid Optical Network Model: As opposed to the fixed transponders of WDM networks, the traffic in flex-grid networks is served by BVTs. We assume that the BVTs can 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 (QoT).

It has been demonstrated in [23] that format flexible transponders have the same power consumption independently of the chosen modulation format. However, the transmission reach depends mainly on the modulation format and the achieved spectrum efficiency [24]. So the main advantage of format flexible transponders relies on the variety of transmission distances, hence the possibility of skipping intermediary regenerators when deemed. On the other hand, it stands to reason that the energy consumption depends on the baud rate used. So baud-rate flexible transponders can trade-off energy consumption for other parameters.

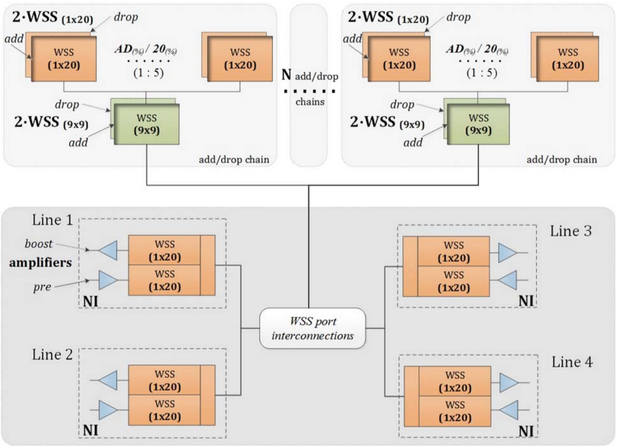


Fig. 7. Colorless, directionless, contentionless (C/D/C) node architecture.

In particular, only the subsystems of the transponder that provide electronic processing exhibit energy consumption that depends on the operating baud rate. Thus, the energy consumption of a flexible transponder is split into two categories: i) static and ii) dynamic energy consumption. This static power allows the electronic maintenance of logic levels in the device, but also the various leakage currents (more and more important with the decrease of feature sizes and the lowering of the threshold levels). The dynamic power consumption of the device depends on the frequency at which the device 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 [25], and this is the assumption that we have adopted here.

In coherent-based transponders, a large part of the power consumption is due to the data processing by application-specific integrated circuits (ASICs) and/or field-programmable gate arrays (FPGAs), noticeably the framer, FEC codec, and digital signal processing (DSP) blocks. In 40 Gb/s transceivers, such devices consume 73% of the whole power consumption, while for 100 Gb/s and higher capacity transponders this ratio will be about 90%.

The model assumed for the BVT transponders is that of the muxponder that has maximum rate of 400 Gb/s. The components that are taken into account for the energy consumption model for the BVT are divided into the following categories: i) client side, ii) E/O modulation, and iii) O/E receiver. The first category consists of the client cards, the component of framer/deframer, and of the FEC module. Note that, at each 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, the modules of photodiode, transimpedance amplifier (TIA), analog-to-digital conversion (ADC), and DSP are included.

In our BVT transponder architecture we assume the use of two lasers for transmitting up to 400 Gbps, with DP-16QAM as the highest modulation format. The energy consumption depends each time on the number of lasers that are active. The equation used to compute the power consumption of the BVT transponder is based on [19]

$$P_{\mathrm{BVT}} = n \cdot (108 + 4.8 \cdot R) \cdot 1.2, \tag{3}$$

where R is the baud rate at which the transponder operates, n is the number of active lasers, and 108 is the summation of the elements that have static power consumption, while 4.8 is used to capture the dynamic consumption and was calculated to fit linearly to 100 and 400 Gbps. Finally, the total consumption assumed for a BVT transponder is increased by 20% to capture the power management consumption.

From the aforementioned components, all the components have fixed energy consumption except of the framer/deframer, FEC, and DSP that depend on the transmission baud rate. Table III presents the transmission options of the assumed BVT model, including the energy consumption for each option.

TABLE III
ENERGY CONSUMPTION OF BVTS

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

IV. DESCRIPTION OF ALGORITHMS

In this section we outline the algorithms we used in our studies for minimizing the energy consumption when planning SLR and MLR fixed-grid WDM and flex-grid optical networks. In particular, the algorithms are referred to as EA-RWA for the MLR and SLR fixed-grid WDM networks and EA-RSA for the flex-grid network.

We start by giving a general definition of the network planning problem that is common in all cases, and then we focus on the differences among the algorithms. 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 architectures are those presented in Subsection III.B, in which the only difference between the fixed- and flex-grid cases is the use of bandwidth-variable WSSs in the latter case. The available transponders in the fixed- and flex-grid cases are also presented in Subsection III.B. Finally, we assume that, in the case of fixed-grid networks (SLR and MLR), the system supports W wavelengths, while in the flex-grid case, the network supports S spectrum slots.

The objective is to serve all traffic and minimize the energy consumed in the corresponding fixed-grid WDM and flex-grid optical networks. To do so, we reduce the number of power consuming components, such as transponders, regenerators, add/drop terminals, and amplifiers, which leads to the reduction of the energy consumed in the whole network. Especially for the case of MLR networks, minimizing the energy consumption of the transponders is achieved by choosing the right type of transponder for each connection. In flex-grid networks, assuming the use of a single type but tunable transponder, the main issue is to choose the right configuration of the transponder for each connection.

