A Joint Multi-Layer Planning Algorithm for IP Over Flexible Optical Networks

Vasileios Gkamas, Konstantinos Christodoulopoulos, and Emmanouel Varvarigos

***Abstract*—We consider the multi-layer network planning problem for IP over flexible optical networks, which consists of three subproblems at two layers: the Routing problem at the IP-layer (IPR), the routing, modulation level (RML), and the spectrum allocation (SA) problems at the optical layer. The input includes the IP end-to-end traffic matrix, the modular model of the IP/MPLS routers, and the feasible transmission configurations of the flexible optical transponders. Demands are served for their requested rates by selecting the IP/MPLS routers modules to be used, the routes in the IP (virtual) topology, and the corresponding paths and spectrum slots in the underlying optical topology, together with the optical transponders' configurations. The proposed algorithm follows a multi-cost approach that solves jointly the IPR, the RML, and the SA problems. It serves demands one-by-one, reusing existing equipment and favoring the deployment of new equipment that could also be reused by subsequent connections, aiming to minimize the total network cost. The problem definition is generic and the proposed algorithm is applicable to both fixed- and flex-grid optical networks. We evaluate the performance gains that can be obtained by the proposed joint multi-layer network planning solution, as opposed to a sequential planning solution that separately plans the IP and optical layers. We also compare a flexible network, using flex-grid optical switches and flexible optical transponders, to a mixed line rate (MLR) network, using fixed-grid or flex-grid optical switches but fixed optical transponders.**

***Index Terms*—Distance adaptive routing and spectrum allocation, flex-grid, IP over flexible (elastic) optical networks, IP over WDM, multi-cost algorithm, planning, routing modulation level and spectrum allocation (RMLSA).**

I. INTRODUCTION

THE continuous growth of consumers' IP traffic, due to the introduction of broadband access and FTTx technologies, and the bursty nature of the applications characterized by rich-content and high-rate, like Video-on-Demand and HDTV, has brought to light the inefficiency of current WDM optical networks. Modern applications do not only entail an increase in the traffic volume, but also an increase in the unpredictability and the dynamic nature of this underlying traffic growth. Moreover, these applications come with stringent service level requirements and heightened end-user Quality of Experience expectations. In this evolving network operations environment, simply providing more capacity is no longer sufficient.

Wavelength division multiplexing (WDM) optical networks are typically used today in core and metro networks. They are usually designed with an overprovisioning factor and are operated statically and independently, without taking into account short- or mid-term traffic dynamics at their edges. This is mainly due to the complicated optical connection establishment process that needs to consider the physical layer (impairments). Thus, WDM networks are not only rigid and static in physical terms, but also rigid and constrained in the operational sense, resulting in poor utilization, stranded capacity, and inability to react to new service demands in a timely manner. Multi-layer optimization across the IP and the optical layer is often mentioned but seldom truly performed in a joint manner, as decisions at the IP layer are taken without considering their impact on the optical layer, and then the optical layer is (re)configured to address the required changes.

Photonic advances have enabled transmission of 100 Gb/s, and coherent detection has lowered the effects of physical layer impairments, but it is obvious that the traditional WDM approach of upgrading the network by statically putting abundant capacity will not be an efficient solution in the forthcoming years. Planning of the optical core and metro network has to be performed as a joint multi-layer process to bring forward savings both in its electrical router edges and the optical network. The rigid bandwidth and reach granularity of WDM networks make such planning inefficient. Moreover, there is also the need to make the optical layer more dynamic and agile, by considering it as part of the whole network, to increase its efficient use and enable end-to-end service provisioning. This is also the approach favored by software defined networks technology, where programmability and flexibility through centralized control is meant to hold for both the IP and the optical layers.

Recently flexible (or elastic) optical networks have emerged [1] based on (i) flex-grid technology that enables the slicing of the spectrum according to the needs, as opposed to the rigid granularity of WDM networks, and (ii) flexible transponders, also known as bandwidth variable transponders (BVTs), which can tune their transmission parameters, trading off the transmission reach for spectrum and/or rate. Flexible optical networks solve various inefficiency problems of traditional WDM networks, providing a finer granularity solution for sub- and super-wavelength capacity. Moreover, their increased flexibility fits well with the dynamic multi-layer network operation that is actually needed.

To enable the multi-layer network planning and operation of flexible optical networks in a joint and effective manner,

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The authors are with the Computer Engineering and Informatics Department, University of Patras, and Computer Technology Institute and Press "Diophantus" Patras 26504, Greece (e-mail: gkamas@ceid.upatras.gr; kchristodou@ceid.upatras.gr; manos@ceid.upatras.gr).

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appropriate control plane extensions and algorithms are needed. The present paper takes a first step towards this end, by focusing on the joint multi-layer planning of a flexible optical network. In the general case, the multi-layer network planning problem consists of problems at two layers: the Routing subproblem at the IP layer (IPR), and the routing, modulation level and spectrum allocation (RMLSA) sub-problem at the optical layer. Further, the RMLSA problem can be broken into two substituent sub-problems, namely a) routing and modulation level decision and b) spectrum allocation (RML+SA). Thus the multi-layer network planning problem consists of three subproblems: IPR+RML+SA that can be jointly or sequentially solved. A variation of the IPR problem is also referred to in the literature as traffic grooming, while the RMLSA problem is also referred to as Distance-adaptive RSA. Distance adaptivity creates interdependencies between routing at the optical (RML) and IP layers (IPR) on the one hand and spectrum allocation (SA) on the other, making it hard (and also inefficient) to decouple these sub-problems.

The proposed joint multi-layer network planning algorithm treats the demands of the IP-layer traffic matrix one-by-one, in some particular sequence. So it is applied here to solve the planning problem, but it can also be used with minor modifications for dynamic network operation (“one time” problem). The proposed algorithm solves the multi-layer network planning problem (IPR+RML+SA) jointly and is an extension of the algorithm used in [2], which considered jointly only the IPR+RML subproblems. As discussed above, we decided *not* to decouple the IPR, the RML and the SA problems, because when flexible transponders are used the rate and spectrum of the optical connection depends on its physical length (RML decision), which in turn affects the IPR and SA decision. 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 multi-layer network planning algorithm that jointly performs the routing at IP and optical layers and the SA follows a multi-cost approach [3]. In multi-cost (or multi-constrained) algorithms, each link is characterized by a vector of cost parameters, in contrast to the traditional single-cost routing where each link is characterized by a scalar cost. By defining appropriate component-wise operations between cost vectors, we can calculate the cost vector of a path. In the proposed algorithm the cost-vector conveys information regarding the transponders’ transmission reach, the use of already established connections, the cost of the IP and optical layer, and the spectrum availability, which are used to solve the joint IPR+RML+SA problem.

The flexible transponders used are assumed to be characterized by a set of so called *transmission tuples* that identify the reach at which a transmission is feasible, given the parameters that are under our control, such as the rate, the spectrum used for the transmission, and the modulation level. Feasibility here refers to the physical layer and signifies acceptable bit-error rate or acceptable quality of transmission (QoT) [4], [13], [21].

The proposed planning algorithm is general and can be applied to any type of optical network: optical networks employing flex-grid optical switches and flexible or even fixed transponders, and WDM networks employing fixed-grid optical switches and single or multiple types of fixed transponders [also referred to as single-line-rate (SLR) and mixed-liner-rate (MLR)]. The only requirement is to describe the input in the form of feasible transmission tuples. In the simulations conducted, we used the proposed joint multi-layer network planning algorithm to plan both flexible networks employing flex-grid optical switches and flexible optical transponders and MLR networks employing fixed-grid or flex-grid optical switches but fixed optical transponders and compared their performance. We also distinguished two cases: Joint Multi-Layer Network Planning (*JML-NP*), where the IPR, RML and SA sub-problems are jointly solved, and Sequential Multi-Layer Network Planning (*SML-NP*), where the IPR, RML and SA sub-problems are sequentially solved.

Using realistic cost, network, and traffic models, taken by IDEALIST project [4], we found that significant cost and spectrum savings can be obtained through joint multi-layer optimization over the IP and the optical layer (*JML-NP*), as opposed to planning the two layers sequentially (*SML-NP*). We also found that when planning the network in a joint multi-layer optimization manner (*JML-NP* case), the flexible network outperforms the MLR network deploying fixed-grid or flex-grid optical switches and fixed optical transponders, in terms of cost for medium and high loads and in terms of maximum spectrum used in all cases. Moreover, in the *SML-NP* case the flexible network outperforms the MLR network with respect to cost and spectrum under all load conditions.

