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Energy-minimized design of IP over flexible optical networks

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SUMMARY

Energy efficiency is an important desirable property for optical networks and a key parameter for the sustainability of the future Internet. In this work, we consider the energy-minimized design problem for IP over flexible optical networks. We provide an energy-aware multilayer network-planning algorithm, which takes as input the network topology, the IP end-to-end traffic matrix, the modular model of the IP/MPLS routers, and the feasible configurations of the flexible optical transponders. The algorithm serves the demands for their requested rates by placing router modules, selecting the paths in the IP topology, and the corresponding paths and spectrum slots in the underlying optical topology, together with the flexible optical transponders' transmission configurations. The algorithm's objective is to minimize the network's energy consumption, jointly accounting for the energy consumption of the routers' modules installed, the transponders used, and their configurations. Using realistic energy consumption and network traffic models, we evaluate the energy savings obtained when the proposed algorithm is applied to a flexible network, as opposed to a mixed-line-rate wavelength division multiplexing optical network. Moreover, we consider two optimization scenarios, comparing the joint energy consumption optimization of IP and optical layers to a sequential optimization of the energy consumed at these two layers. Copyright © 2015 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Despite the undisputed energy efficiency benefits brought about through the use of information and communications technology (ICT), the ICT industry itself has recently been identified as a major contributing factor to the emission of greenhouse gasses, held responsible for the global warming problem. According to [1], about 8% of the total world's electricity is consumed by ICT, and many concerns have been raised regarding the limitations that energy consumption may put on Internet growth. It is a common knowledge that the number of end users and their demanded network speeds exhibit a very rapid growth. This yields an exponential increase in the bandwidth demand, and the need for Internet service providers to keep on deploying and continuously upgrading their network infrastructures, resulting to a consequent continuous increase in the telecommunications networks' energy consumption [2, 3]. So the design of energy-aware algorithms for core and metro telecommunication networks seems to be more imperative than ever.

The dominant technology used today for establishing connections in core and metro networks is wavelength division multiplexing (WDM) over optical fibers, where data are transmitted over

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lightpaths, that is, all-optical WDM channels spanning a single or several consecutive fibers. However, WDM optical networks are rigid and static in physical terms resulting in poor utilization, stranded capacity, and inability to adjust to new service demands in a timely manner. To overcome these inefficiency problems of typical WDM optical networks and meet the future needs for bandwidth in an effective and more flexible manner, elastic (or flexible) optical networks have been proposed. Flexible networks are based on (i) flex-grid technology that enables the slicing of the spectrum according to the actual needs, as opposed to the rigid granularity of WDM networks and on (ii) flexible transponders, also known as bandwidth variable transponders, which provide tunability of several transmission parameters. Moreover, the increased flexibility can play a role in improving the energy efficiency, as opposed to the rigid WDM optical networks [4–6].

In this paper, we focus on the energy-minimized design of Internet Protocol (IP) over flexible optical networks. At the IP layer, we consider the IP/MPLS routers located at the edges of the optical network that aggregate the traffic to be forwarded over the flexible optical network. Because packets are forwarded transparently over lightpaths, there is no packet/header processing in the optical network, and the majority of the energy is consumed at the electronic edges or the intermediate IP/MPLS routers of the network that process the packets. Other types of routers and protocols (such as MPLS-traffic engineering or optical transport network) can be used at the edges of the optical network, to make a virtual/IP topology and serve the traffic over the optical network. The solution to be proposed can be extended in a straightforward way to account for such differences. In this work, we extend our previous work [7] and propose an energy-aware multilayer planning algorithm for IP over flexible optical networks. In [7], we showed that planning an optical network in a jointly multilayer optimization process can yield important spectrum and cost savings both at its electrical router edges and in the optical equipment. In this paper, we show that corresponding savings in energy consumption occur both at the IP and optical layers when these layers are planned through a joint process, and that the savings are more pronounced when the underlying optical network is based on flexible as opposed to mixed-line-rate (MLR) technology.

The multilayer network planning problem of an IP over flexible optical network consists of sub-problems at two layers: the IP-layer routing (IPR) sub-problem at the IP layer, and the routing, modulation level, and spectrum allocation (RMLSA) sub-problem at the optical layer. The RMLSA problem can further be broken into two substituent sub-problems, namely, (i) routing and modulation level (RML) selection and (ii) spectrum allocation (SA). Following the same approach we adopted in [7], the proposed energy-aware algorithm solves the multilayer network planning problem (IPR + RML + SA) jointly with objective being the minimization of network's energy consumption. As in [7], we decided *not* to decouple the IPR, RML, and SA problems. This is because in the case that flexible transponders are used (described by the so-called *feasible transmission tuples* [8–10]), the rate of an optical connection depends on its physical length (RML decision), which in turn affects the IPR and SA decisions. This is the reason that algorithms that decouple these three sub-problems by sequentially planning the IP and optical layers or performing SA independently are bound to be inefficient and waste resources.

The proposed energy-aware multilayer network-planning algorithm is general as (i) it can be applied to both flexible and fixed-grid MLR or single-line-rate networks; the only requirement is to describe the input in the form of feasible transmission tuples, and (ii) it can also be used to jointly or sequentially (separately) plan the IP and optical layers. In the case of joint multilayer network planning (JML-NP), the IPR, RML, and SA sub-problems are jointly solved, while in the case of sequential multilayer network planning (SML-NP), the IPR, RML, and SA sub-problems are sequentially solved.

We conducted simulation experiments using realistic energy, network, and traffic models and found that the flexible network outperforms the MLR network, in terms of energy consumption, for all traffic cases examined and regardless of the planning solution adopted (JML-NP or SML-NP). Moreover, we observed that for both flexible and MLR networks, the total energy consumption is smaller when joint multilayer optimization over the IP and the optical layer (JML-NP) is applied, as opposed to planning the two layers sequentially (SML-NP).

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The rest of the paper is organized as follows. In Section 2, the related work is presented, while Section 3 describes the network architecture and the multilayer network planning problem. Section 4 describes the network energy consumption model, while Section 5 describes the proposed energy-aware multilayer network planning algorithm. Simulation results are presented in Section 6. Finally, our conclusions are given in Section 7.

