Optimization Techniques for Incremental Planning of Multilayer Elastic Optical Networks

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***Abstract*—As optical networks become increasingly flexible and software driven, network operators need to reconsider their present mode of network planning and operation, which traditionally relies on long planning periods, performed independently for the IP edges (logical topology) and the optical transport layer (physical topology). Network planning assuming fully loaded end-of-life conditions fails to follow traffic evolution and results in capacity overprovisioning, underutilized equipment, and stranded investments. We argue that it would be beneficial to have shorter upgrade cycles and a multiperiod network planning approach that accounts jointly for the upgrade of the optical but also the IP edges of the network. We formulate the incremental multilayer planning problem of an IP over elastic optical network and propose an integer linear programming (ILP) algorithm to solve it. The ILP model leverages the reconfigurability of both network layers to delay equipment deployment and benefit from cost erosion. Our objective is, through repurposing of existing network resources, to deploy in a period the minimum additional network equipment (capital expenditures) to cope with traffic changes from the previous period but also to minimize changes in transitioning between the two periods (operational expenditures). The proposed planning approaches are validated through simulations based on realistic network scenarios, where we also study the effect of the upgrade period duration.**

***Index Terms*—Elastic optical networks; Incremental capacity planning; Joint multilayer planning.**

I. Introduction

The continuous growth of IP traffic and the emergence of new services are leading to a huge increase in traffic volume [1]. Future fifth-generation (5G) networks will engender a wide range of new services, such as ultra-high-definition video streaming, augmented and virtual reality, cloud gaming, smart homes, etc. The considerable challenge faced by telecom operators is to cater to higher capacity and efficiency but also to high unpredictability and dynamicity. This requires an agile network infrastructure, spanning from the access toward the metro/regional and core segments of the network [2].

Optical transport networks used today in metro/regional and core networks are designed and operated in a static manner. The optical transport network is planned assuming long upgrade periods. To ensure that the resulting network will cope with increasing traffic until the next upgrade, future needs are forecasted and capacity is overprovisioned. The extra capacity allocated results in underutilized equipment and unnecessary investments for long periods of the network lifecycle. The longer the upgrade periods, the more the overprovisioning, and the higher the unnecessary investment paid upfront. Moreover, such an approach fails to capture traffic evolution and technology maturation (equipment cost decreasing or new more advanced equipment becoming available). Finally, another factor that contributes to overprovisioning is that the different segments of the network are upgraded independently. To make things worse, overprovisioning is performed not only at the network capacity level but also at the physical layer. The current practice is to establish lightpaths (optical connections) and estimate their quality of transmission (QoT) so that it remains acceptable until their end of life (EOL). Because the QoT deteriorates with time due to equipment aging, increased interference from new connections, etc., QoT estimation is done with high margins that are too pessimistic in the early years [3].

The advent of elastic optical networks (EONs) combined with optical transport platforms that facilitate the setting up and tearing down of lightpaths within minutes or even seconds [4] creates all the necessary conditions to achieve a truly programmable and flexible networking environment. Moving toward this direction, EONs can exploit the bandwidth variable transponders (BVTs) to reconfigure the lightpaths to meet dynamic traffic requirements [5]. Combining EONs with the IP layer reconfigurability can facilitate a pay-as-you-grow approach, where little equipment is installed and continuously reoptimized and upgraded. However, this has to be done in a coordinated manner for both the IP and optical segments [6]. Thus, a multiperiod multilayer network planning approach with short periods is required. This would closely capture the traffic evolution and avoid overprovisioning by incorporating smaller but more frequent network updates. The required upgrades could be limited by exploiting the optical and IP (multi-) layer reconfigurability and would also benefit from technology maturation that would be missed in longer upgrade periods.

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Toward this end, we propose an integer linear programming (ILP) model that jointly considers multilayer and incremental multiperiod planning. The challenge is to capture the effects of time-dependent planning parameters, such as traffic evolution, technology maturation, and equipment cost decrease. These are not known in the long term, and the longer we predict them the more uncertainty we would introduce. So in our model, we assume a given period duration, and we optimize the deployment of the additional network equipment and the changes imposed by the transition between the current and the next state.

Our results indicate that combining multilayer and incremental network planning significantly reduces the total cost of ownership. Cost-efficient network solutions are obtained by exploiting the reconfigurability capabilities of flexible equipment so as to adapt to the time evolution of planning parameters. We also verify that additional savings are achieved by adopting shorter network upgrade periods.