The rest of the paper is organized as follows. Section II presents the related work, while Section III describes the network architecture and the multi-layer network planning problem. Section IV describes the joint multi-layer network planning algorithm. Simulation results are presented in Section V. Finally, our conclusions are given in Section VI.

II. RELATED WORK

Multi-cost routing and wavelength assignment (RWA) algorithms for fixed-grid WDM optical networks have been investigated in the past. A multi-cost approach with parameters being the OSNR, the number of free wavelengths, and the link cost is presented in [6]. In [7], impairment-aware multi-cost RWA algorithms for online traffic in transparent optical networks are proposed. The cost vector includes impairment generating source parameters or noise-related parameters, so as to indirectly or directly account for the optical layer effects. In [8], the authors extend the work of [7] to account for regenerators and present a multi-cost approach for translucent WDM networks.

We now turn our attention from WDM to flexible optical networks. In [9] the authors address the offline RSA problem with dedicated path protection in elastic optical networks and they provide an integer linear programming formulation to solve it. A distance-adaptive RSA algorithm for dynamic flexible networks is proposed in [10], in order to select the proper modulation format according to the transmission reach. In [11], a dynamic RMLSA scheme in flexible optical wavelength-division multiplexed networks with modulation format conversion ability is proposed. The RMLSA problem for planning a flexible optical network has been investigated in [12]. Algorithms for planning flexible optical networks under physical layer constraints are also proposed in [13], while in [16] a nonlinear programing model is proposed to formulate the complete RSA problem, at which the spectrum continuity constraints, the transmission distance constraints, and the relationship between the traffic bitrate and the signal bandwidth are jointly considered.

Traffic grooming algorithms for IP over optical networks has also received a great deal of attention. In [14] an IP over flexible optical multi-layer routing and grooming algorithm is proposed, which employs a bandwidth threshold, an auxiliary graph, and two grooming policies. The authors in [15] introduce a multi-layer auxiliary graph to jointly solve the IP-layer routing and optical-layer RSA, and they also propose various traffic-grooming policies. Finally, in [5] the authors propose a novel multi-layer capacity planning approach for IP over optical networks. They give extra attention on the process of creating the IP (virtual) topology (considering the impact at the IP layer topology when they bypass routers), leveraging a commercial IP planning tool; then they consider the design and cost impact of several multi-layer restoration schemes.

To the best of our knowledge multi-cost algorithms have not yet been applied to flexible optical networks and/or IP over WDM or flexible online or offline problems. Since such problems are quite complicated, with many optimization parameters involved, multi-cost seems a reasonable approach to address them. Note that the multi-cost framework adopted here is mainly used for serving a single demand (online traffic) [3], [6]–[8], which is the case also for the proposed algorithm, although it is used here in an iterative way for serving all demands and thus plan the whole network.

The novelty of our proposed solutions compared to previous works is threefold. First, the problem definition and the network planning algorithm proposed is quite general and takes generic but realistic transmission specifications as input (based on [19]–[21]), which are given in the form of feasible transmission configurations of the transponders used. So, it can be used for joint or sequential multi-layer planning of both flexible and fixed-grid optical networks, using fixed or flexible transponders. Second, the proposed joint multi-layer network planning algorithm includes distance adaptivity/modulation level decisions, making the problem more realistic and difficult due to inter-dependencies between the RML and the IPR and SA sub-problems. So, the proposed algorithm is more sophisticated compared to previous algorithms, solving jointly all the inter-related sub-problems. Third, in contrast to previous works, we consider more parameters in our optimization formulation. In particular, we consider more accurately the IP layer, by using a detailed modular model for the IP/MPLS routers deployed at the edges of the optical network. Moreover, our algorithm, in addition to allocating the routes at the IP and the optical layers and spectrum at the optical layer in a cross-optimized way, it also selects the transmission configurations of optical transponders and the number of IP/MPLS routers modules needed.

III. NETWORK ARCHITECTURE AND PROBLEM DESCRIPTION

We are given an optical network domain that consists of optical switches and fiber links. The optical switches function as reconfigurable optical add drop multiplexers (ROADMs) employing the flex-grid technology, and support optical connections (lightpaths) of one or a contiguous number of 12.5 GHz spectrum slots. At each optical switch, none, one or more IP/MPLS routers are connected (these routers comprise the edges of the optical domain). Short reach transceivers are plugged to the IP/MPLS routers leading to flexible (tunable) transponders at the ROADMs. Alternatively, flexible (tunable) colored transceivers could be plugged to IP/MPLS routers ports, generating signal that could directly enter the optical network domain. Since the two above alternatives are almost equivalent, in terms of cost and functionality, we will focus in the transponder case.

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 entering the ROADM (optical switch) is routed over the optical network in lightpaths (all-optical connections). We assume that a number of transmission parameters of the flexible transponders are under our control, affecting the optical reach at which they can transmit. At the destination of a lightpath the packets are converted back to electrical signal at the transponder that functions as an optical receiver in this case (O/E conversion). The packets at the receiver are forwarded and handled by the corresponding IP/MPLS router. This IP/MPLS router can be: (i) the final destination of some packets in the domain, in which case these packets will be forwarded further towards their final destination through other domains or lower hierarchy level networks attached to that router, or (ii) an intermediate hop, in which case the related packets will re-enter the optical network to be eventually forwarded to their domain destination. Note that lightpaths are bidirectional and thus in the above description an opposite directed lightpath is also installed, and the transponders used act simultaneously as transmitters and receivers. Also, note that packet processing is performed electronically and in particular at the IP/MPLS routers, while optical switches function as transparent pipes between IP/MPLS router end-points.

We are also given the traffic matrix Λ that corresponds to the IP traffic at the IP/MPLS routers that is forwarded over the optical domain under study. Our goal is to establish lightpaths, and route the traffic over these lightpaths and through possibly intermediate IP/MPLS routers to the end IP/MPLS router destination. For this reason the network is also referred to as IP over flexible optical network. We assume that the IP/MPLS routers are modular (a more detailed description will be given in the following). We also assume that at the optical layer the optical switches and fiber links are deployed, but not the transponders.

As discussed in the introduction, the planning of an IP over flexible network consist of three inter-related sub-problems: (i) the IP routing (IPR), (ii) the routing and modulation level (RML), and (iii) the Spectrum Allocation (SA). In the IPR problem we decide on the modules to install at the IP/MPLS routers, how to map traffic onto the lightpaths (optical connections), and which intermediate IP/MPLS routers will be used to reach the domain destination. In the RML problem we decide how to route the lightpaths and also we select the transmission configurations of the flexible transponders to be used. In the

SA we allocate spectrum slots to the lightpaths, avoiding slot overlapping (assigning the same slot to more than one lightpaths) and ensuring that each lightpath utilizes the same spectrum segment (spectrum slots) throughout its path (spectrum continuity constraint). The use of flexible optical transponders, where the rate, reach, and spectrum are not given but have to be decided, is the reason RML decisions affect the two other sub-problems, significantly complicating the network planning problem.

Following the IDEALIST cost model [4], we view an IP/MPLS router as a modular device, built out of (single or multi) chassis, that incorporates the physical and mechanical assembly, the internal switch, the power supplies, the cooling system, the control and management plane and the related software. A chassis provides a specified number of bi-directional slots with a nominal (maximum) transmission speed. Into each router slot, a linecard of the corresponding speed can be installed. Each linecard provides a specified number of ports at a specified speed and occupies one slot of the IP/MPLS router. In our performance results we consider a scalable multi-chassis router for core nodes, with up to 72 chassis, and a 16 router slot capability per chassis. Note, however, that our problem definition and proposed algorithms are generic and can work with other router models as well.

Regarding the optical network, we assume the use of flexible transponders, also referred to as BVTs that can control a number of parameters, such as the modulation format, the utilized spectrum, the baudrate and the rate that they transmit. The configurations of a transponder of type t are indicated by transmission tuples (d_t, r_t, b_t, c_t), where d_t is the reach for which a transmission of rate r_t (gpbs) using b_t spectrum slots (including guardband) is feasible (that is, it has acceptable QoT). The last parameter c_{t} corresponds to the cost of the transponder. Note that the definition of a specific rate and spectrum incorporates the choice of the modulation format of the transmission. Different types of transponders, with different costs have different sets of transmission tuples, and this definition is generic, so as to be able to formulate any such option. A fixed transponder can be expressed by a set consisting of a single tuple in the above formulation. The transponders are driven by equal rate linecards at the IP/MPLS routers, with each linecard supporting one or more transponders of the same type.