2. RELATED WORK

A great deal of work has been performed over the past few years on the energy optimization of traditional WDM optical networks. The energy-minimized design problem for IP over WDM networks was studied in [11], where the authors propose solutions that include mixed integer linear programming (MILP) models and heuristics, to minimize the energy consumption in an IP over WDM network. In [12], the authors propose an energy-aware traffic grooming algorithm for WDM networks, by assuming modular switches. They formulate the problem using MILP, while they are also providing some simple heuristics. A novel approach based on MILP to reduce energy in IP over WDM networks by turning on/off line-cards (LCs) and chassis of routers based on time-of-the-day traffic variation is proposed in [13]. In [14], the authors study the energy-aware design of multi-shelf IP over WDM networks, by analyzing the power consumption of different components, including multi-shelf IP core routers, reconfigurable optical add drop multiplexer, and WDM line system; then, they propose a two-step MILP design model, which provides sufficient design details for implementation. Moreover, in [15], the authors evaluate the energy consumption of an IP over WDM network assuming a router with modular ports and provide an MILP formulation for minimizing energy consumption utilizing the lightpath bypass (transparency) concept. Energy minimization in translucent WDM optical networks is addressed in [16], proposing an algorithm to reduce the energy-consuming regenerators, amplifiers, add/drop terminals, and so on. The energy consumption minimization problem of IP over WDM optical networks was also addressed in [17], where the authors propose an energy-oriented model.

Many research works also concern energy minimization of flexible (elastic) optical networks. Various energy-aware resource allocation heuristic algorithms are proposed in [4] for both static and dynamic traffic with time-varying demands and flexible OFDM-based networks. In [5], the authors propose a heuristic solution that provides an energy-minimized design of long-haul flexible optical networks by avoiding under-utilization of network resources, such as optical fibers, transponders, and amplifiers and conclude that the energy efficiency of the flexible architecture can outperform the fixed architecture by a factor of 4.2 (6.4) for low and 1.8 (1.9) for high traffic demands, respectively. Moreover, a novel adaptive transmission strategy in flexible coherent optical OFDM transmission systems is proposed in [6], aiming to optimize the system operation in terms of energy and spectrum consumptions for a transmission demand with a required data rate. In [18], an energy-efficient virtual topology design scheme for IP over flexible optical networks is proposed, and the authors conclude that the proposed scheme can significantly save power consumption. Finally, in [19], the authors study the power consumption of IP-over-flexible optical networks with different flexible optical transponders, and they show that significant energy saving is achievable using sliceable transponders.

To the best of our knowledge, this is the first time that the energy-minimized design of IP over flexible optical networks considers jointly the IP and optical layers by including distance adaptivity/modulation level decisions, which make the problem more difficult to solve. Also, compared to previous works [18, 19], we consider in more details the IP layer, by using a detailed modular multi-chassis model for the IP/MPLS routers that are used at the edges of the optical network, and we also provide a more detailed energy consumption model for flexible transponders.

3. NETWORK ARCHITECTURE AND PROBLEM DESCRIPTION

We assume a multilayer optical network that consists of optical switches and fiber links that form the optical network and IP/MPLS routers connected to the optical switches that form the edges of the optical network. The IP/MPLS routers are modular and can host multiple LCs, each one

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providing a specified number of bidirectional slots with a nominal (maximum) transmission speed (we will come back to this in Section 4 (A)). A LC of the corresponding speed can be installed into each LC chassis slot, while each LC occupies one slot, providing a specific number of ports at specific speed. Each LC port is connected to a gray transceiver that is then connected to one transponder of equal rate at the optical switch. In the flexible network under study, we assume that the transponders are flexible and can be tuned at several transmission configurations described by the so-called *feasible transmission tuples* [8–10]. These feasible transmission tuples take into account the physical (optical) layer impairments and define the reach that a transmission of certain rate and spectrum can achieve. We will come back to this in Section 4(B).

The optical switches function as reconfigurable optical add drop multiplexers employing the flex-grid technology and support lightpaths (optical connections) of one or a contiguous number of 12.5 GHz spectrum slots. None, one, or more modular multi-chassis IP/MPLS routers are connected at each optical switch, while a transponder is used to transform the electrical packets transmitted from the IP source router to the optical domain, acting as an optical transmitter in this case (E/O conversion). The traffic that enters the optical switch crosses over the optical network in lightpaths and reaches the destination's optical switch. There, the packets are converted back to electrical signal at the transponder that functions as an optical receiver in this case (O/E conversion), and handled by the corresponding IP/MPLS router. The IP/MPLS router can be the final destination, in which case, the packets are forwarded to metro/access networks attached to the router, or an intermediate hop, in which case the packets are again forwarded over a new lightpath towards the final router destination. Note that optical connections are bidirectional and thus the optical transponders act simultaneously as transmitters and receivers. Also note that the packets/headers are not processed in the optical layer; the IP/MPLS routers are responsible for the electronic processing of the packets traversing the network and in particular for grooming them and forwarding them to the correct lightpaths, so that they reach their end destination.

The multilayer network planning problem takes as input the given IP over flexible network topology, the model of the routers, the feasible configurations of the transponders, and the IP layer traffic matrix aggregated by the domains adjacent to the IP/MPLS routers that is forwarded over the optical network. Its goal is to decide on the IP/MPLS modules and the optical transponders to install and establish lightpaths and forward the traffic over them and through possibly intermediate IP/MPLS routers to the destination IP/MPLS routers, so as to minimize the total network's energy consumption. Note that we assume that at the optical layer, the optical switches and fiber links are deployed, but not the transponders and the IP/MPLS modules. So to solve (i) the IPR sub-problem, we have to decide on the modules to install at the IP/MPLS routers, how to map traffic onto the lightpaths, and which intermediate IP/MPLS routers will be used to reach the domain destination; (ii) the RML sub-problem, we have to decide how to route the lightpaths, where to place the transponders, and also to select the transmission configurations of those flexible transponders; and (iii) the SA sub-problem, we have to allocate spectrum slots to the lightpaths, avoiding slot overlapping.

The network (optical network and the IP/MPLS routers at its edges) is represented by a directed graph $G=(N, L)$, where N is the set of nodes and L is the set of links. The graph consists of two types of nodes, IP nodes and optical nodes, and two layers, the virtual (electrical or IP) layer and the optical (physical) layer. A virtual node represents a modular multi-chassis IP/MPLS router, while an optical node represents a flex-grid optical switch. In the graph, we also define three types of links:

(a) An interlayer link (l_{vo} or l_{ov}) connects a virtual node to an optical node and the opposite. Note that we distinguish between the two directions of an interlayer link driven by the way paths are explored by our algorithm, although lightpaths are created bidirectionally. An l_{vo} or l_{ov} link represents the use of a (flexible or fixed) transponder, that is, it corresponds to an E/O or O/E conversion, respectively.
(b) An optical link (l_o) corresponds to a fiber and connects two optical switches.
(c) A virtual link (l_v) corresponds to an established lightpath with residual spare capacity that connects two IP/MPLS routers.

Figure 1 presents an illustrative topology of the examined IP over flexible network.