The rest of the paper is organized as follows. Section II presents the related work, while in Section III, we formally state the incremental planning of a multilayer IP over EON problem. Section IV describes the joint incremental and multilayer planning techniques, while the ILP formulation for solving the optimization problem follows in Section V. Performance results are presented in Section VI. Our conclusions follow in Section VII.

II. Related Work

Significant research has focused on multilayer network optimization [7–9], with multiperiod network planning [10–14] also receiving recent attention. Regarding IP over (elastic or fixed) optical networks, the authors of [7] highlight the role played and the significant cost savings achieved by a design process that optimizes the base IP topology introducing router bypass. To reduce the aggregation level of incoming flows, the authors of [8] exploit EON technology's finer granularity to allow grooming at the optical layer. To this end, they propose a new architecture for national IP/multiprotocol layer switched (MPLS) networks interconnected through an EON core. The authors of [9] examine the planning problem of a multilayer IP over EON from the perspective of capital expenditures (CAPEX) minimization by accounting for modular IP/MPLS routers at the optical network edges along with BVTs.

Multiperiod planning aims to optimize the cost of transport networks over a long time frame. There are two approaches for multiperiod planning: 1) global optimization assuming knowledge of the traffic and equipment characteristics/prices for all periods [10,11] and 2) incremental planning [12–14]. The authors of Ref. [10] incorporate multilayer and multiperiod planning in a single optimization step. In their attempt to study the migration scenario from a networking point of view, the authors of Ref. [11] propose a single-layer ILP model. Multiperiod planning is used to study the migration of the network from single- to mixed-line rate and investigate the deployment of an optimal channel mix based on reach and equipment prices.

To quantify the degree of traffic dynamicity and growth that would justify higher initial investment in (flex-rate) BVT technology, the authors of Ref. [12] propose an ILP model for multiperiod analysis that accounts for hardware provisioning requirements over multiple periods of increasing traffic. To achieve savings over the current provisioning practice of using EOL physical layer margins, the authors of Ref. [13] present an algorithm to provision lightpaths based on actual physical performance and use it in a multiperiod planning scenario for just-in-time equipment deployment. In a similar concept, [14] models the progressive aging of the transmission channel and quantifies the benefits of dynamically adjusting the BVT to the physical network quality.

In this paper, we take an incremental planning approach for the joint planning of a multilayer IP over EON network. The incremental approach is motivated by the increased traffic dynamicity and unpredictability resulting from the advent of new services and 5G technology. Under such conditions, it seems hard to have *a priori* knowledge of the exact traffic volume and pattern for the entire network lifecycle, while it is possible to have rather good forecasts of short-term traffic growth. Our objective is to deploy at each period the minimum amount of additional network resources required to cope with traffic changes from the previous period, optimizing both the CAPEX of the equipment used and the operational expenditures (OPEX) associated with the changes imposed by the transition between the two periods.

Even though multilayer planning and incremental multiperiod planning have been extensively researched, to the best of our knowledge no other work apart from [15] gives a formal description and optimal solution to the combination of these planning approaches. In Ref. [15], we provided the formal description and optimal solution to the problem only considering optical layer reconfigurability. In this paper, we extend [15] and propose techniques that exploit both optical layer reconfigurability and IP layer grooming capabilities, examining the impact of each layer in the incremental planning process. Additionally, we consider nonuniform traffic evolution scenarios (to account for the impact of traffic dynamicity), and we also study the impact of the upgrade period duration.

In summary, the main novelties of this work are the following: first, we formulate and provide an optimal algorithm to solve the aforementioned problem, leveraging the reconfigurabilty of network equipment at both layers to avoid capacity overprovisioning and improve the cost efficiency of the network. Second, the proposed model introduces a penalty on the reconfiguration of existing connections at both layers [lightpaths and IP/MPLS label switched paths (IP-LSPs)], to restrict the extent of modifications performed between periods and associated costs and disruptions. In this way, we obtain a trade-off between the equipment added (CAPEX) and the changes performed (OPEX) between successive periods (which might require manual intervention or service disruption). Third, we use the proposed algorithm to examine the effect of the upgrade period durations, and we verify that small and frequent upgrades can yield significant savings, which can be further increased by considering technology maturation and cost erosion of network equipment.