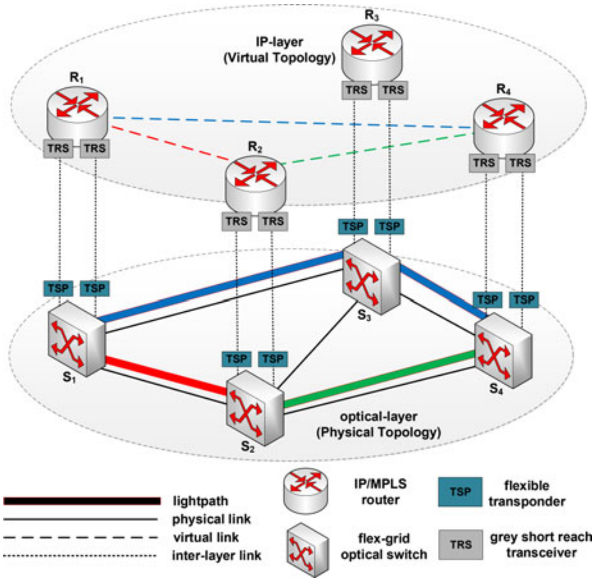

Fig. 1. Architecture of IP over flexible optical network.

The optical network topology and the IP/MPLS router edges are 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 (or virtual) nodes and optical (or physical) nodes, and two layers, the IP (or virtual) layer, where all the IP nodes are located, and the optical (or physical) layer, where all the optical nodes are located. A virtual node represents an IP/MPLS router, while an optical (physical) node represents a flex-grid optical switch, assumed to support F spectrum slots of a given granularity, e.g., 12.5 GHz. In the network graph G, the set L consists of three types of links, inter-layer (l_{ov} or l_{vo}), optical (l_o) and virtual (l_v) links. An inter-layer link connects a virtual (electronic/IP) node with an optical node and represents the use of a (flexible or fixed) transponder, that is, it corresponds to an O/E or E/O conversion. Note that we distinguish between the two directions of the inter-layer links, with l_{ov} denoting an optical-to-virtual and l_{vo} a virtual-to-optical inter-layer link, since we create single direction paths that we make bidirectional in the end. For each type (one or more) of transponders available, we create corresponding inter-layer links with distinct cost vectors (we will come back to this in the next section). An optical link l_o corresponds to a fiber and connects two optical switches. For optical links we keep track of their spectrum slots availability as will be described in the next Section. A virtual link l_v corresponds to a lightpath that connects two IP/MPLS routers. Thus, a virtual link between two IP/MPLS routers is created when a lightpath with residual capacity is established between the two optical switches connected to the IP/MPLS routers. This lightpath can traverse one or more optical links and pass transparently over zero or several intermediate optical nodes. So, at the beginning of planning, the set L of graph G includes only the optical links (l_o) and inter-layer links (both l_{ov} and l_{vo}) connecting IP nodes to optical nodes, while as the network is planned in iterative steps and lightpaths are established the related virtual links l_v are added in the graph.

Fig. 1 presents an illustrative example of the examined IP over flexible network, where four IP/MPLS routers comprise the IP (virtual) layer, four flex-grid optical switches comprise the optical (physical) layer and two types of transponders are used, each one supporting different transmission tuples. Also three lightpaths ($S_1 \leftrightarrow S_4$, $S_1 \leftrightarrow S_2$, and $S_2 \leftrightarrow S_4$) have been established at the optical layer, and the three related virtual links (from node R_1 to node R_4, from node R_1 to node R_2 and from node R_2 to node R_4) were created at the IP layer. Note that the opposite direction virtual links were also created, that may have different remaining capacity. A new demand from ingress node R_2 to egress node R_4 can be served by lightpaths already established from node S_2 to node S_4, if their remaining capacity is adequate, or by establishing a new lightpath.

IV. JOINT MULTI-LAYER NETWORK PLANNING ALGORITHM

In this section, we describe the joint multi-layer network planning algorithm for IP over flexible optical networks. As stated before, the developed algorithm is used to serve a single demand and thus in order to serve the whole traffic matrix we iteratively use them for each demand, one-by-one, in a particular order (see Section IV-B). Since different orderings for serving the demands may result in different costs, simulated annealing techniques can be used to find good orderings.

A. Multi-Cost IPR+RML+SA Algorithm

We now describe the multi-cost algorithm used to jointly solve the IPR+RML+SA problem for a single demand. The planning problem assumes as input the network topology and the traffic matrix. We order the demands, and serve them one-by-one, using the algorithm presented in this section. So at each step, the single demand multi-cost algorithm takes as input the demand to be served (source or ingress IP/MPLS router, destination or egress IP/MPLS router, and demand rate), the IP over flexible network described by graph *G*, the transponders' feasible configurations (described by the set of related tuples) and the state of the network, in terms of previously established lightpaths (including the spectrum utilization of links) and IP routing decisions. Following the multi-cost approach we define for each type of link (inter-layer, optical and virtual) a cost vector that incorporates information regarding both the optical and the virtual (IP) layers (see Section IV-A1a). Appropriate operators are also defined to combine the cost vectors of links to obtain the cost vector of paths (see Section IV-A1b). The algorithm carries out two steps: in the first step (see Section IV-A2a) it calculates the cost vectors of candidate non-dominated paths from the source to the destination. A domination relationship is used to prune the solution space by removing paths that would not be selected by the optimization function (second step). Then, in the second step (Section IV-A2b) an optimization function is applied to the cost vectors of the candidate paths found in step 1, which transforms the multi-cost vectors into single-cost scalars, and the algorithm selects the optimum.

1) Computing the Cost Vector of a Path:

a) Cost vector of a link: Each link is assigned a cost vector consisting of six cost parameters, two of which are actually vectors. These parameters are the following:

- An integer variable D_l representing the length of the link. The length of a virtual (l_v) or an inter-layer link (l_{ov} or l_{vo}) is equal to 0.
- An integer variable C_l representing the transponder's cost. In case of an inter-layer link (l_{ov} or l_{vo}), C_l is equal to the cost of the particular transponder used (when multiple transponder types are available, we create one inter-layer link for each type), and 0 for other types of links.
- A float variable P_l representing the additive cost of the modular router (having as reference its cost up to this point), which again is non-zero only for an inter-layer link (l_{ov} or l_{vo}), and zero otherwise. For the given state of the network, the IP/MPLS router at the start of a l_{vo} link, or the end of a l_{ov} link, has a number of chassis, linecards and free ports. A new linecard must be installed when there are no free ports (all installed linecards are full), and a new chassis must be installed when all the slots of the chassis are used. So, (i) when there are free ports at the router, $P_l = 0$, (ii) when linecards are full but the chassis is not, P_l is set to the cost of a new linecard of the related rate, and (iii) when we need to add a chassis, P_l is set to the additive cost of the chassis and a linecard. Note that the cost of adding a chassis might not be linear.
- A vector $\overline{H}_l = ((r_1, d_1, b_1)\ ,\ (r_2, d_2, b_2)\,, \ldots, (r_m, d_m, b_m))$ of size 3*m* (*m* is the number of feasible transmission tuples), defined only for a virtual-to-optical inter-layer link (type l_{vo}), 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 transponder that the inter-layer link represents. Note that the vector $\overline{H}_l$ is defined only for links of type l_{vo}, and is empty for the other direction (l_{ov}) and other types of links.
- A Boolean variable F_l that is equal to 1 if *l* is a virtual link (representing 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 (inter-layer and virtual links), the vector has elements equal to 1.

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

$$\overline{V}_l = \left(D_l, C_l, P_l, \overline{H}_l, F_l, \overline{W}_l\right). \tag{1}$$

b) Cost vector of a path: A path in the graph is built link by link, so that at each step a path is extended by adding a virtual, optical or inter-layer link. We assume that 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 (a sub-path corresponds to a lightpath). A sub-path can be a virtual link (an already established lightpath), or a new lightpath (a sequence of a virtual-to-optical inter-layer link, followed by one or more optical links, followed by an optical-to-virtual inter-layer link). For each sub-path *m* of the latter category (new lightpath), the algorithm decides on its rate, denoted by $r_{\max}$, which is chosen the maximum rate of the tuples available when reaching the sub-path's terminating IP node.