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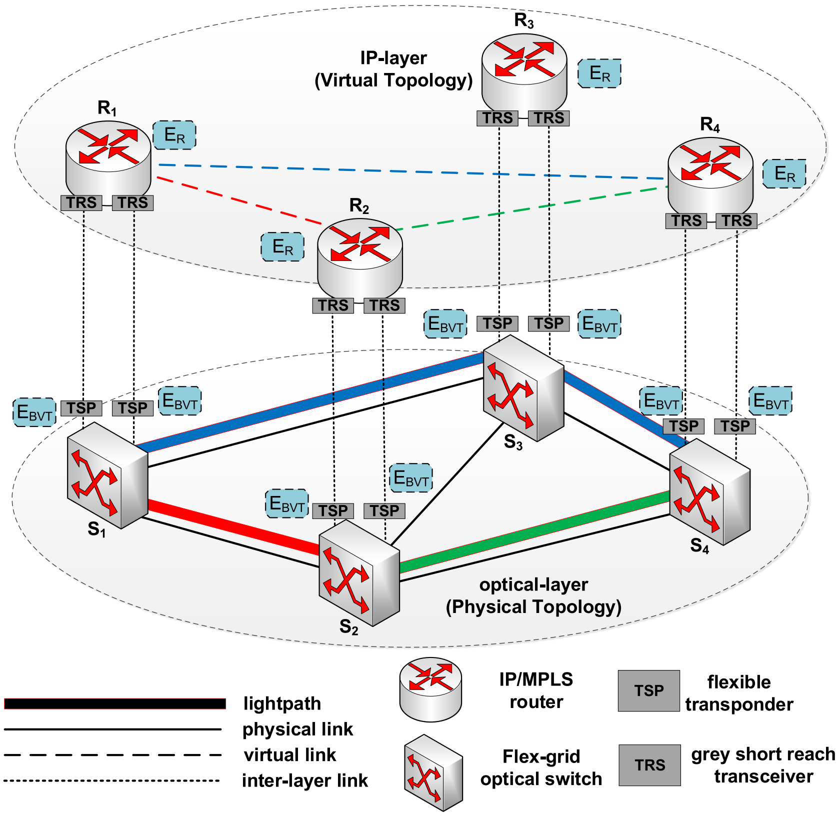

Figure 1. Architecture of IP over flexible optical network. MPLS, multiprotocol label switching; TRS, transceiver; TSP, transponder.

4. NETWORK ENERGY CONSUMPTION MODEL

We now present in detail the energy consumption model used in our study. In the IP over flexible optical network under study, the main energy consumption contributors are the IP/MPLS routers and the flexible transponders.

(A) IP/MPLS router energy consumption model

We assume a modular multi-chassis IP/MPLS router model, like Cisco CRS-3 with 24-slot fabric-card chassis [20], which can be dimensioned according to the traffic it is planned to carry by the proposed energy-aware algorithm.

The IP/MPLS router includes various chassis, the physical and mechanical assembly, the switch, power supplies, cooling, control, and management plane hardware and software. In our model, the IP/MPLS router consists of three hierarchical types: (i) LCs chassis (LCC) that provide a specified number of bidirectional slots with a nominal (maximum) transmission speed to host LCs; (ii) fabric cards (FCs) that interconnect a specified number of LCC; and (iii) FC chassis (FCC) that provide a specified number of slots for hosting FCs. We assume that (i) each LCC can host up to 16 LCs; (ii) to interconnect three LCCs, eight FCs are required; and (iii) each FCC can host 24 FCs. The detailed structure of the assumed modular multi-chassis IP/MPLS router is depicted in Figure 2.

The IP/MPLS router energy consumption model takes as input the number and kind of LCs installed, the number of LCCs hosting them, the number of FCs, and the number of FCC required for hosting the FCs. Given the aforementioned assumptions, the energy consumption of a modular multi-chassis IP/MPLS router is computed as

$$E_R = \sum_{i=1}^{N} E_{LC}^{i} + N_{LCC} \cdot E_{LCC} + \left\lceil \frac{N_{LCC}}{9} \right\rceil \cdot E_{FCC} + \left\lceil \frac{N_{LCC}}{3} \right\rceil \cdot E_{FC}, \quad (1)$$

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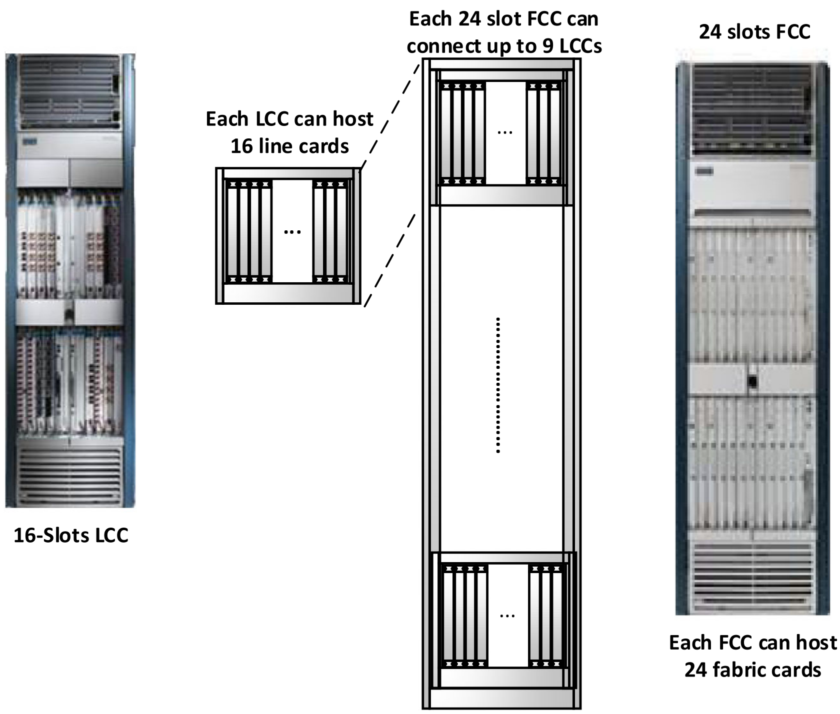

Figure 2. IP/MPLS modular multi-chassis router model. LCC, line-cards chassis; FCC, fabric cards chassis.

where N is the number of installed LCs,

- E^i_{LC} is the energy consumption of i-th LC,
- N_{LCC} is the number of installed LCC,
- E_{LCC} is the energy consumption of one LCC,
- E_{FCC} is the energy consumption of one FCC, and
- E_{FC} is the energy consumption of one FC.

The parameter N_{LCC} is computed as

$$N_{LCC} = \left\lceil \frac{C}{K} \right\rceil, \ 2 \leq N_{LCC} \leq 72, \tag{2}$$

where C is the total switching capacity in Tb/s of the modular multi-chassis IP/MPLS router and K is the capacity of a fully equipped shelf-hosting FCs. Note that in our performance results, we assume a modular multi-chassis IP/MPLS router with the previously described hierarchy and figures, and up to 72 FCC; the problem definition and the algorithm are however generic and can work with other models as well.