III. PROBLEM STATEMENT

A. Network Architecture

We assume an EON domain composed of optical switches and fiber links. The fiber links consist of single-mode fiber spans and erbium-doped fiber amplifiers (EDFAs). The optical switches function as reconfigurable optical add-drop multiplexers (ROADMs) employing flex-grid technology and support lightpaths of one or more contiguous 12.5 GHz spectrum slots. Note that the solutions to be proposed will also be valid for fixed-grid WDM networks (50 GHz wavelengths), which can be viewed as a special and simpler case of EONs. At each optical switch, zero, one, or more IP/MPLS routers are connected, comprising the edges of the optical domain. An IP/MPLS router is connected to the ROADM via BVT transponders that transform the client signal for optical long-haul transmission. We also assume that the optical nodes can be equipped with bandwidth variable regenerators (BVRs) of similar specifications with BVTs that can be used to regenerate the optical signal.

The source BVT transponder, functioning as a transmitter, converts the electrical packets coming from the IP source router to optical signals (electrical-to-optical conversion). Then the traffic entering the ROADM is routed over the optical network along the established lightpaths. We assume that a number of transmission parameters of the BVTs and the BVRs are under our control, affecting the rate and reach at which they transmit. The lightpath passes transparently or translucently (if BVRs are required to restore signal quality) through intermediate ROADMs and reaches the destination ROADM, where it is dropped. The signal is converted back to electrical at the destination BVT that operates as the optical receiver (optical-to-electrical conversion), and the packets are forwarded to the corresponding IP/MPLS router. This forms a virtual or IP link between the lightpath source and destination IP/MPLS routers. Note that lightpaths are assumed to be bidirectional, and thus in the above description an opposite directed lightpath is also installed, and transponders act simultaneously as transmitters and receivers. An IP/MPLS router that is reached can be the final destination or an intermediate hop in this domain. If it is the final destination in the IP domain, the packets are forwarded to the next domain. If it is an intermediate hop on the virtual topology, the packets are routed back to the optical network over a new lightpath and can traverse more intermediate IP/MPLS router hops to reach the domain destination. The IP links that compose the IP/MPLS path in the domain are called the virtual (IP) path or the IP-LSP.

From the optimization point of view, the network consists of two layers, the IP (or virtual or logical) layer and the optical (or physical) layer. The optical lightpaths are installed on the physical topology, by assigning routes, modulation format, and spectrum. A virtual link is defined by a lightpath or a series of regenerated lightpaths. The virtual links compose the virtual topology on top of which we establish the IP-LSPs, i.e., the virtual paths to serve the IP/MPLS traffic.

B. Incremental Multilayer Planning

Due to the rather static and inflexible nature of current optical transport networks, the planning process uses long planning periods. Aiming to avoid capacity overprovisioning and unnecessary investments that affect cost efficiency, we introduce a periodic reoptimization process that can facilitate a pay-as-you-grow approach. Through periodic reoptimization of the network, operators are able to detect early signs of QoT degradation, equipment aging, and capacity exhaustion. Note that the period's length determines how closely traffic evolution and technology maturation will be captured.

We implement the concept of periodic reoptimization by adopting an incremental planning approach. We assume that the upgrade process of the multilayer network is performed periodically and makes decisions on how to support the traffic for the next planning period, given the current state of the network and the equipment availability and prices. So, the assumption is that this process is performed successively and separately for each period, having the knowledge (forecast) of the traffic only of the next period and no further future knowledge.

In the initial planning period (period t_0), both (IP and optical) layers are simultaneously optimized with the objective being the minimization of the cost. An algorithm such as that in Ref. [16] can be used for this step. At the start of a new period t_N, the incremental model takes as input the new traffic, the current equipment availability and prices, the previous state of the network at t_{N-1}, [including the state of the resources (established lightpaths and IP-LSPs)], and information about physical resources (installed/available equipment and its location). The optimization process considers jointly the IP and physical layers and the previous network state and aims at minimizing both the added network equipment (CAPEX) and the equipment displacements and reconfiguration between the two successive network states (OPEX).