Similarly to a link, a path is characterized by a cost vector $\overline{V_p} = \left(D_p, C_p, P_p, \overline{H}_p, F_p, \overline{W}_p, \overline{R}_p, \overline{p}\right)$, whose six first parameters are the previously described ones for a link, plus two new parameters: $\overline{R}_p$ denoting the set of the chosen rates $r_{\max}$ of the previous sub-paths, and $\overline{p}$ defining the list of identifiers of the links that comprise path *p*. Note that parameter D_p represents the optical length of the current sub-path, that is the length of the optical links from the last IP/MPLS router (last point where E/O conversion was performed). Assume that we extend path *p* by adding link *l* to obtain path p'. The cost vector of p' is calculated using the associative operator $\oplus_{l_{ov}}, \oplus_{l_{vo}}, \oplus_{l_o}, \oplus_{l_v}$, to $\overline{V}_p$ and $\overline{V}_l$, depending on the type of the link *l*. To be more specific:

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

$$\overline{V}_{p'} = \overline{V}_p \oplus_{l_o(l_v)} \overline{V_l} = (D_p + D_l, C_p + C_l, P_p + P_l, \{(r_i, d_i, b_i) \in \overline{H}_p | D_p + D_l \le d_i \text{ and } Q(\overline{W}_p \,\&\, \overline{W}_l) \ge b_i\}, F_p + F_l, \overline{W}_p \,\&\, \overline{W}_l, \overline{R_p}, \{\overline{p}, l\}). \quad (2)$$

- if *l* is a virtual-to-optical inter-layer link (l_{vo})

$$\overline{V}_{p'} = \overline{V}_p \oplus_{l_{vo}} \overline{V_l} = (0, C_p + C_l, P_p + P_l, \overline{H}_l, F_p + F_l, \overline{1}, \overline{R_p}, \{\overline{p}, l\}). \quad (3)$$

- if *l* is an optical-to-virtual inter-layer link (l_{ov})

$$\overline{V}_{p'} = \overline{V}_p \oplus_{l_{ov}} \overline{V_l} = (D_p + D_l, C_p + C_l, P_p + P_l, \emptyset, F_p + F_l, \overline{W}_p \& \overline{W}_l, \{\overline{R_p}, r_{\max} = \max_i (r_i | (r_i, d_i, b_i) \in \overline{H}_p \text{ and } Q(\overline{W}_p) \ge b_i)\}, \{\overline{p}, l\}) \quad (4)$$

where “&” denotes the bitwise Boolean “and” operation, and $Q(\overline{W}_p)$ denotes the largest void of the slot availability vector $\overline{W}_p$. Note that the spectrum continuity constraint is enforced in sub-paths by the definition of the slot availability vector and the “&” operation. The values of the cost parameters of the links differ depending on the type of link. Thus, e.g., although in both optical and virtual links the length of the new path p' is defined as the sum of the length of path p plus the length of the additional link l ($D_p{}' = D_p + D_l$), D_l is zero for a virtual link and equal to the length of the fiber for an optical link. We used different of definitions associative operators for the links in order to perform special actions: to reset the length ($D_{p'} = 0$), re-initialize the transmission tuple set ($\overline{H}_{p\prime} = \overline{H}_l$) and reset the spectrum availability ($\overline{W}_{p\prime} = \overline{1}$) when extending the path by adding a virtual-to-optical link, and to reset the transmission tuple set ($\overline{H}_{p\prime} = \emptyset$) and select the maximum rate tuple $r_{\max} = (\max_i (r_i | (r_i, d_i, b_i) \in \overline{H}_p \text{ and } Q(\overline{W}_p) \ge b_i))$ when extending the path by adding an optical-to-virtual link.

2) Single Demand Algorithm Description: The proposed multi-cost routing algorithm consists of 2 steps, the first of which computes the set of non-dominated candidate paths to serve the demand, and the second one which selects the optimal path. We assume that the we know the network topology, the current state of the network (established lightpaths, spectrum slots utilization, used router modules) and the feasible transmission configurations of the available flexible (or fixed) transponders. The algorithm runs for a specific demand with source *s* and destination *d,* both IP (virtual) nodes of graph *G,* and a demanded rate *r*. In case a demand requires rate bigger than the one supported by the transponders, then it is split to sub-demands of the supported rates, and the algorithm is executed that many times. The algorithm constructs a reduced graph $G_A = (N_A, L_A)$ from G, which includes all nodes and all links except for the virtual links (established lightpaths) that have remaining capacity lower than the demanded *r*.

a) Step 1: Computing the set of non-dominated paths $P_{\mathrm{n-d}}$: The goal of this step is to find a set of candidate paths for efficiently serving the demand. The algorithm that computes the set of non-dominated paths P_{n-d} runs on the reduced graph G_A. For given source and destination nodes $s, d \in N_{\mathrm{A}}$, we define:

- M_i as the set of cost vectors of the paths from node s to node $n_i \in N_{\mathrm{A}}$.
- $M = \cup_{i \ne s} M_i$ as the set of all vectors to all nodes.
- $M_i^f \subseteq M_i$ as the set of *final* vectors to node n_i.
- $M^f = \cup_{i \ne s} M_i^f \subseteq M$ as the set of all *final* vectors to all nodes.
- $R_p^{\max} = \max_m (r_m \in \overline{R_p})$ as the maximum rate among all sub-paths of *p*, that is, among all elements of $\overline{R_p}$.

This algorithm also utilizes a domination relationship between paths that have the same end-node (and same source by definition) to reduce the number of paths considered. In particular, we say that path p_1 dominates path p_2 with the same end-node (notation $p_1 > p_2$), if the following holds:

$$p_1 > p_2 \text{ iff } L_{p_1} \le L_{p_2} \text{ and } C_{p_1} + P_{p_1} \le C_{p_2} + P_{p_2} \text{ and } F_{p_1} \le F_{p_2} \text{ and } R_{p_1}^{\max} \ge R_{p_2}^{\max} \text{ and } \overline{W}_{p_1} \ge \overline{W}_{p_2}. \quad (5)$$

A path that dominates another path has smaller length, less additive network cost (cost of transponders and additive cost of routers), utilizes less virtual links, has higher maximum rate among its sub-paths and has available at least the same spectrum slots. Since the optimization function *f* to be applied to the cost vectors of the paths in the second step of the multi-cost routing algorithm is monotonic in each of these costs, the dominated paths would have never been selected, so the solution space along with the execution time of the algorithm will be reduced, without losing optimal solutions.

The algorithm used to compute the set of non-dominated paths is a generalization of Dijkstra’s algorithm that only considers scalar link costs and is described in pseudo-code in Fig. 2. 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 cost, in case of a tie, the smallest number of virtual links, etc. By definition, this path is non-dominated since the parameters that comprise the cost vectors are additive and non-negative and this path has at least one parameter smaller than the other paths. 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 added link. Two additional checks are performed when adding an optical link: we check if the extended path has at least one transmission tuple (i) with higher rate than the required and (ii) requiring bandwidth smaller than the largest spectrum void ($\exists i | (r_i, d_i, b_i) \in \overline{H}_{p_{j'}},\ r_i \ge r \text{ and } b_i \le Q(\overline{W}_{p_{j'}})$), and discard it if one of the above does not hold.

Then, the algorithm selects a non-final path between the source and one of its neighbors, or between the source 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

```
$P_{n-d}$ ← Compute_the_set_of_Non_Dominated_Paths ($G_A,s,d,r,\overline{V}_l$)
##Initialization
$M^f=\{\},M=\{\}$
for all links $l \in L_A$ starting at $s \in N_A$, $M=M\cup\overline{V}_l$
while $M \neq M^f$
    ##Choose the optimum path vector
    find path p in M whose vector $\overline{V}_p$ has minimum network cost. In case of
    tie, select the one with minimum number of virtual links, etc.
        $n$ ← ending node of selected path p
        $M^f=M^f\cup\overline{V}_p$
    ##Obtain new paths and discard dominated paths
    for all $n_j \in N_A$ neighbors of n (connected through $l = n,n_j \in L_A$)
        ##Obtain the cost vector of the new path $p_j$'
        $\overline{V}_{p_j'}=\overline{V}_p\oplus\overline{V}_l$ , with $\oplus=\oplus_o$ or $\oplus_v$ or      or $\oplus_{ov}$ depending on link
        ##Discard the new path $p_j$' if it runs out of transmission tuples
        if (l is optical link) and ($\{(r_i,d_i,b_i)\in\overline{H}_{p_j'},\ r_i \geq r$ and $b_i \leq Q(\overline{W}_{p_j'})\}=\varnothing$)
            check the next neighbor $n_j$
        end if
        ##Check if the new path $p_j$' is dominated
        for all $\overline{V}_{p_j} \in M_i$ ($p_j$ are paths ending at node $n_j$)
            if $p_j > p_j'$ (">" is the domination relationship)
                check the next neighbor $n_j$ (discard the new path $p_j$')
            else if $p_j' > p_j$
                $M=M-\{\overline{V}_{p_j}\}$ (discard the old path $p_j$)
            end if
        end for
        $M=M\cup\{\overline{V}_{p_j'}\}$, (add the new path $p_j$' to the set of paths)
    end for
end while
end algorithm (return $P_{n-d}=M_d^f$)
```

Fig. 2. Pseudo-code of the algorithm which computes the set of non-dominated paths from the given source to the given destination.

if it is dominated by one of the previously calculated paths; otherwise, it is added to the set of non-dominated paths of the specific end node, while all the previously calculated paths that are dominated by it (if any) are discarded.