In the aforementioned energy consumption model, (i) the energy consumption of the router was computed taking into account the energy consumption per LC and not per utilized LC's port, as it is very small compared to the total energy consumption of the modular multi-chassis IP/MPLS router, and (ii) the energy consumption of an LC was assumed to be fixed regardless of its ports' speed, that is, the energy consumption of 10×40, 4×100, and 1×400 Gbps LCs was assumed to be the same, because we expect them to have very small differences. In Eq. (1), we could also include another scaling parameter, expressing the traffic served by the LCs multiplied with the energy consumption per gigabits per second; however, again, this amount was assumed for simplicity to be negligible, as it is very small compared to the total energy consumption of the modular multi-chassis IP/MPLS router.

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(B) Flexible transponder energy consumption model

We assume that the flexible transponders can control a number of transmission parameters that affect the optical reach at which they can transmit, such as the modulation format, the utilized spectrum, and the baud-rate, or a subset of them. The configurations of a flexible transponder are indicated by transmission tuples (d_t, r_t, b_t, e_t), where d_t is the reach (km) at which a transmission of rate r_t (gpbs) using b_t spectrum slots (including guardband) is feasible with acceptable Quality of Transmission and e_t is the corresponding energy consumption. Note that the definition of a specific rate and spectrum incorporates the choice of the modulation format of the transmission. It is obvious that a fixed transponder can be also expressed by a single tuple in the aforementioned form. Moreover, different types of transponders with different energy consumption have different transmission tuples, and this definition is generic, so as to be able to formulate such options. As the transmission reach of a flexible transponder depends on the modulation format and the achieved spectrum efficiency, the energy consumption of a flexible transponder depends on the used baud-rate.

It has been demonstrated that flexible transponders have the same energy consumption independently of the chosen modulation format [21] but the energy consumption depends on the baud-rate. For the calculation of flexible transponders' energy consumption, we assume an energy model similar to that defined by IDEALIST European project [10]. We assume that the flexible transponder is implemented as a muxponder with 400 Gbps maximum rate and includes the following components: (i) client cards and framer/deframer components at client side (ii) drivers and lasers for E/O modulation, and (iii) local oscillator, photodiode, transimpedance amplifier, forward error correction, analog to digital converter, digital signal processing, and digital to analog converter for O/E modulation at the receiver. However, although all the aforementioned flexible transponder's components are taken into account for the calculation of its energy consumption, only those that provide electronic processing exhibit energy consumption that depends on the operating baud-rate. So the energy consumption of a flexible transponder is divided into two parts: (i) the static part, which allows the electronic maintenance of logic levels in the device, but also the various leakage currents and (ii) the dynamic part, which depends on the frequency at which the device operates.

At the proposed flexible transponder architecture, we assumed the use of two lasers for transmitting up to 400 Gbps with DP-16QAM as the highest modulation format and that the energy consumption depends on the number of lasers that are active. The energy consumption of a flexible transponder is computed according to the following equation:

$$E_{BVT} = n \cdot (108 + 4,8 \cdot R) \cdot 1,2 \tag{3}$$

where R is the baud-rate at which the transponder operates and n is the number of active lasers. The value 108 (in Watts) is the static energy consumption and is derived by summing the energy consumption of the related elements, while the value $4{,}8 \cdot R$ captures the dynamic energy consumption and was calculated to fit linearly to the consumption of 40 and 100 Gbps fixed transponders. In the aforementioned equation, we also included an additional 20% of consumption for energy management purposes.

5. ENERGY-AWARE MULTILAYER NETWORK-PLANNING ALGORITHM

The proposed energy-aware multilayer network planning algorithm is an extension of the planning algorithm we proposed in [7]. The algorithm serves the demands one by one in some particular order and is executed until it serves all demands in the traffic matrix. In our studies, we used the highest demand first ordering, but other orderings can be easily defined. Because different orderings for serving the demands may result in different network's energy consumption, we used simulated annealing meta-heuristic [8] to search among different orderings and select the best one. The node where the algorithm runs is assumed to know the modular model of the routers and the feasible transmission configurations of the optical transponders and the current state of the network (network topology, established lightpaths, slot utilization of links, and used router modules). The algorithm runs for a single demand (taken from the ordering) with specific virtual nodes as the source and destination and a demanded rate. In the case where the demanded rate is higher than that

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supported by the transponders, then the demand is split into sub-demands of the supported rates, and the algorithm is executed multiple times. The algorithm constructs an auxiliary graph G_A from G, which includes all nodes and all links except for the virtual links (established lightpaths) that have remaining capacity lower than the demanded rate.

The energy-aware multilayer network-planning algorithm solves jointly the IPR + RML + SA problems using a multi-cost routing algorithm. Multi-cost (also known as multi-constrained) algorithms have been used to solve various QoS optimization problems in the past [22]. The proposed multi-cost algorithm runs on the auxiliary graph G_A and creates for each link a cost vector (depending on the link's type) that incorporates information for both optical and IP layers. In particular, the cost vector of a link of graph G_A has the following parameters:

- An integer variable D_l representing the length of the link. The length of a virtual (l_v) or an interlayer link (l_{ov} or l_{vo}) is equal to 0.
- A float variable C_l representing the transponder's energy consumption that is computed according to Eq. (3).
- A float variable E_l representing the additive energy consumption of the router (having as reference its energy consumption up to this point), which is non-zero only for an interlayer link (both l_{ov} or l_{vo}), and zero otherwise. When there are free ports at the router's LCs, $E_l = 0$, when LCs are full but the LCC is not, E_l is set to the energy consumption of a new LC, and when we need to add new LCC, E_L is set to the additive energy consumption of the LCC and an LC.
- A vector $\overline{H}_l = ((r_1, d_1, b_1), (r_2, d_2, b_2), \ldots, (r_m, d_m, b_m))$ whose i-th element (r_i, d_i, b_i) records a transmission tuple, where d_i is the feasible reach for rate r_i and spectrum b_i for the specific transponder. These are taken from the transmission tuples of the corresponding flexible transponder that the interlayer link represents. The vector $\overline{H}_l$ is defined only for a virtual to optical interlayer link (l_{vo}), while it is zero for the other direction (optical to virtual – l_{ov}) and other types of links. Also, we define as r_{max} the maximum rate over all transmission tuples in vector $\overline{H}_l$.
- A Boolean variable F_l that is equal to 1, if the link is a virtual link (which represents an established lightpath), and 0 otherwise.
- A Boolean vector $\overline{W}_l$ of size F (F is the number of spectrum slots) representing the slot availability of the optical links. In particular, element $\overline{W}_{l,i}$ is equal to 1 if the i-th slot on optical link l is available and 0 otherwise. For all other links (interlayer and virtual links), the vector has elements equal to 1.