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, since searching for absolute optimums for several scenarios would be time consuming. In particular, the heuristic algorithms we used for the different cases follow a similar logic. They serve all the demands defined in the static traffic matrix one-by-one according to a specific ordering, remembering the choices made for previous served requests so that we can 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) depends significantly 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 or utilizing a network interface over another path, could differ later when the chosen path becomes congested and requires adding more add/drop terminals, while the avoided path turns out to be relatively empty. Since the ordering plays an important role, our algorithms use a simulating annealing (SA) metaheuristic to search among different orderings.

For the SLR-RWA algorithm we used the heuristic algorithm presented in [26]. This algorithm precalculates k-shortest paths for each demand. Then for each path, given the transmission reach of the specific SLR transponder, the algorithm allocates a regenerator at the previous node of the link that, when added, makes the path longer than the given transmission reach. The algorithm takes into account the optical switch architecture, the add/drop terminal NIs utilized up to that point, and the regeneration points of each of the k-paths. It selects the path that minimizes the incremental energy consumption of serving the demand at hand and continues serving the next demand.

For the MLR RWA heuristic algorithm, we used a heuristic variation of the MLR algorithm of [27]. In this case, each demand can use different types of transponders (with different reaches). So, for each of the k-shortest paths, we do similar calculations as in the SLR case, but this time for each type of transponder, and we make all these options available to the algorithm. The algorithm selects the one that results in the smallest increase of the energy consumption in the network and moves on to serve the next demand.

Finally, for the flex-grid case we extended the heuristic algorithm presented in [28] to make it energy aware. The different configurations of the transponders are passed to the algorithm as feasible transmission configuration tuples $t = (l_t, r_t, b_t, g_t, c_t, v_t)$, as shown in Table III. The algorithm is extended to include in its weighted multiobjective cost the energy consumption of serving a request. Following similar steps as the fixed-grid algorithms, 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, this algorithm has 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 others (see [28] for a more detailed description about domination operation). Then the algorithm calculates the incremental network energy consumption of each option, taking into account the demands served up to that point (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 our experiments the weighting coefficient for the energy consumption in the minimization function was set so as to solely minimize the energy, neglecting the spectrum used. We also present results for minimizing solely the spectrum used in Subsection V.E, and considered it to be the energy-unaware solution that formed the basis for our comparison. Note that the proposed flex-grid RSA algorithm is general and can also be used to minimize the energy consumption of the SLR and MLR cases by appropriately defining the transmission tuples.

V. Illustrative Results

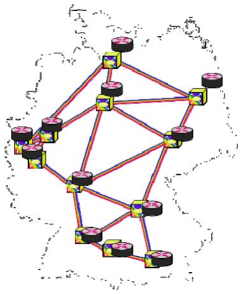
In this section we evaluate the energy consumption and the CAPEX cost of several realistic networks under the network architectures and models presented in Section III and varying degrees of traffic. In particular, we assume that the networks under study are deployed using fixed-grid WDM (both in the 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 IV. As discussed in Section III, 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 I. Two types of WDM networks are considered: SLR where all the transponders are of the same type, one of those presented in Table I, and MLR where all the transponders of Table I are available. The reach values are the same for both the SLR and MLR cases.

For the flexible network, the width of the spectrum slot is considered to be 12.5 GHz, 320 slots are available, and the available transmission configuration of the BVTs are those presented in Table III.

The topologies used in our simulations are i) the Deutsche Telekom (DT) (Table IV), ii) the Telefonica

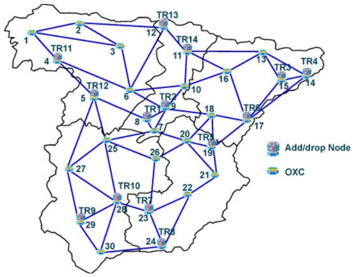
TABLE IV
DT NATIONAL BACKBONE NETWORK



Operator	Location		Segment Covered		
DT	Germany		Core		
	Nodal Degree			Link Length (km)	
Nodes	Average	Max	Links	Average	Max
12	3	5	40 *bidirectional*	243	459

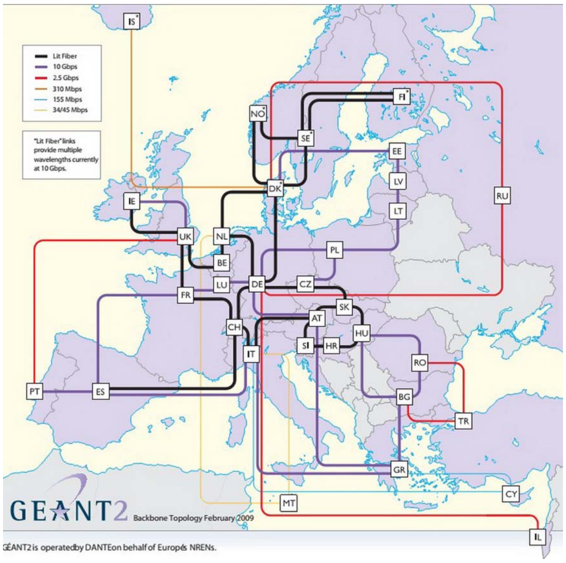
(TID) (Table V), and iii) the GÉANT (Table VI). For these networks we also used realistic traffic matrices. The traffic matrices of the DT and TID networks used in our simulations are based on traffic models provided by the operators (DTAG and TID) participating in the IDEALIST project [19]. According to the aforementioned traffic models, the traffic loads for the DT and TID networks for year 2012 are equal to 1917.33 and 834.94 Gbits/s, respectively. The data concerning the GÉANT network are available to us through the DICONET project, which was completed in 2009, and as a result the reference traffic matrix we used is that of 2009. The traffic load for the GÉANT network for the year 2009 is equal to 2236 Gbits/s and the yearly traffic growth is equal to 35%, which results for the year 2012 to a traffic load of 5501.40 Gbits/s. We assumed that traffic increases by 35% per year, and graph results for 12 years with a step of 2 years for all networks. 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. Unless otherwise stated, the OXC architecture employed is the C/D/IC (Subsection III.A).