The basic difference with Dijkstra's algorithm is that a set of non-dominated paths between the source and each node is obtained instead of a single path; a node for which a path has already been found is not finalized (as in the simple Dijkstra case), since it may have to be considered again later. Actually, instead of finalizing nodes, we finalize the paths. The algorithm finishes when no more paths can be extended (all paths are final) and returns the set of non-dominated paths P_{n-d} that has been calculated between the source *s* and destination *d*.

For example, consider the network with graph *G* of Fig. 3. We suppose a transponder configuration with 1.500 km reach for a transmission of 100 Gb/s. Also four lightpaths have been established: (a) from virtual node V_1 to node V_3 through nodes $P_1 \rightarrow P_2 \rightarrow P_3$, with remaining capacity $R_l = 80$ Gb/s, (b) from virtual node V_2 to node V_7 through nodes $P_2 \rightarrow P_5 \rightarrow P_7$, with remaining capacity $R_l = 100$ Gb/s, and the opposites, (c) from V_3 to V_1 through nodes $P_3 \rightarrow P_2 \rightarrow P_1$ with remaining capacity $R_l = 80$ Gb/s, and (d) from V_7 to V_2 through nodes $P_7 \rightarrow P_5 \rightarrow P_2$ and remaining capacity $R_l = 100$ Gb/s. Assume that we want to serve a new demand with rate 100 Gb/s from V_1 to V_7. We construct the reduced network graph G_A, where we remove the virtual links $V_1 \rightarrow V_3$ and $V_3 \rightarrow V_1$, as their remaining capacity is not sufficient. The algorithm begins by initializing the set *M* with the link $V_1 \rightarrow P_1$. Then it examines the paths in set *M*, selects $V_1 \rightarrow P_1$ (since it is the only one available), and makes it final (adding it to set M^f). Then the algorithm expands $V_1 \rightarrow P_1$ to all the neighbors of node P_1, that is using the links $P_1 \rightarrow P_2$, $P_1 \rightarrow P_3$ and $P_1 \rightarrow P_4$. The path $V_1 \rightarrow P_1 \rightarrow P_3$ is discarded as its length exceeds the maximum transmission reach (no remaining transmission tuple has rate higher than the demanded). The cost vectors of the two new paths $V_1 \rightarrow P_1 \rightarrow P_2$ and $V_1 \rightarrow P_1 \rightarrow P_4$ are computed and inserted in the set *M*. Then the algorithm will search the set *M*, select $V_1 \rightarrow P_1 \rightarrow P_2$ that has the shortest length, finalize it and expand it. Links $P_2 \rightarrow V_2$, $P_2 \rightarrow P_3$ and $P_2 \rightarrow P_5$ will be examined. Path $V_1 \rightarrow P_1 \rightarrow P_2 \rightarrow P_3$ will be discarded (as its length which is 1.700 km exceeds the maximum transmission reach of transponder which is 1.500 km), while the other two will be included in set *M*. Note that the length of the path $V_1 \rightarrow P_1 \rightarrow P_2 \rightarrow V_2$ will be reset to zero, enabling it to reach P_3 at a later iteration. Also path $V_1 \rightarrow P_1 \rightarrow P_2 \rightarrow V_2$ when selected will also be expanded using the virtual link $V_2 \rightarrow V_7$ (previously established lightpath). The algorithm will continue its execution by selecting at each step the best non-final path computed up to that point, and examining its neighbors. When more than one paths reach the same end node, it will apply the domination relationship to discard those that are worse with respect to all parameters. The execution of the algorithm is completed when $M = M^f$, that is, when there are no more non-final paths to expand.

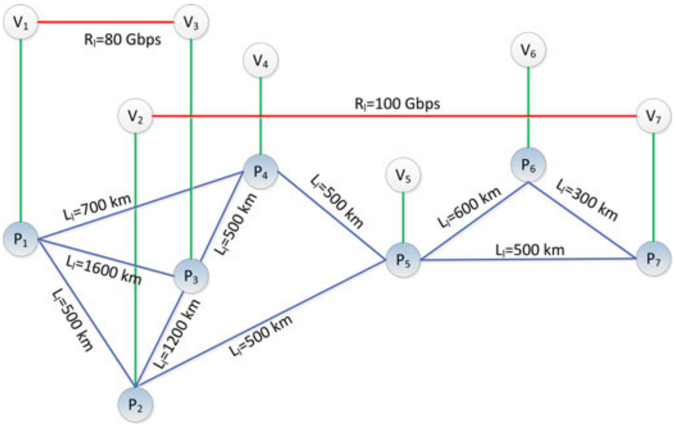

Fig. 3. IP over flexible network graph.

b) Step 2: Selecting the optimal path: In the second step of the multi-cost routing algorithm, we apply an optimization function $f(\overline{V}_p)$ to the cost vector $\overline{V}_p$ of all paths in P_{n-d} calculated in the first phase. The function *f* yields a scalar cost per candidate path enabling us to select the optimal one. Note that the optimization function has to be monotonic in each of the cost components.

We used an optimization function that calculates for each candidate path *p* the additive network cost $(C_p + P_p)$ and selects the one with the smallest, while in case of tie, the path with the smallest number of virtual links (established lightpaths) is selected, and in a case of a tie, the one with the maximum rate among all sub-paths. Note that in paths creation process (first step) we have already taken decisions on what transmission tuple to use for each sub-path (the one with the highest rate from the ones available which also requires bandwidth that is smaller than the longer spectrum void). We decided to focus on cost and not to consider the spectrum in the optimization function defined above, but the algorithm has verified that the candidate paths passed in this phase, have at least the required spectrum slots for each sub-path to establish the related lightpaths. In this study we use the first-fit policy to allocate spectrum to each sub-path, but other policies can be used, such as most-used, best fit, etc. The algorithm can be modified to take into account the spectrum at sub-path tuple selection and/or at the optimization function, which could decide not only the path to use but also optimize SA jointly. Finally, note that different optimization functions can be defined for all demands, but also we can have different functions for different demands, depending on demand's QoS requirements and other considerations; for example, we could choose the path with minimum number of virtual links, or the one that achieves the higher added capacity over cost ratio, to name just a few.

B. Network Planning—Iterative Execution of Algorithm

The proposed joint multi-layer network planning algorithm described above is designed to serve a single demand. To serve the whole traffic matrix and plane the whole network we order the demands and serve them one-by-one. We keep track of the modules installed at the routers, the established lightpaths, the assignment of demands to them, their remaining capacity, and the spectrum utilization of the links. When a demand is served we update accordingly the above data structures and the graph G and then move to serve the next demand. Since the order in which the demands are served plays an important role, simulated annealing can be used to search among different orderings to improve the solution [13].

C. Generality of the Proposed Algorithm

Although the algorithm described above is used for solving the joint multi-layer network planning problem in IP over flexible networks, it is quite generic and can be also used for (a) planning optical networks deploying fixed-grid or flex-grid optical switches and fixed optical transponders of single or multiple types (SLR or MLR), (b) sequential planning of IP over flexible or fixed-grid optical networks (what we call sequential multi-layer network planning, *SML-NP*) and (c) minimizing network parameters other than the cost, for example the energy consumption.

To be more specific, to plan a SLR or MLR network, the algorithm takes as input the description of the capabilities of the fixed transponders in the tuple format, discussed in Section III. This is quite straightforward; the fixed rate transponders of a SLR network are described with a single transmission tuple, while the fixed rate transponders of a MLR network are described by a set of single tuples, and in particular the set consists of as many tuples as the number of transponder types available. In case that we want to sequentially plan the IP and optical network (*SML-NP*), we consider that the IP routing decisions (IPR) are taken without taking into account the distance constraints and the RML decisions. To implement this, in the case of *SML-NP* we set the reach of the flexible (or fixed) transponders equal to infinity and use an optimization function that does not include the cost of the optical layer. When solving the RML problem for *SML-NP* case we use an optimization function that neglects the IP/MPLS router's costs. Moreover, the inter-layer links are assumed to use transponders only at the source and the destination, while all other inter-layer links are assumed to be deployed with optical regenerators. To be more specific the same process is followed in both *JML-NP* and *SML-NP* cases. At the end of the planning algorithm, all intermediate transponders that are not used for grooming purposes are replaced by regenerators (to save in cost). Since no grooming is performed in the *SML-NP* case at intermediate nodes, all intermediate transponders become regenerators, while in *JML-NP*, this replacement depends on the traffic and is seldom performed. In future we plan to integrate regeneration placement in the algorithm formulation.