Thus, the cost vector $\overline{V}_l$ characterizing a link l is given by

$$\overline{V}_l = \left(D_l, C_l, E_l, \overline{H}_l, F_l, \overline{W}_l\right). \tag{4}$$

The paths in the network are built link by link, so that at each step, a path is extended by adding any type of link. A path p consists of a number of sub-paths m, where each sub-path m is defined as the path between two consecutive IP nodes (that is, a sub-path corresponds to a lightpath). Similarly to a link, a path is characterized by a cost vector of the following eight parameters:

$$\overline{V}_p = \left(D_p, C_p, E_p, \overline{H}_p, F_p, \overline{W}_p, \overline{R}_p, \overline{p}\right), \tag{5}$$

which are the previously described parameters of a link, plus a new parameter $\overline{R}_p$ denoting the set of the chosen rates r_m for each new lightpath (r_m is set equal to the maximum rate of the tuples available when reaching the sub-path's terminating IP node), and a new parameter $\overline{p}$ defining the list of identifiers of the links that comprise the path p. Assume that p' is a path that is obtained, by adding the link l with $\overline{V}_l$ cost vector at path p with $\overline{V}_p$ cost vector. The cost vector of p' is calculated using the associative operator $\oplus_{l_{ov}}$, $\oplus_{l_{vo}}$, $\oplus_{l_o}$, and $\oplus_{l_v}$, to V_p and V_l, depending on the type of the link l. To be more specific,

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- if l is an optical link (l_o) or a virtual link (l_v),

$$\begin{aligned}\overline{V}_{p'} &= \overline{V}_p \oplus_{l_o(l_v)} \overline{V}_l \\ &= \big(D_p + D_l, C_p + C_l, E_p + E_l, \big\{(r_i, d_i, b_i) \in \overline{H}_p \,\big|\, D_p + D_l \le d_i \text{ and } Q\big(\overline{W}_p \& \overline{W}_l\big) \ge b_i\big\}, \\ &\quad F_p + F_l, \overline{W}_p \& \overline{W}_l, \overline{R_p}, \{\overline{p}, l\}\big),\end{aligned} \tag{6}$$

- if l is a virtual-to-optical interlayer link (l_{vo}),

$$\overline{V}_{p'} = \overline{V}_p \oplus_{l_{vo}} \overline{V}_l = \big(0, C_p + C_l, E_p + E_l, \overline{H}_l, F_p + F_l, \overline{1}, \overline{R_p}, \{\overline{p}, l\}\big), \tag{7}$$

- if l is an optical-to-virtual interlayer link (l_{ov}),

$$\begin{aligned}\overline{V}_{p'} = \overline{V}_p \oplus_{l_{ov}} \overline{V}_l = \big(&D_p + D_l, C_p + C_l, E_p + E_l, \varnothing, F_p + F_l, \\ &\overline{W}_p \& \overline{W}_l, \{\overline{R_p}, r_{\max} = \max_i \big(r_i \big| (r_i, d_i, b_i) \in \overline{H}_p \text{ and } Q\big(\overline{W}_p\big) \ge b_i\big)\}, \{\overline{p}, l\}\big),\end{aligned} \tag{8}$$

where '&' denotes the bitwise Boolean AND operation and $Q\big(\overline{W}_p\big)$ denotes the largest void of the slot availability vector $\overline{W}_p$. Note that the link cost values differ, depending on the link type.

The energy-aware multilayer network planning algorithm that jointly solves the IPR + RML + SA problems is executed in two steps (Figure 3). In the first step, the algorithm finds a set of candidate non-dominated paths from the demand's source to the demand's destination that could serve the demand. It utilizes a domination relationship between paths that have the same end node in order to reduce the number of paths considered, removing paths that are in all costs inferior and thus are bound not to be selected by the optimization function (to be applied at the second step). More specifically, because the optimization function to be applied is monotonic in each of these costs, the dominated paths would never be optimal, and the solution space along with the execution time of the algorithm is reduced without losing optimal solutions. The domination relationship is defined as follows: A path that dominates another path has smaller length, less additive energy consumption (energy consumption of transponders and additive energy consumption of routers), utilizes less virtual links, and has higher maximum rate among its sub-paths.

The algorithm that computes the set of non-dominated paths is a generalization of Dijkstra's algorithm that only considers scalar link costs. It first obtains a non-dominated path between the source and a direct neighbor node. This path is selected so as to have the smallest network energy consumption, and in case of a tie, the smallest number of virtual links and so on. The algorithm marks this path as final and extends it through the outgoing links of its end node, so as to calculate new paths and their cost vectors using the appropriate associative operator $\oplus$, according to the

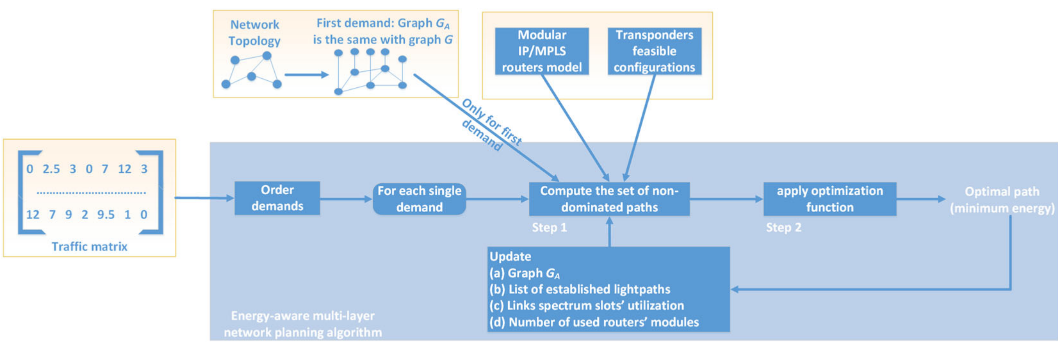

Figure 3. Description of multilayer network-planning algorithm. IP, Internet protocol; MPLS, multiprotocol label switching.

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added link. Then, the algorithm selects a non-final path between the origin and one of its neighbors, or between the origin and one of the neighbors of the previously considered neighbor, marks it as final, extends it using the corresponding outgoing links, calculates new paths, and so on. For each new path that is calculated, the algorithm applies the domination relationship between the new path and all the paths with the same end node that have been previously calculated. The new path is discarded if it is dominated by a previously calculated path; otherwise, it is added to the set of non-dominated paths of the specific end node, and any previously calculated paths that are dominated by it (if any) are discarded. The algorithm finishes when no more paths can be extended and returns the set of non-dominated paths between the source and the destination. In the second step, an optimization function is applied to the cost vectors of the found candidate paths from demand's node to demand's destination, which transforms the multi-cost vectors into scalars and selects the optimum path. In our proposed algorithm, the optimum is defined as the one with the minimum transponders and routers energy consumption, or in case of tie, the one with the minimum number of virtual links and so on. Different optimization functions could be defined, according to connections/network specifications and requirements.