TABLE V
TID NATIONAL BACKBONE NETWORK



Operator	Location		Segment Covered		
TID	Spain		Core		
	Nodal Degree			Link Length (km)	
Nodes	Average	Max	Links	Average	Max
30	3.7	5	56 *bidirectional*	148	313

TABLE VI
GÉANT BACKBONE NETWORK



Operator	Location		Segment Covered		
DANTE	Europe		Core (Continental)		
	Nodal Degree			Link Length (km)	
Nodes	Average	Max	Links	Average	Max
34	3.2	5	54 *bidirectional*	752	2361

A. Total Power Consumption

In this section we present the energy consumption of the SLR, MLR, and flexible networks, for the three reference networks listed above (Fig. 8). We also introduce a new metric to measure the energy efficiency of the network, called *energy transportation efficiency*, defined as the ratio of the total traffic transmitted in the network over the related energy consumption (Mbits/joule). This metric depicts in a clearer way the associations between the physical network topology and the energy consumed to serve the requested capacity (Fig. 9).

In all examined networks (Fig. 8) the flex-grid network (EA-RSA algorithm) is shown to exhibit the lowest power consumption, at heavy load. At medium load, the energy consumption of the flex-grid network is quite close to that of the MLR, with the MLR being slightly more efficient at light load. As load increases, the MLR network becomes less efficient, giving an advantage to the flexible network that exploits the higher number of transmission options it has at its disposal. The point that this happens is the year 2018, with small variations between the different network scenarios. The performance of the SLR case for the three

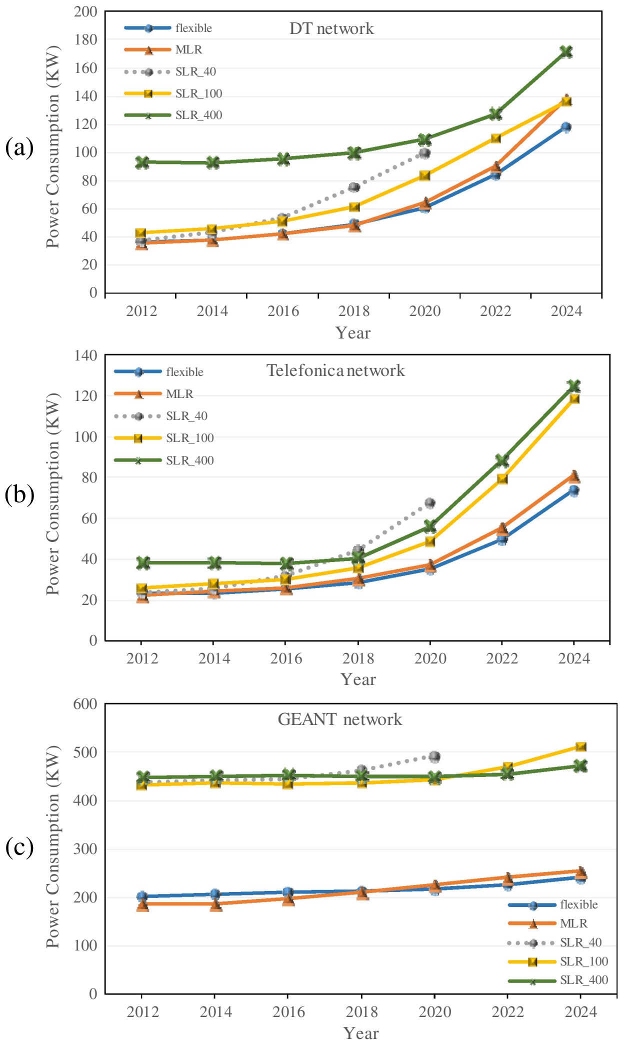


Fig. 8. Total power consumption for (a) the DT network, (b) the TID network, and (c) the GÉANT network.