Finally, to minimize other network parameters, like energy consumption, appropriate changes must be done at the structures used at the proposed algorithm. More specifically, a) the link and path cost parameters of cost vector should be replaced with corresponding energy consumption parameters, like energy consumption of (flexible or fixed) transponders and additive energy consumption of routers, b) in the domination relation applied at the first step of the multi-cost algorithm, the cost of paths should be replaced by the energy consumption of paths, and c) in the optimization function applied at the second step of the multi-cost algorithm, the network cost should be replaced by the network energy consumption, to select the path with the smallest additive network energy consumption.

V. PERFORMANCE RESULTS

To evaluate the performance of the proposed algorithm, we conducted a number of simulation experiments using MATLAB. At the experiments presented below, we define the following cases of networks:

(a) MLR optical network employing fixed-grid 50 GHz optical switches and fixed 40 and 100 Gb/s transponders (*fixed-grid/fixed-TSP*),
(b) MLR optical network employing 12.5 GHz flex-grid optical switches and fixed 40, 100 and 400 Gb/s transponders (*flex-grid/fixed-TSP*),
(c) flexible optical network employing 12.5 GHz flex-grid optical switches and flexible transponders, also referred to as BVTs (*flex-grid/flex-TSP*).

The reason that in the first case we are not assuming the use of 400 Gb/s transponders is that such devices are expected to require 75 GHz spectrum, which does not fit in traditional 50 GHz fixed-grid WDM systems. We also distinguished the case where a joint or sequential multi-layer network planning (*JML-NP* or *SML-NP*, respectively) solution is applied to each of the above networks. For all these cases (three different types of networks and the two planning options), we evaluate the

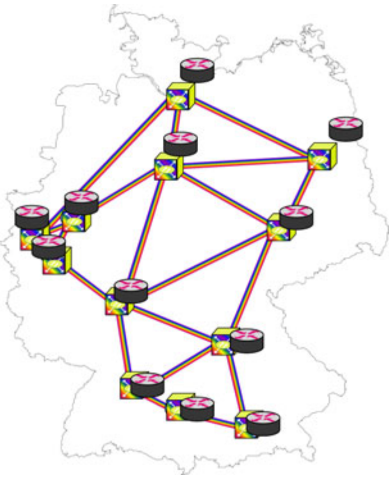

Fig. 4. Generic DT topology with 12 nodes and 40 directed links.

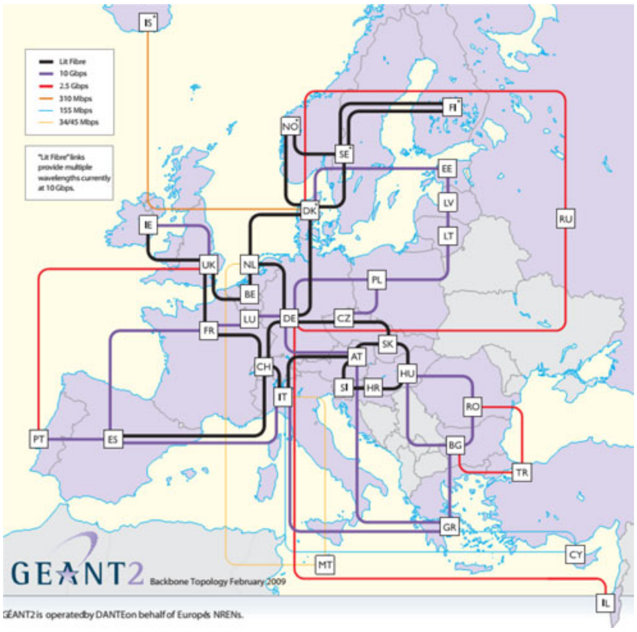

Fig. 5. Generic GEANT topology with 34 nodes and 108 directed links.

proposed algorithm that is quite generic (as discussed in Section IV-C).

We used two reference networks in our simulations with different characteristics in terms of number of nodes and link lengths: the Deutsche Telekom (DT) and the GEANT network, so that the results obtained are representative of real networks. DT (see Fig. 4) is an IP backbone network with 12 optical nodes, a single IP core router per optical node, and 20 link 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 (see Fig. 5) is an IP backbone network with 34 optical nodes and 54 link edges (108 bidirectional edges) with an average length of 752 km and maximum length of 2361 km. The GEANT topology used at the simulations is that of February 2009, as we have not available information for later years. For the case of DT network, we created traffic matrices for the period from 2014 up to 2024 based on real traffic for 2011, assuming 35% uniform increase per year, while for the case of GEANT network, we created traffic matrices for the period from 2014 up to 2024, based on real traffic for 2009, assuming 25% uniform increase per year. The performance metrics we used for the comparisons, are the maximum spectrum used (measured in GHz), the cost of transponders, the cost of routers and the total cost of network computed as the sum of transponders and routers cost, which is our main focus.

In the case of the flex-grid networks (*flex-grid/fixed-TSP* and *flex-grid/flex-TSP*), each fiber of the DT network has 320 spectrum slots available, each of width 12.5 GHz. For GEANT we assumed two fibers with a maximum of 640 spectrum slots available. In the case of the fixed-grid network (*fixed-grid/fixed-TSP*), we assumed 80 wavelengths of 50 GHz width each for the DT network, and two fibers for the GEANT with 160 wavelengths in total. For the GEANT network we assumed that the spectrum in both fibers is 4 THz, but we cannot switch lightpaths from one fiber to the other, so in this sense the spectrum can be considered as a continuous 8 THz-wide segment. The reason for making this choice is that currently the devised algorithm considers a single contiguous set of spectrum to model the optical links, but note that enabling switching between the fibers would increase the network efficiency. The proposed algorithm can be extended to integrate this additional degree of flexibility, but this was omitted for the sake of brevity.

The transmission tuples (reach, rate, spectrum, cost) 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 [19]–[21]. Note that the transmission tuples shown in Table I concern a single type of flexible

TABLE I
TRANSMISSION TUPLES OF FLEXIBLE TRANSPONDERS

Reach (Km)	Capacity (Gb/s)	Required Spectrum (in GHz)	Cost (ICU)
4000	40	87.5	1.76
3600	40	75	
3200	40	62.5	
2500	40	50	
2100	40	37.5	
1800	40	25	
3800	100	87.5	
3500	100	75	
3100	100	62.5	
2400	100	62.5	
2000	100	50	
1700	100	37.5	
2500	200	87.5	
2200	200	75	
1900	200	62.5	
900	200	62.5	
700	200	50	
450	200	37.5	
2500	400	175	
2200	400	150	
1900	400	125	
900	400	125	
700	400	100	
450	400	75	

TABLE II
TRANSMISSION TUPLES OF FIXED-GRID TRANSPONDERS

Reach (Km)	Capacity (Gb/s)	Required Spectrum (in GHz)	Cost (ICU)
2500	40	50	0.48
2000	100	50	1
450	400	87.5	1.36

TABLE III
COST OF LINECARDS AND SINGLE CHASSIS IP/MPLS ROUTERS IN IDEALIST COST UNITS (ICU)

Type	Cost (ICU)
Core router with 1 chassis of 16 slots and 400 G capacity per slot	4.30
10 × 40G linecard for core router	2.56
4 × 100G linecard for core router	2.88
1 × 400G linecard for core router	2.74

transponder. In case of *SML-NP*, the cost of the regenerators was set as 80% of transponder cost [18]. Note that the cost of flexible transponders was taken to be 30% higher than that of the equivalent 400 Gb/s fixed rate transponder.

The different types and the related cost of the linecards (assumed to be 400 Gb/s capacity in total) are shown in Table III. Note that we assumed that flexible transponders are always interfaced with 400 Gb/s linecards, although they could be configured to transmit at lower loads. The cost of an IP/MPLS router with 1 chassis of 16 slots is shown in Table III, while the cost of a multi-chassis router is computed according to the following equation:

$$
\begin{aligned}
P &= \; 6,02 \cdot n_{ch} + 1,76 \cdot \left\lceil \frac{n_{ch}}{9} \right\rceil + 9,11 \cdot \left\lceil \frac{n_{ch}}{3} \right\rceil, \\
n_{ch} &= \; \left\lceil \frac{C}{K} \right\rceil, 2 \leq n_{ch} \leq 7
\end{aligned}
\tag{6}
$$

where n_{ch} is the number of linecard chassis installed, *C* is the total switching capacity in Tb/s, and *K* is the capacity of a fully equipped linecard chassis (taken to be 16 × 400 Gb/s here). The costs of transponders, linecards and routers used in our simulations are derived from the CAPEX model defined in the context of the EU project IDEALIST [4].