As shown in Fig. 1, the proposed model exploits the flexibility of BVTs that can be used in numerous different configurations to carry client traffic. This allows an initial design that is scalable through the years because it is possible to increase a client's port rate by increasing, when feasible, the number of optical carriers or by using higher-order modulation formats with the possible addition of BVRs (because higher-order modulation formats entail a decrease in the optical reach) and the possible displacement of the already installed ones. Additionally,

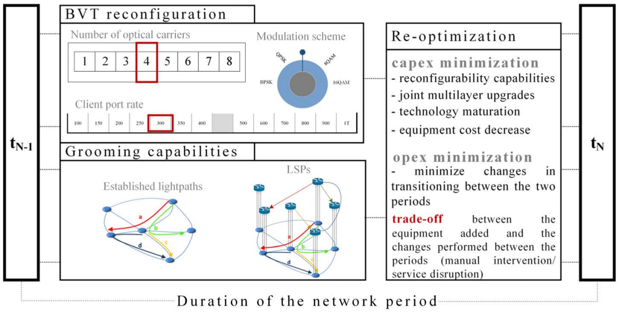

Fig. 1. Incremental multilayer planning process.

network resources can be made available by reoptimization of the previous network state exploiting the grooming/reconfiguration capabilities of both layers to enable spare capacity utilization. Our model takes into account the traffic dynamics, cost evolution, and technology development to achieve greater cost savings.

IV. INCREMENTAL MULTILAYER PLANNING OPTIMIZATION TECHNIQUES

We assume, in our study, that accurate QoT and reach estimation is available at the start of each period. Mechanisms for this purpose are developed in the ORCHESTRA project, where physical layer information obtained from software optical performance monitors is processed using data analytics/correlation methods to yield accurate physical layer knowledge [17]. This can be used in dynamic use cases to reoptimize the network following the observe-decide-act control loop or for planning purposes, as done here.

Three techniques, based on the reconfigurability of IP and optical equipment, are useful in leveraging multiperiod and multilayer planning simultaneously. The first technique uses IP grooming capabilities to minimize the cost of added equipment at both network layers. The second technique exploits optical layer reconfigurability to delay equipment deployment and benefit from cost erosion to minimize the network cost over a long period of time. The third technique considers in a single optimization step the joint minimization of 1) the IP and optical network layer equipment cost and 2) the cost of the changes (e.g., IP rerouting, lightpath teardown, BVT reconfiguration, setup of new lightpaths, etc.) required for the transition between two periods.

A. *Virtual Layer Reoptimization*

The incremental planning technique based on virtual topology reoptimization (VTR) focuses on the grooming capabilities of the IP layer to exploit the flexibility the IP layer provides in a multiperiod planning scenario. Through IP rerouting and regrooming, VTR tries to efficiently use the spare capacity of the lightpaths and IP-LSPs established in the previous period. When the spare capacity of existing IP-LSPs is inadequate to serve the current state demands, new equipment is added.

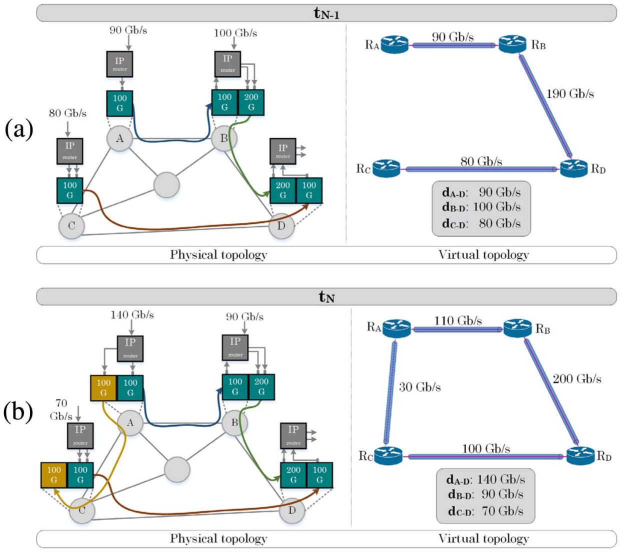

Fig. 2. Example of IP layer reconfiguration in an incremental planning scenario: (a) previous network state (t_{N-1}) and (b) current network state (t_N).