As it was previously mentioned, the algorithm used to plan the multilayer optical network in an energy-aware manner is a variation of the algorithm we proposed in [7], which was extended as follows: (i) The link and path cost parameters of cost vectors were replaced with the corresponding energy consumption parameters (energy consumption of flexible or fixed transponders and additive energy consumption of routers); (ii) in the domination relationship applied at the first step of the multi-cost algorithm, the cost of paths was replaced by the energy consumption of paths; and (iii) in the optimization function applied at the second step of the multi-cost algorithm, the network cost was replaced by the network energy consumption, to select the path with the smallest additive energy consumption. For a more detailed description of the multi-cost routing algorithm we extended, the reader is referred to [7].

6. PERFORMANCE RESULTS

To evaluate the performance of the proposed algorithm and also quantify the energy consumption benefits that can be obtained when the proposed algorithm is applied to plan multilayer optical networks, we conducted a number of simulations using MATLAB. In the experiments to be presented, we define the following network scenarios, regarding the type of network (flexible versus MLR) and planning approach (joint versus sequential):

(a) flexible (elastic) network with joint multilayer network planning (flex-JML-NP),
(b) fixed-grid MLR network with joint multilayer network planning (fixed-JML-NP),
(c) flexible (elastic) network with sequential multilayer network planning (flex-SML-NP), and
(d) fixed-grid MLR network with sequential multilayer network planning (fixed-SML-NP).

For the aforementioned scenarios, we also distinguish the following two cases: (i) The network is planned having as objective the minimization of its total energy consumption (*min-energy* objective) and (ii) the network is planned having as objective the minimization of its total cost (*min-cost* objective).

For simulation purposes, we used two reference networks with very different characteristics in terms of number of nodes, links length and traffic served, the Deutsche Telekom (DT), and GEANT networks, so that the results obtained are representative of real networks. DT (Figure 4) is an IP backbone network with 12 optical nodes, a single IP core router per optical node, and 20 fiber edges (40 bidirectional edges) with an average length of 243 km and maximum length of 459 km. It interconnects PoPs, and it serves internal traffic generated and consumed by residential subscribers exclusively. GEANT (Figure 5) is an IP backbone network with 34 optical nodes and 27 fiber edges (54 bidirectional edges) with an average length of 752 km and maximum length of 2361 km. The GEANT topology used in the simulations is the one existing in February 2009, as we do not have information available for later topologies. For the case of the DT network, we created traffic matrices for the period from 2014 up to 2024 based on real traffic for 2011, assuming a 35% traffic increase per year, while for the case of GEANT network, we created traffic matrices for the same

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period, based on real traffic for 2009, assuming a growth rate of 25% per year. The performance metrics we used for the comparisons are the energy consumption of transponders, the energy consumption of routers, and the total energy consumption of the network computed as the sum of the aforementioned two metrics.

In the case of the flexible networks (flex-JML-NP and flex-SML-NP), we assumed that each link of DT network is a single fiber with 320 spectrum slots available of 12.5 GHz width while we assumed two fiber links for GEANT with a total of 640 spectrum slots of 12.5 GHz width. Similarly, in the case of the fixed-grid MLR networks (fixed-JML-NP and fixed-SML-NP), we assumed 80 wavelengths of 50 GHz width for the DT network and 160 wavelengths of 50 GHz width for the GEANT.

The transmission tuples (reach, rate, spectrum, and energy consumption) of the used flexible and fixed transponders (bandwidth variable and fixed bandwidth transponders) are shown in Tables I and II, respectively, and are based on [9, 23, 24]. The energy consumption of the various modules installed at modular multi-chassis IP/MPLS routers is depicted in Table III and is computed as 90% of the maximum energy consumption values defined by the vendors [25, 26], while the energy consumption of each router is computed according to Eq. (1).

(A) DT network results

In this section, we describe the results obtained for the DT reference network. Table IV depicts transponder, router, and network energy consumption (in kW) for each case of network with JML-NP and min-energy objective, and reference years from 2014 to 2024. Concerning the transponders' energy consumption, we observe that during the whole period of reference, the flex-JMP-NP case outperforms the fixed-JML-NP case, and with the pass of time and as the traffic increases, the difference between the transponder energy consumptions between the two aforementioned networks increases. This was expected as the flexible transponders are better utilized than fixed transponders, especially at high loads, and are consequently more energy efficient. Concerning network total energy consumption among the two network cases, the flex-JMP-NP network has smaller network energy consumption during all the examined period. The difference in the energy consumptions observed between the flex-JMP-NP case and the fixed-JML-NP case increases as the years progress; this is because at light loads, lower energy consumption/low-rate fixed

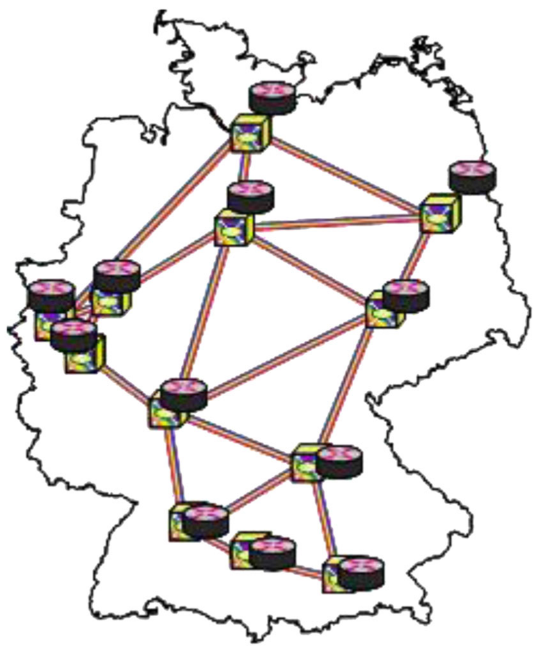

Figure 4. Generic Deutsche Telekom (DT) topology. 12 nodes and 20 links (we assumed 40 directed links).