A. DT Network Results

Table IV shows the maximum spectrum (in GHz) used for each network case examined with *JML-NP* or *SML-NP* and for years 2014 to 2024, for DT reference network. Concerning the *JML-NP* case, we observe that the *flex-grid/flex-TSP* network outperforms both *fixed-grid/fixed-TSP* and *flex-grid/fixed-TSP* optical networks, while the *fixed-grid/fixed-TSP* network exhibits the worst performance. This was expected since in the flexible network the flexible transponders used, utilize exactly the amount of spectrum they require, while in the *fixed-grid/fixed-TSP* and *flex-grid/fixed-TSP* networks the transponders are fixed and utilize 50 GHz per lightpath, and either 50 or 75 GHz (for the 400 Gb/s), respectively. Also we observe that after 2022 the *fixed-grid/fixed-TSP* network experiences blocking due to insufficient spectrum, since traffic increases and in this network we assumed that we cannot use 400 Gb/s transponders. This shows the inefficient spectrum usage of fixed-grid compared to flex-grid networks, especially at high loads. Concerning the *SML-NP* case, we observe the same findings as those observed at the *JML-NP* case, in terms of spectrum, expect the fact that in the case of *fixed-grid/fixed-TSP* network the connections are blocked after 2020. Comparing the joint multi-layer network planning (*JML-NP*) case as opposed to the sequential (*SML-NP*) case, we observe that in the case of *fixed-grid/fixed-TSP* and *flex-grid/fixed-TSP* networks, the spectrum used is smaller during the whole period of reference, when the *JML-NP* is applied. In the case of *flex-grid/flex-TSP* network, the spectrum used is the same at low loads (years 2014 and 2016), while at higher loads the *JML-NP* case also outperforms the *SML-NP* case.

The transponder, router and total network cost for each network case when planned jointly (*JML-NP*) and reference years from 2014 to 2024 is shown in Table V. The *fixed-grid/fixed-TSP* network presents the highest cost from 2016 to 2022 (then the traffic is blocked), as it requires a high number of low-rate fixed 40 and 100 Gb/s transponders to serve the traffic, unable to use the more efficient 400 Gb/s for certain high demands. Among the three network cases, the *flex-grid/flex-TSP* network has the smallest network cost during all the examined periods, except for year 2014, where the other networks have slightly smaller costs. Note that the cost difference between the *flex-grid/flex-TSP* and the *flex-grid/fixed-TSP* cases increases as the years progress; this is because at light loads, low-cost/low-rate fixed transponders are sufficient to serve the traffic (*flex-grid/fixed-TSP* network), while flexible transponders used in the *flex-grid/flex-TSP* are not fully utilized, resulting in some waste and cost increase. Although routing at the IP layer alleviates this problem, through appropriate traffic grooming, still at low load (year 2014) the *flex-grid/fixed-TSP* network turned out to be slightly better than *flex-grid/flex-TSP*. As traffic increases, the utilization and the efficiency of flexible transponders increases. Combining this with the additional flexibility of more transmission options gives the advantage to the *flex-grid/flex-TSP* which outperforms both *fixed-grid/fixed-TSP* and *flex-grid/fixed-TSP* networks, regarding the total network cost, at medium and high loads. Note that in the above calculations the cost of flexible transponders was taken to be 30% higher than that of the equivalent fixed rate transponders. Higher savings could be obtained if this was lower.

Table VI shows the transponder, router and network cost for each case of network with *SML-NP* and reference years from 2014 to 2024. We observe that among the three network cases and during the whole period of reference, the *flex-grid/flex-TSP* network presents the best performance, which is explained as before. Concerning joint multi-layer planning (*JML-NP*), we observe that at all network cases *JML-NP* exhibits lower cost than the sequential *SML-NP* algorithm during the whole examined period especially for the *fixed-TSP* cases. This is explained as follows: in the case of *SML-NP* network, the IPR sub-problem is solved without taking into account the reach constraints at the optical layer (the RML decisions). This, results in utilizing mostly 400 Gb/s transponders and linecards, so the

TABLE IV
SPECTRUM FOR EACH CASE OF NETWORK WITH *JML-NP* OR *SML-NP*, AND REFERENCE YEARS FROM 2014 TO 2024, WHEN USING DT AS REFERENCE NETWORK

Year	Joint multi-layer network planning			Sequential multi-layer network planning		
	Fixed-grid/fixed-TSP	Flex-grid/fixed-TSP	Flex-grid/flex-TSP	Fixed-grid/fixed-TSP	Flex-grid/fixed-TSP	Flex-grid/flex-TSP
2014	550	550	250	700	700	250
2016	900	825	350	1100	825	350
2018	1250	1075	487.5	1300	1200	512.5
2020	2350	1275	812.5	2500	1500	925
2022	3950	2300	1525	–	2400	1587.5
2024	–	3200	2750	–	3800	2812.5

TABLE V
TRANSPONDER, ROUTER AND NETWORK COST (IN ICU) FOR EACH CASE OF NETWORK WITH *JML-NP*, AND REFERENCE YEARS FROM 2014 TO 2024, WHEN USING DT AS REFERENCE NETWORK

Year	Fixed-grid/fixed-TSP			Flex-grid/fixed-TSP			Flex-grid/flex-TSP		
	Transponder cost	Router cost	Network cost	Transponder cost	Router cost	Network cost	Transponder cost	Router cost	Network cost
2014	72.96	61.76	134.72	66,24	60.88	127.12	59.84	76.72	136.56
2016	128.96	110.77	239.73	107.20	112.85	220.05	77.44	133.69	211.13
2018	212.24	186.23	398.47	147.28	175.19	322.47	112.64	197.25	309.89
2020	373.36	314.32	687.68	240.80	324.76	565.56	179.52	319.24	498.76
2022	661.44	643.46	1304.90	403.52	654.74	1058.26	309.76	627.09	936.85
2024	–	–	–	684.48	1186.20	1870.68	531.52	1024.43	1555.95

TABLE VI
TRANSPONDER, ROUTER AND NETWORK COST (IN ICU) FOR EACH CASE OF NETWORK WITH *SML-NP*, AND REFERENCE YEARS FROM 2014 TO 2024, WHEN USING DT AS REFERENCE NETWORK

Year	Fixed-grid/fixed-TSP			Flex-grid/fixed-TSP			Flex-grid/flex-TSP		
	Transponder cost	Router cost	Network cost	Transponder cost	Router cost	Network cost	Transponder cost	Router cost	Network cost
2014	94.67	83.84	178.51	79.78	110.52	190.30	59.84	93.16	153.00
2016	147.65	136.05	283.70	109.72	182.97	292.69	77.44	139.17	216.61
2018	239.62	205.11	444.73	160.76	261.67	422.43	122.85	216.43	339.28
2020	394.00	359.17	753.17	231.36	488.71	720.07	193.25	378.38	571.63
2022	–	–	–	378.93	899.36	1278.29	306.06	640.22	946.28
2024	–	–	–	622.64	1460.96	2083.60	538.21	1047.43	1585.64

establishment of the related lightpaths might not be always feasible in terms of reach. The tunability of flex-TSP partially alleviates this issue and this is why this problem is more profound in the fixed-TSP cases. Also, note that this reach mismatch issue is relative small in the DT topology with short links.

Concerning the distribution of total network cost between the IP/MPLS routers and transponders, we observe that at *flex-grid/fixed-TSP* and *flex-grid/flex-TSP* network cases and regardless the planning solution used (*JML-NP* or *SML-NP*), the largest percentage of cost is due to IP/MPLS routers, while at *fixed-grid/fixed-TSP* network, the dominant cost is that of (fixed) transponders. The latter is explained by the inability to use the cost-efficient 400 Gb/s for certain connections that need them. In the *flex-grid/flex-TSP* network the percentage of cost due to IP/MPLS routers is bigger, compared to the *flex-grid/fixed-TSP* network when a *JMP-NP* solution is applied. This is because in the case of the *flex-grid/flex-TSP* network, only 400 Gb/s linecards were used with the flexible transponders with only one available port, although at certain cases the transponders are tuned to operate at lower rate. Note that the advantage of the flexible solution (*flex-grid/flex-TSP*) at high load is due to the lower cost of both the transponders and the electrical cost (IP/MPLS routers) compared to the *flex-grid/fixed-TSP* network.