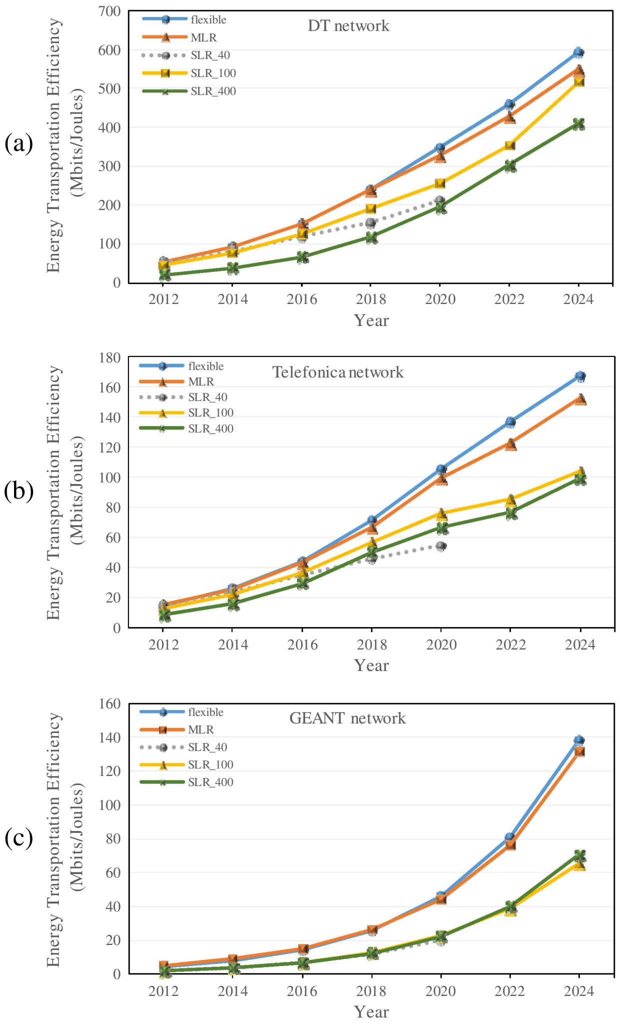


Fig. 9. Energy efficiency for (a) the DT network, (b) the TID network, and (c) the GÉANT network.

different transmission rates is inferior to the MLR and flexible networks in all traffic scenarios examined. This is expected, since the MLR can take the form of any of these and utilize the SLR 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 by the demanded capacity between each pair of nodes. For a light load, the SLR of 40 Gb/s is more efficient than the other two SLR options. Also the performance of the SLR of 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 than 40 Gb/s and probably at some point after the maximum load we have examined, 400 Gb/s would also become more efficient than 100 Gb/s. Note that we stop presenting the performance for the SLR of 40 Gb/s after the year 2020 since, after that, we start exhibiting blocking with the 80 provisioned wavelengths for the WDM network. Note also that the performance of the SLR network solutions for the GÉANT network is substantially worse than that obtained for 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 GÉANT network that make it inefficient to serve traffic with a single type of transponder/regenerator, as done in the SLR solutions.

From Fig. 8 it becomes evident that the flexible network and the MLR WDM network exhibit similar energy efficiency under almost all traffic conditions examined, clearly outperforming any of the SLR WDM networks. The reason is that the flexible and MLR networks are capable of exploiting the different transmission options, which gives them the ability to fine-tune the transmission rate to the actual capacity demanded.

The results in energy efficiency obtained for the three examined networks are presented in Fig. 9. For the DT topology [Fig. 9(a)], the flexible network performs similarly to the MLR for the first years of our study, outperforming it for years 2022 and 2024, where the 100 Gb/s wavelengths become the predominant ones, which explains the similar performance of the MLR and the 100 Gb/s networks. The slight difference in energy efficiency between the flexible and the MLR networks is justified from the finer granularities of the different modulation formats, compared to the wavelengths in MLR.

In the TID topology [Fig. 9(b)], we observe similar performance in terms of energy efficiency as in DT, with the difference that in this case the 100 Gb/s network is clearly outperformed under most of the traffic conditions considered in the study. The main reason for this is the long distances traveled by some paths in this network, which result in the placement of a high number of regenerators, causing an increase in power consumption for the 400 and 100 Gb/s networks, since their reach is 500 and 2000 km, respectively.

The difference that arises in the GÉANT topology [Fig. 9(c)] is that the MLR network follows closely the flexible network until the last year of the study. The GÉANT topology is characterized by many long distance paths, which leads, as in the TID topology, to the placement of regenerators that increase the power consumption. The flexible network has the ability to adjust to the long distances of some paths in this network, exploiting the different subcarrier modulation formats and rates that offer the maximum reach, while the MLR network for these paths is able to use the 40 Gb/s wavelength that offers a reach of 2500 km.

B. Capital Expenditure

In this section we present the CAPEX metric for the three reference networks (Fig. 10) when planned using a SLR, MLR, or flex-grid networking solution.

Similarly to the previous case, the flexible and the MLR algorithms have very close performance, with the flexible network being worse in most cases and improving as the offered load increases. It is worth noting here that in the above calculations the costs of the BVTs and the flex-grid WSSs are assumed to be 30% higher than those of the corresponding WDM equipment. Note also that the algorithms used were designed to optimize the energy consumption and thus the CAPEX cost was indirectly optimized.

The flex-grid solution seems more cost efficient than MLR when there is large versatility/variance in the path lengths and the demands, so as to make use of the various transponder configurations, as in the case of the GÉANT network [Fig. 10(c)] at heavy load. The more diverse is the network and its traffic, the more advantageous will be the use of flex-grid over fixed-grid technologies. Again the performance of the SLR networks is much worse compared to the MLR and flex-grid cases.