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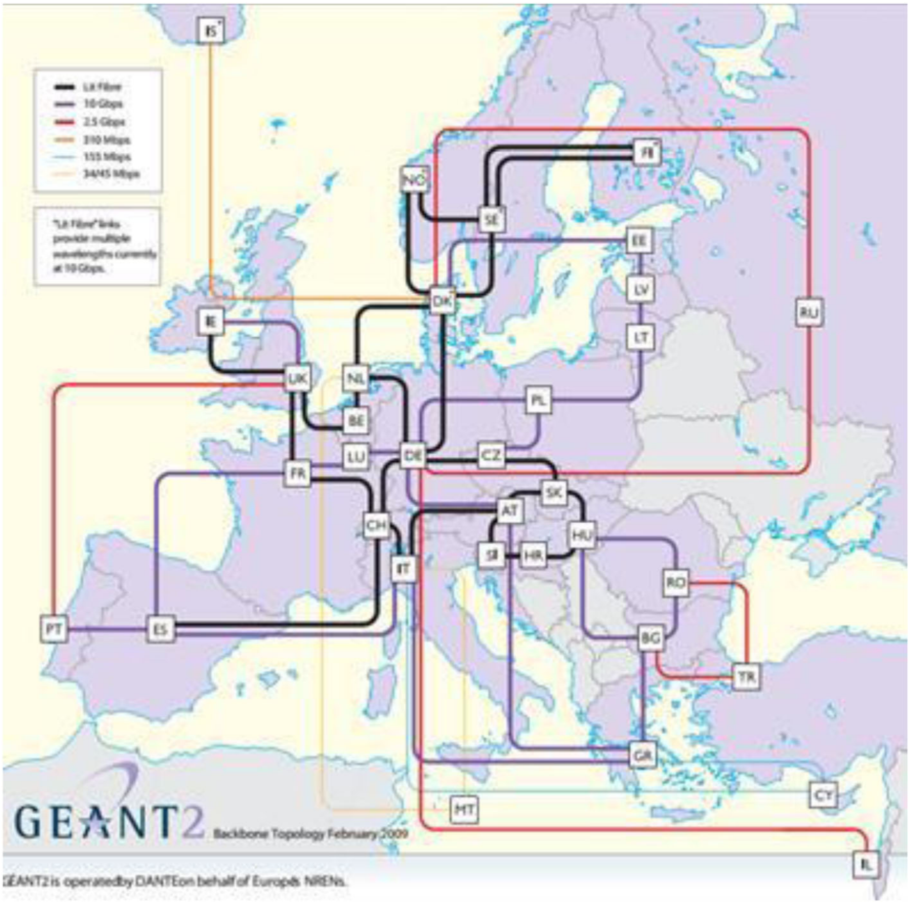

Figure 5. Generic GEANT topology. 34 nodes and 27 links (we assumed 54 directed links).

transponders are sufficient to serve the traffic, while flexible transponders used in the flex-JMP-NP are not fully utilized, so the difference between the energy consumption of the flex-JMP-NP case and the fixed-JML-NP case is small. However, as traffic increases, the utilization and the efficiency of the flexible transponders increase; this effect combined with the additional flexibility of more transmission options gives the advantage to the flex-JMP-NP, which outperforms the fixed-JML-NP network in terms of total network energy consumption.

Table V depicts transponder, router, and network energy consumption (in kW) for each case of network with SML-NP and min-energy objective, and reference years ranging from 2014 to 2024. The findings are similar to those obtained in the case where a joint multilayer planning algorithm is applied to the MLR and flexible optical networks: The flex-SML-NP network outperforms

Table I. Transmission tuples of flexible transponders

Reach (km)	Rate (Gb/s)	Required spectrum (in GHz)	Energy consumption (W)
2500	40	50	155
1800	40	25	155
1700	100	37.5	270
2000	100	50	270
1900	200	75	320
700	200	50	270
1900	400	125	630
700	400	100	432
450	400	75	432

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the fixed-SML-NP network in terms of transponder and total network energy consumption with their difference increasing as load increases. Comparing the total network energy consumptions in Tables IV and V, we observe that when the JML-NP algorithm with min-energy objective is applied to an MLR optical network, the resulting total energy consumption is smaller during the whole period of reference, as opposed to the case where the network is planned according to a sequential multilayer network solution. For the case of flexible optical networks, at low load, the energy consumption of the flex-JML-NP network is slightly higher than that of flex-SML-NP (although the flex-JML-NP network keeps the transponders energy consumption an advantage), while at high loads, the flex-JML-NP network outperforms the flex-SML-NP in terms of energy consumption. This is explained as follows: In the case of SML-NP algorithm, the connections are groomed without taking into account the reach constraints at the optical layer, and therefore the RML decisions. This results in utilizing a higher number of 400 Gbps transponders and LCs that are expensive in terms of energy consumption compared to the JML-NP case.

Concerning the distribution of network total energy consumption between the IP/MPLS routers and transponders, we observe that at both MLR and flexible optical networks, and regardless of the planning solution applied (JML-NP or SML-NP), the largest percentage of network total energy consumption is due to IP/MPLS routers. Also, we observe that the percentage of energy consumption due to IP/MPLS routers is bigger in the case of flexible as opposed to MLR optical network, regardless of the planning solution applied. This is because in the case of the flexible optical networks, fewer transponders are deployed as opposed to MLR optical network, so few LCs are also utilized.

Table II. Transmission tuples of fixed transponders

Reach (Km)	Rate (Gb/s)	Required spectrum (in GHz)	Energy consumption (W)
2500	40	50	155
2000	100	50	270
450	400	75	432

Table III. Energy consumption of IP/MPLS routers modules

Module	Energy consumption (W)
Line-card chassis	2754
Fabric card chassis	7520
Fabric cards	256
10×40 G, 4×100 G, 1×400 G line-cards	108

Table IV. Transponder, router, and network energy consumption (in kW) for each case of network with JML-NP and min-energy objective, and reference years from 2014 to 2024, using Deutsche Telekom as reference network

	Fixed-JML-NP			Flex-JML-NP		
Year	Transponder energy consumption	Router energy consumption	Network energy consumption	Transponder energy consumption	Router energy consumption	Network energy consumption
2014	16.07	38.34	54.41	11.12	37.69	48.82
2016	23.37	51.79	75.16	17.09	50.92	68.01
2018	36.67	59.72	96.39	24.31	58.64	82.96
2020	61.09	83.20	144.29	37.59	80.61	118.20
2022	106.64	177.58	284.21	64.07	170.07	234.14
2024	186.89	294.36	481.26	106.46	273.98	380.44

JML-NP, joint multilayer network planning.

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Table V. Transponder, router, and network energy consumption (in kW) for each case of network with SML-NP and min-energy objective, and reference years from 2014 to 2024, using Deutsche Telekom as reference network

	Fixed-SML-NP			Flex-SML-NP		
Year	Transponder energy consumption	Router energy consumption	Network energy consumption	Transponder energy consumption	Router energy consumption	Network energy consumption
2014	22.97	39.74	62.71	10.11	38.77	48.89
2016	28.90	53.41	82.30	15.32	52.11	67.43
2018	41.59	61.24	102.83	23.25	59.62	82.86
2020	66.43	105.99	172.42	37.15	102.64	139.79
2022	109.97	200.91	310.87	61.23	181.47	242.69
2024	192.10	313.75	505.85	106.94	280.89	387.83

SML-NP, sequential multilayer network planning.