Finally, in the following we report on the execution times of the algorithm under heavy load (year 2024) for the DT network. The results were taken using a laptop with i5 processor and 4 GB of RAM.

- 456 s for the *flex-grid/flex-TSP* network with *JML-NP*.
- 914 s for the *flex-grid/fixed-TSP* network with *JML-NP*.
- 2001 s for the *flex-grid/flex-TSP* network with *SML-NP*.
- 4750 s for the *flex-grid/fixed-TSP* network with *SML-NP*.

From the above we observe that the execution time of the algorithm is smaller when it is applied to a flexible as opposed to a MLR network both when a *JML-NP* or a *SML-NP* solution is applied; the reason being that the MLR network uses three types of transponders and thus the related network graph has triple the number of inter-layer links, when compared to the

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TABLE VII
SPECTRUM FOR EACH CASE OF NETWORK WITH *JML-NP* OR *SML-NP*, AND REFERENCE YEARS FROM 2014 TO 2024, WHEN USING GEANT AS REFERENCE NETWORK

Year	Joint multi-layer network planning			Sequential multi-layer network planning		
	Fixed-grid/fixed-TSP	Flex-grid/fixed-TSP	Flex-grid/flex-TSP	Fixed-grid/fixed-TSP	Flex-grid/fixed-TSP	Flex-grid/flex-TSP
2014	2350	2350	1425	4150	4050	1575
2016	3350	3350	1900	5600	5400	1900
2018	4550	4550	2300	7200	6850	3537.5
2020	6600	5500	3587.5	–	–	4437.5
2022	–	8000	4862.5	–	–	5175
2024	–	–	–	–	–	–

TABLE VIII
TRANSPONDER, ROUTER AND NETWORK COST (IN ICU) FOR EACH CASE OF NETWORK WITH *JML-NP*, AND REFERENCE YEARS FROM 2014 TO 2024, WHEN USING GEANT AS REFERENCE NETWORK

Year	Fixed-grid/fixed-TSP			Flex-grid/fixed-TSP			Flex-grid/flex-TSP		
	Transponder cost	Router cost	Network cost	Transponder cost	Router cost	Network cost	Transponder cost	Router cost	Network cost
2014	196.80	145.92	342.72	196.80	145.92	342.72	154.88	205.50	360.38
2016	274.32	193.92	468.24	274.32	193.92	468.24	207.68	304.14	511.82
2018	414.64	262.72	677.36	406.56	260.20	666.76	260.48	413.17	673.65
2020	597.60	489.88	1087.48	589.36	482.61	1071.97	369.60	657.49	1027.09
2022	–	–	–	866.96	686.50	1553.46	499.84	879.94	1379.78
2024	–	–	–	–	–	–	–	–	–

TABLE IX
TRANSPONDER, ROUTER AND NETWORK COST (IN ICU) FOR EACH CASE OF NETWORK WITH *SML-NP*, AND REFERENCE YEARS FROM 2014 TO 2024, WHEN USING GEANT AS REFERENCE NETWORK

Year	Fixed-grid/fixed-TSP			Flex-grid/fixed-TSP			Flex-grid/flex-TSP		
	Transponder cost	Router cost	Network cost	Transponder cost	Router cost	Network cost	Transponder cost	Router cost	Network cost
2014	283.50	204.80	488.30	281.44	210.28	491.72	170.02	287.13	457.15
2016	390.36	276.80	667.16	383.35	293.96	677.31	211.55	352.89	564.44
2018	531.43	382.13	913.56	519.41	425.10	944.51	309.94	549.03	858.97
2020	–	–	–	–	–	–	412.19	775.28	1187.47
2022	–	–	–	–	–	–	554.05	1043.20	1597.25
2024	–	–	–	–	–	–	–	–	–

flex-grid cases with a single (but tunable) transponder. Also we observe that the execution time of the algorithm is considerably smaller in the case of a *JML-NP* solution as opposed to *SML-NP* solution. This is due to the fact that in the case of *SML-NP* we executed the algorithm twice for planning separately the IP and optical layers. Note that the execution time of the algorithm can be vastly reduced, by using techniques such as look-ahead, and limiting the search space of nodes, according to the requirements of the dynamic scenarios.

B. GEANT Network Results

Table VII shows the maximum spectrum (in GHz) used in each examined network with *JML-NP* or *SML-NP*, for reference years from 2014 to 2024 and GEANT reference network. Concerning the *JML-NP* case, we observe that the *flex-grid/flex-TSP* network outperforms both *fixed-grid/fixed-TSP* and *flex-grid/fixed-TSP* optical networks, while the *fixed-grid/fixed-TSP* network presents the worst performance. The reason for these findings is the same, as the one explained in the case of DT network. Also we observe that after 2020 the connections of the *fixed-grid/fixed-TSP* network are blocked due to insufficient spectrum, since traffic increases and 400 Gb/s transponders are unavailable. Concerning the *SML-NP* case, we observe similar findings with those found in the *JML-NP* case, in terms of spectrum, except that after 2016 the connections of the *fixed-grid/fixed-TSP* and *flex-grid/fixed-TSP* network are blocked. Comparing the joint (*JML-NP*) and the sequential (*SML-NP*) optimization case, we observe that at all network cases, the spectrum used by *JML-NP* is smaller than that used by *SML-NP* during the whole period of reference.

The transponder, router and total network cost for each network case, when planned jointly (*JML-NP*) and reference years from 2014 to 2024 is shown in Table VIII for GEANT network.

We observe that during years 2014 and 2016 the *fixed-grid/fixed-TSP* and *flex-grid/fixed-TSP* networks present the same network cost. Also we observe that for the period from 2014 to 2018 the *flex-grid/fixed-TSP* network has lower cost, but after 2018 the *flex-grid/flex-TSP* network becomes better and as the traffic increases the difference increases as well. Note that this crossing happens in GEANT later than in DT network. As in the case of DT network, this is because low-cost/low-rate fixed transponders are more efficient at low load, while flexible transponders are not fully utilized, wasting cost. As traffic increases, the utilization and the efficiency of flexible transponders increases, and *flex-grid/flex-TSP* eventually outperforms the other cases.

Table IX shows the transponder, router and network cost for each case of network with *SML-NP* and reference years from 2014 to 2024. In the case of GEANT network and *SML-NP*, the *flex-grid/flex-TSP* case outperforms the other two network cases, during the whole period of reference. More, as the load increases their cost difference increases. Concerning the joint multi-layer (*JML-NP*) as opposed to the sequential multi-layer (*SML-NP*) planning, we observe that at all network cases, the *JML-NP* network has much lower cost than the *SML-NP* network. The reason for these findings is the same as the one given for the DT network, with the additional disadvantage for the *SML-NP* case of longer lightpaths in GEANT topology.

Finally, concerning the distribution of network cost, the findings are slightly different than the DT network. We observe that at *flex-grid/fixed-TSP* case the largest percentage of cost is due to fixed transponders, while at *flex-grid/flex-TSP* case the cost of IP/MPLS routers dominates, regardless the planning solution applied (*JML-NP* or *SML-NP*). This is because of the longer lightpaths that makes the use of lower rate fixed transponders more efficient, requiring fewer linecards (of more low-rate ports), for the *fixed-TSP* cases.

VI. CONCLUSION

We presented a joint multi-layer network planning algorithm that can be applied to both flex-grid and fixed-grid optical networks. The algorithm takes as input the feasible transmission configurations of flexible or fixed transponders defined to account for physical layer limitations, a model for the modular IP/MPLS routers and the traffic matrix. It serves demands for their requested rates by jointly selecting the modules of the routers, the routes in the IP (virtual) topology and the corresponding paths, and spectrum slots in the underlying optical topology, together with the transponders transmission configuration. Using realistic transmission specifications for flexible networks, our results show that savings can be obtained through joint multi-layer optimization over the IP and the optical layer, as opposed to planning the two layers sequentially. We also verified that flex-grid optical networks outperform fixed-grid in terms of maximum spectrum used, when a joint or a sequential multi-layer network planning approach is applied. In case of joint multi-layer network planning, flexible network is slightly more expensive at light load compared to fixed-MLR networks, but as load increases it becomes more efficient and cheaper. Moreover, in the case of sequential multi-layer network planning, a flexible network is less expensive than a fixed-grid network both at low and high loads. The above remarks magnify the need for planning the network with a joint multi-layer approach.

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Authors’ biographies not available at the time of publication.