We did not assume any decrease in prices of the component costs over time. Our study is comparative and we considered that the components used will follow similar learning curves and, therefore, the cost changing through time will not affect our comparison. The assumption that the network components used will follow similar learning curves is based on their architecture, since the various components (e.g., 100G transponders and 400G transponders) consist of the same building blocks.

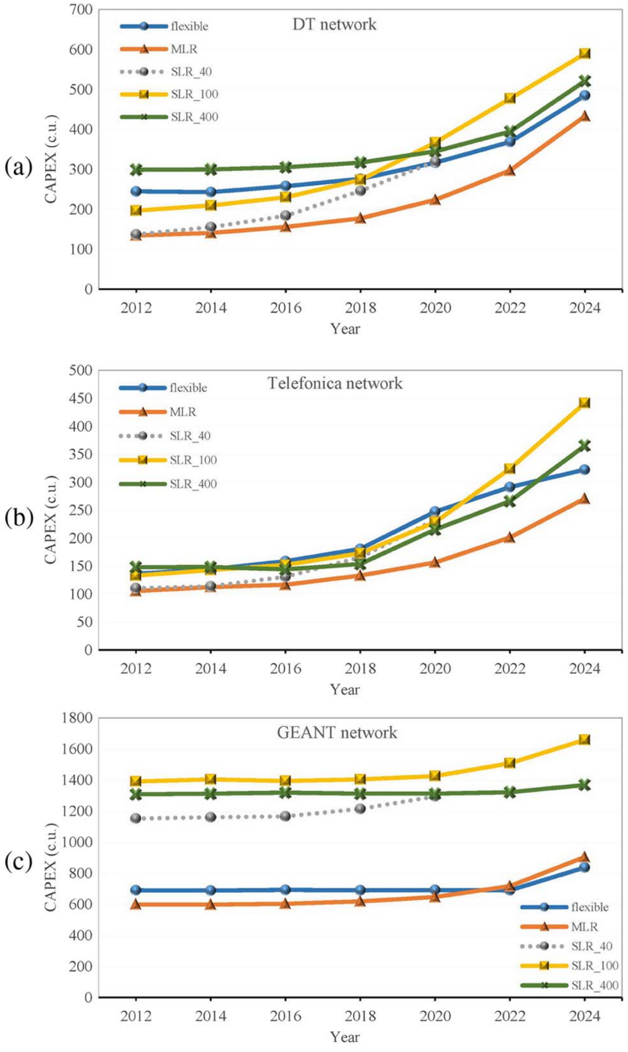


Fig. 10. CAPEX for (a) the DT network, (b) the TID network, and (c) the GÉANT network.

C. Maximum Spectrum Used

We now present the results obtained regarding spectrum utilization for the three reference networks and the three different optical technologies (Fig. 11). The flex-grid solution, due to the intrinsic characteristic of finer granularity and many transmission options, achieves in all cases the lowest spectrum utilization. Second comes the MLR, which also takes advantage of the different transmission modes, but there are fewer than the ones available in the flex-grid case. The SLR 400 Gb/s network achieves very low maximum spectrum utilization in cases where the link lengths of the network are small enough to be able to support high rate transparent transmissions [DT and TID, Figs. 11(a) and 11(b)]. The high rate transmission in such cases is possible only with the use of a large number of regenerators. As a matter of fact, the wavelength continuity constraint is relaxed, achieving consequently better spectrum utilization. Using many regenerators, however, has a negative effect

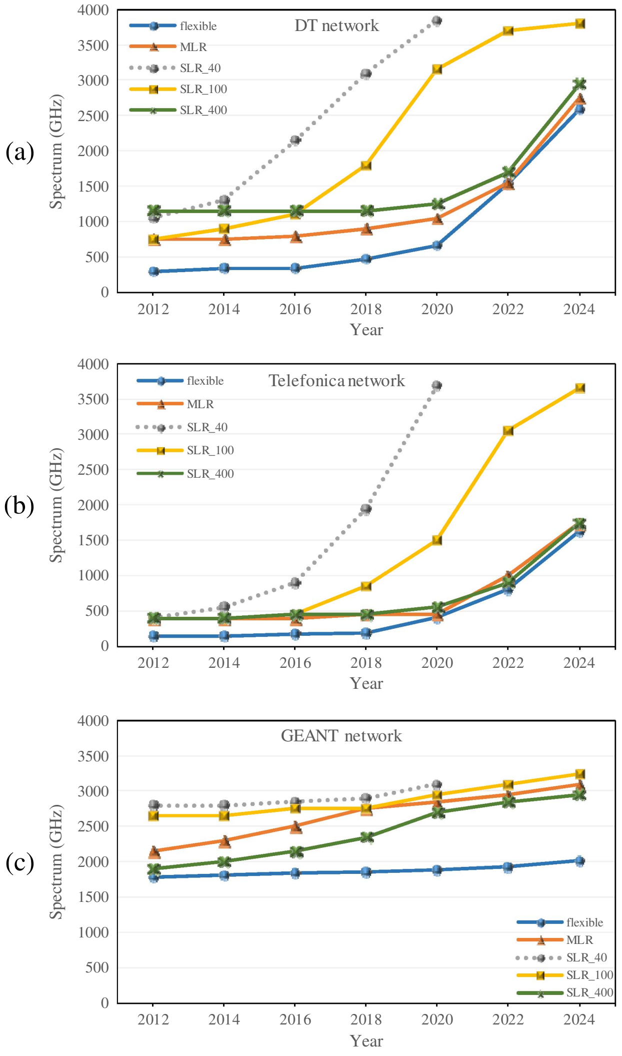


Fig. 11. Maximum spectrum used for (a) the DT network, (b) the TID network, and (c) the GÉANT network.