Table VI depicts network energy consumption (in kW) for each case of network with min-energy and min-cost objective, and reference years from 2014 to 2024. As expected, we observe that in all cases, the network energy consumption is smaller when the objective of the planning algorithm is network energy consumption minimization, as opposed to network cost minimization. We also observe that the difference between the energy consumption of flex-JML-NP and flex-SML-NP networks when the objective of planning is energy consumption minimization, as opposed to cost minimization, is bigger in the case of the flex-JML-NP network. This shows how well the elasticity provided by flexible optical networks is exploited by the joint multilayer planning in terms of energy efficiency.

(B) GEANT network results

In this section, we describe the results obtained when using GEANT as the reference network. Table VII (Table VIII) shows the transponder, router, and network energy consumption (in kW) for each case of network with JML-NP (or SML-NP, respectively) and min-energy objective, and reference years from 2014 to 2024. The findings in both the JML-NP and SML-NP planning cases are similar to those obtained for the DT network, that is, the network's total energy consumption is smaller for the flexible rather than the MLR optical network, and their difference increases as load increases. However, the difference between the energy consumption of MLR and flexible optical networks when planned either in a joint (JML-NP) or sequential (SML-NP) optimization manner is larger for the GEANT network than for the DT network. This is because GEANT is a bigger network than the DT network, in terms of number of nodes, link lengths, and amount of traffic served, and so the transponders (especially the flexible ones) are better utilized and are more energy efficient due to higher loads, longer distance paths, and more O/E and E/O conversions at IP/MPLS routers for signal regeneration, all of which increase energy consumption.

Table VI. Network energy consumption (in kW) for each case of network with min-energy and min-cost objective, and reference years from 2014 to 2024, using Deutsche Telekom as reference network

	Min-cost				Min-energy			
Year	Fixed-JML-NP	Flex-JML-NP	Fixed-SML-NP	Flex-SML-NP	Fixed-JML-NP	Flex-JML-NP	Fixed-SML-NP	Flex-SML-NP
2014	54.92	54.65	65.22	54.65	54.41	48.82	62.71	48.89
2016	74.60	71.87	89.25	71.87	75.16	68.01	82.30	67.43
2018	96.26	88.88	112.37	91.04	96.39	82.96	102.83	82.86
2020	158.15	140.35	191.35	152.36	144.29	118.20	172.42	139.79
2022	303.80	259.48	338.02	258.40	284.21	234.14	310.87	242.69
2024	488.27	414.02	520.54	416.00	481.26	380.44	505.85	387.83

JML-NP, joint multilayer network planning; SML-NP, sequential multilayer network planning.

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Finally, Table IX depicts network energy consumption (in kW) for each case of network with min-energy and min-cost objective, and reference years from 2014 to 2024. The findings are similar to those obtained for the DT network, except for the fact that the traffic is blocked at specific years and network cases. Although we observe that in the case of MLR optical networks and for both planning solutions (JML-NP and SML-NP), at very high load (year 2024), the traffic is blocked in both cases of optimization (min-cost and min-energy).

Table VII. Transponder, router, and network energy consumption (in kW) for each case of network with JML-NP and min-energy objective, and reference years from 2014 to 2024, using GEANT as reference network

	Fixed-JML-NP			Flex-JML-NP		
Year	Transponder energy consumption	Router energy consumption	Network energy consumption	Transponder energy consumption	Router energy consumption	Network energy consumption
2014	59.63	104.98	164.61	50.73	104.54	155.27
2016	78.72	108.22	186.94	70.47	107.89	178.36
2018	111.93	112.64	224.58	92.39	112.97	205.36
2020	160.04	162.54	322.58	135.54	152.12	287.65
2022	231.51	201.10	432.61	179.55	190.67	370.22
2024	–	–	–	262.84	275.10	537.94

JML-NP, joint multilayer network planning.

Table VIII. Transponder, router, and network energy consumption (in kW) for each case of network with SML-NP and min-energy objective, and reference years from 2014 to 2024, using GEANT as reference network

	Fixed-SML-NP			Flex-SML-NP		
Year	Transponder energy consumption	Router energy consumption	Network energy consumption	Transponder energy consumption	Router energy consumption	Network energy consumption
2014	80.09	108.65	188.74	44.56	123.61	168.17
2016	106.76	112.32	219.08	60.90	142.18	203.08
2018	143.54	139.54	283.08	99.83	157.26	257.09
2020	202.32	190.08	392.40	124.54	239.33	363.87
2022	275.05	228.96	504.01	204.76	255.40	460.16
2024	–	–	–	278.64	418.34	696.97

SML-NP, sequential multilayer network planning.

Table IX. Network energy consumption (in kW) for each case of network with min-energy and min-cost objective, and reference years from 2014 to 2024, using GEANT as reference network

	Min-cost				Min-energy			
Year	Fixed-JML-NP	Flex-JML-NP	Fixed-SML-NP	Flex-SML-NP	Fixed-JML-NP	Flex-JML-NP	Fixed-SML-NP	Flex-SML-NP
2014	164.39	160.32	199.66	184.70	164.61	155.27	188.74	168.17
2016	191.16	184.63	236.52	217.98	186.94	178.36	219.08	203.08
2018	234.50	222.89	306.34	285.23	224.58	205.36	283.08	257.09
2020	333.57	304.40	–	390.81	322.58	287.65	392.40	363.87
2022	455.15	376.51	–	538.24	432.61	370.22	504.01	460.16
2024	–	559.75	–	712.99	–	537.94	–	696.97

JML-NP, joint multilayer network planning; SML-NP, sequential multilayer network planning.

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7. CONCLUSIONS

We studied the energy-minimized design problem for IP over flexible networks. We proposed an energy-aware multilayer network-planning algorithm that can be applied to both flexible (elastic) and fixed-grid MLR optical networks. The algorithm takes as input the network topology, the IP end-to-end traffic matrix, the modular model of the IP/MPLS routers, and the feasible configurations of the flexible optical transponders. It serves the demands for their requested rates, by selecting the router modules to install, the routes in the IP topology, the placement of transponders, the corresponding paths, and spectrum slots in the underlying optical topology, together with the flexible optical transponders transmission configurations. Our results show that significant energy savings can be obtained when the proposed energy-aware multilayer planning algorithm is applied to a flexible, as opposed to a fixed-grid MLR, optical network. Additional energy savings can be obtained when the flexible or fixed-grid MLR optical network is planned using the proposed JML-NP algorithm as opposed to planning in a sequential manner.

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