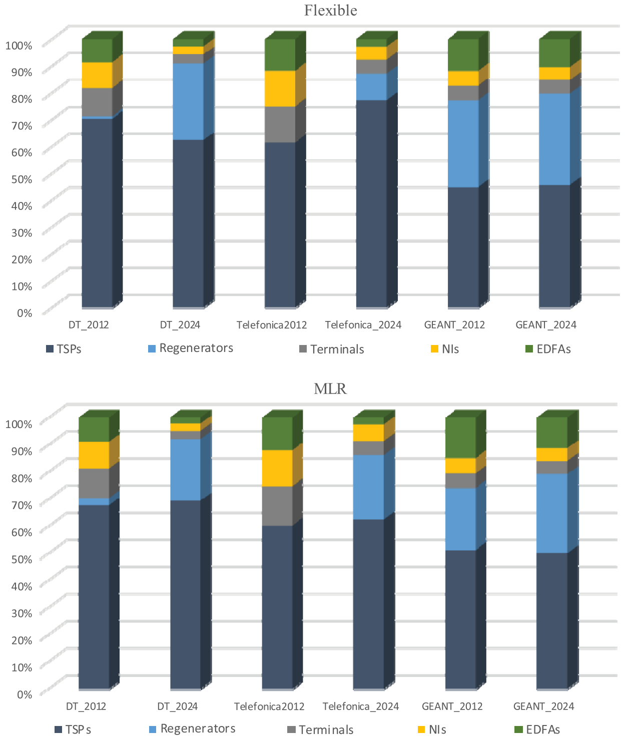


Fig. 12. Power consumption per component for (a) the flexible network and (b) the MLR network.

on the energy consumption and the CAPEX cost, explaining why the SRL 400 Gb/s case has the worst performance with respect to these two metrics, as shown in the previous sections.

D. Energy Consumed per Component Type

In this section we report on the contribution of every component of a flexible network and a MLR network in the total power consumption for the three topologies of our study.

Figure 12(a) shows that for the flexible DT and TID network topologies and light traffic (year 2012), almost 70% of the total power expended in the WDM layer is consumed by the transponders. As traffic increases, a larger number of regenerators is needed, changing the energy profile of the network, since regenerators consume a significant amount of power. In contrast, the GÉANT topology is characterized by many paths with long distance, and its traffic matrix contains many low rate demands, justifying the use of regenerators from the first years of our study (2012) where the traffic load is low. We also observe that the above specific characteristics of the network physical topology result in a steady contribution of each component through the years. Similar results are obtained for the MLR network and are presented in Fig. 12(b). We observe that transponders consume the majority of energy under current traffic conditions, but the regenerators are going to increase their percentage as time progresses and traffic increases.

E. Trading Off Energy for Spectrum

In this section we evaluate two different objective functions for the flex-grid 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 spectrum slots, or different configurations of the BVTs trade-off energy versus spectrum consumption. Similarly, when the objective is the minimization of spectrum, the energy consumed in the network turns out to be significantly higher. Note that minimizing spectrum utilization is a typical objective used in many planning algorithms. By taking this into account we can consider the spectrum minimization objective as resulting in an energy-unaware design. Thus, when we compare the performance obtained using the energy-aware algorithms with the related algorithms with a spectrum minimization objective

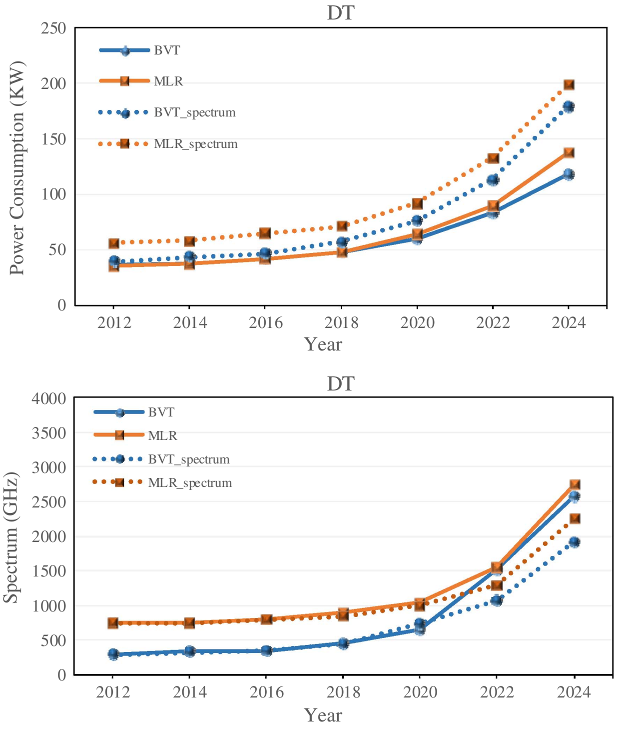


Fig. 13. Power savings versus spectrum occupancy: DT network.

we can observe the energy savings achieved by energy-aware planning.

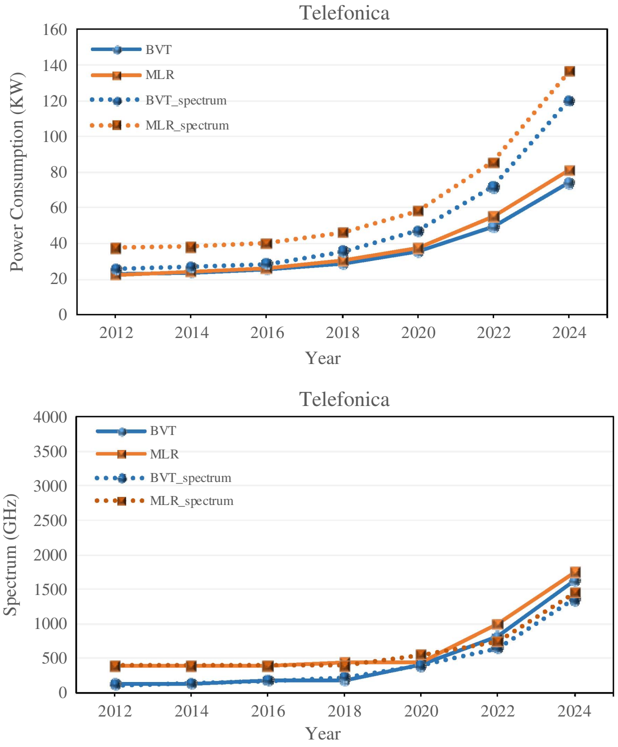


Fig. 14. Power savings versus spectrum occupancy: TID network.

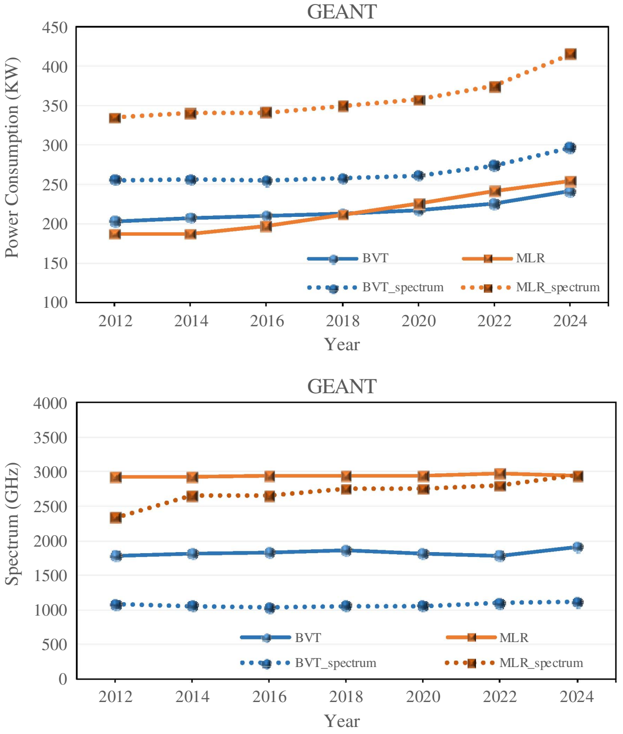


Fig. 15. Power savings versus spectrum occupancy: GÉANT network.

From Figs. 13 and 14 we can observe that for both the DT and TID topologies we can achieve noteworthy power savings when using an energy-aware algorithm as opposed to an energy-unaware approach (spectrum minimization). It is worth noting that the sacrifice is small since the spectrum utilization is relatively close to the best we can achieve when using the spectrum minimization objective.

On the other hand, in the GÉANT topology with the versatility characteristics of links and demands, to achieve power savings we have to sacrifice considerably more spectrum (Fig. 15). So, we observe that there is an interesting trade-off between power and spectrum minimization that depends on the specific characteristics of the network that can be exploited by the operators.

F. Energy-Price-Aware Planning

In reality, in core networks, not all nodes have the same energy cost. This is especially the case for continental networks, such as GÉANT [29] and NSFNET [30], but is also true even for national networks. This provides an additional optimization dimension that can be exploited in network planning.

In Table VII we present the electricity prices for industrial consumers for countries participating in the GÉANT network, as of the second semester of 2012 [31].

To take advantage of this case, we have extended our EA-RSA algorithm for planning flex-grid networks in order to take into account the price of energy at each node when

TABLE VII
ELECTRICITY PRICES IN COUNTRIES OF THE GÉANT NETWORK

Electricity Prices for Industrial Consumers
for Countries in the GÉANT Network
Electricity—Band IC: 500 MWh < Consumption < 2000 MWh

2012 2nd Semester

Country	€/100 kWh	Country	€/100 kWh
Austria (AT)	11.66	Iceland (IS)[a]	12.56
Belgium (BE)	13.4	Italy (IT)	23.29
Bulgaria (BG)	9.35	Lithuania (LT)	13.84
Switzerland (CH)[a]	16.76	Luxemburg (LU)	10.74
Cyprus (CY)	27.32	Latvia (LV)	13.44
Czech (CZ)	12.34	Montenegro (MT)	18.9
Germany (DE)	17.27	Netherlands (NL)	11.59
Denmark (DE)	25.92	Norway (NO)[a]	10.46
Estonia (EE)	9.81	Poland (PL)	11.76
Spain (ES)	14.47	Portugal (PT)	14.09
Finland (FI)	9.15	Romania (RO)	10.52
France (FR)	9.42	Russia (RU)[a]	8.36
Greece (GR)	13.81	Sweden (SE)	9.7
Croatia (HR)[a]	18.86	Slovenia (SL)	11.29
Hungary (HU)	13.57	Slovakia (SK)	15.25
Ireland (IE)	15.75	Turkey (TR)[a]	20.96
Israel (IL)[a]	14.66	United Kingdom (UK)	14.43
EU-27 (EU)			14.66

[a] Countries for which data were not publicly available. We considered that the electricity prices for these countries were evenly distributed between the min and max of the EU-27 prices.

placing regenerators. Changes in the placement of regenerators can have an important impact on the monetary cost of the power consumed. We can reduce the monetary cost by avoiding placing regenerators in cities with high energy prices, putting them instead in neighboring countries with lower energy prices, or even breaking the demand into multiple lower rate connections, taking advantage of the higher reach they offer if the source has much lower electricity cost than intermediate nodes.

In Fig. 16 we present the improvement we achieved by energy-price-aware planning, using real data for the electricity prices (Table VII). As depicted, an improvement in the monetary cost of the energy consumed in the network between 7.49% and 10.21% can be achieved.

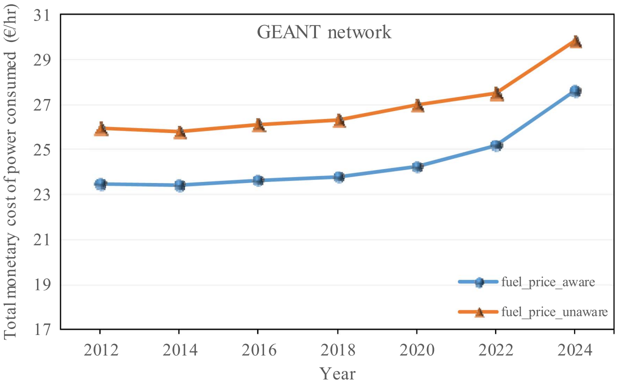


Fig. 16. Monetary savings through relocation of regenerators based on the fuel price per country.

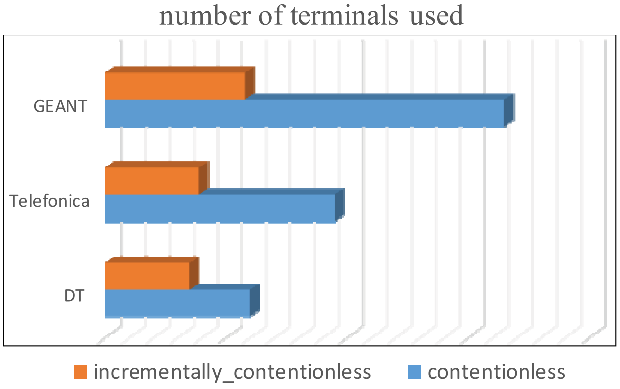


Fig. 17. Power consumption of the terminals used according to the two different OXC architectures.

G. Number of Terminals Used for the Two Different OXC Architectures

In Fig. 17, we present the number of terminals used under 2024 traffic conditions for the three different topologies for the flexible network and for the two different OXC architectures described in Section III, namely the contentionless OXC architecture (C/D/C) and the incrementally contentionless (C/D/IC). Even though the contentionless architecture offers full flexibility, it consumes up to 60% more power than the incrementally contentionless architecture. Thus, the price to pay for full node flexibility also includes higher power consumption.

The increase of the energy consumption depicted in Fig. 17 that arises from the extra equipment used in the fully flexible architecture and the high power consumption of the 9 × 9 WSS was the decisive factor for our focusing on the incrementally contentionless architecture, which, even though not fully flexible, is less power hungry. The fully flexible OXC seems very promising for dynamic traffic and rapid deployment of new transponders, while the incrementally contentionless architecture is more efficient when planning the network for specific traffic, following a pay as you grow approach.

VI. CONCLUSION

The inevitable growth of Internet traffic through time leads to increased power consumption of Internet infrastructures and devices. To fulfill the need for networks to keep their own power consumption growth under control, we developed analytical models for the energy consumption of a fixed- or flex-grid optical layer. We applied our model on real topologies and traffic scenarios, obtaining results for the power consumed by every element in the optical layer and in every node of the network topologies. We combine the CAPEX/OPEX model developed with sophisticated energy-aware algorithms to evaluate the energy efficiency in different network topologies. Finally, we extended our work by accounting for actual location-based electricity prices, showing that in a continental network important monetary savings can be obtained by adjusting the routing decisions based on such information.

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