Figure 2 presents an illustrative example of the examined multilayer network, where four IP/MPLS routers compose the IP (virtual) layer, and four flex-grid optical switches together with BVTs supporting different transmission tuples compose the optical (physical) layer. More specifically, in Fig. 2(a), three lightpaths ($A\leftrightarrow B$, $B\leftrightarrow D$, and $C\leftrightarrow D$) have been established at the optical layer, and three IP-LSPs ($R_A\leftrightarrow R_B$, $R_B\leftrightarrow R_D$, and $R_C\leftrightarrow R_D$) have been set up at the IP layer. In Fig. 2(b), the transition between two network states corresponding to periods t_{N-1} and t_N is depicted. The capacity of some IP-LSPs may be inadequate due to high congestion on some virtual topology links, in which case a virtual topology reconfiguration has to be performed to groom and balance the traffic avoiding the heavily utilized resources. In the example presented in Fig. 2(b), upon transition between state t_{N-1} to t_N, the remaining capacity of IP-LSP $R_B - R_D$ (200 Gb/s) is unable to serve the demands d_{A-D} (140 Gb/s) and d_{B-D} (90 Gb/s). The virtual topology can be reoptimized by establishing a new IP-LSP ($R_A - R_C$) that allows grooming part of d_{A-D} (30 Gb/s) and d_{C-D} (70 Gb/s) demands [dotted red line in Fig. 2(b)]. The objective of VTR is to exploit the IP grooming capabilities to minimize the cost of added equipment at both layers of the network, which in this example was to add 100 GB/s lightpath $A\leftrightarrow C$ and the corresponding $R_A - R_C$ IP-LSP.

B. *Optical Layer Reoptimization*

The incremental planning technique based on optical layer reoptimization (OLR) exploits the reconfigurability of optical equipment to delay new equipment deployment and decrease the total cost of the network over multiple periods. In this technique, the IP grooming capabilities are limited because our goal is to understand the impact of the optical layer flexibility in the evolution of the network lifecycle.

The advantages of this technique stem from the use of BVTs and flex-grid ROADMs. BVTs can adjust their bandwidth by changing the modulation format, baud rate, and number of carriers (according to the particular BVT's specifications). This is typically combined with a spectrum reconfiguration, making use of the flex-grid ROADMs. Through the use of BVTs, we avoid the future purchase of many different transponders—one can deliver a wide range of required capacities, as depicted in the example of Fig. 3. A somehow related benefit of using BVTs is their ability to trade off reach for capacity. Reallocating transponders to connections and making use of this trade-off, we can accommodate abrupt traffic changes and postpone or avoid equipment investments. The main benefit of investment delay is that technology maturation usually leads to reductions in equipment price.

As an illustration of the OLR technique, consider Fig. 3, where three lightpaths ($B \leftrightarrow A$, $A \leftrightarrow C$, and $C \leftrightarrow D$) and three IP-LSPs ($R_A \leftrightarrow R_B$, $R_B \leftrightarrow R_D$, and $R_C \leftrightarrow R_D$) have been established at the optical and the IP layer, respectively. In Fig. 3(a), a 100 Gb/s demand (d_{B-C}) is allocated a lightpath of 100 Gbps polarization division multiplexed quadrature phase shift keying (PDM-QPSK). This leaves a large capacity margin because 200 Gbps could be transmitted over the same path using PDM-16 quadrature amplitude modulation (QAM). Assuming that the deployed transponder is rate-flexible (BVT) and 200 Gbps capable, when the demand (d_{B-C}) grows (in period t_N) to 160 Gb/s, the extra capacity can be allocated without replacing the transponder but by simply changing its modulation format from PDM-QPSK to PDM-16QAM [Fig. 3(b)]. Demands d_{A-D} and d_{C-D} are served following a similar process for the other two lightpaths ($A \leftrightarrow C$ and $C \leftrightarrow D$). Note that OLR is unable to reroute the already established IP-LSPs. Thus, it exploits only BVT reconfigurability to serve growing demands, whereas when the capacity margins of the BVTs are depleted, new equipment is deployed.

C. Joint Multilayer Reoptimization

The incremental planning technique based on joint multilayer reoptimization (JMR) fully exploits the reconfigurability of the optical network equipment and the grooming capabilities of the IP layer. In this technique, we jointly consider both the CAPEX of the equipment used in both layers of the network and the OPEX associated with the changes (e.g., IP rerouting, lightpath teardown, BVT reconfiguration, setup of new lightpaths, etc.) imposed by the transition between two network periods.

Using JMR, the optical and IP layer of the network are used in a coordinated manner to increase its capacity, extend its life, decrease deployment cost, and minimize the required manual interventions. An illustration of JMR is presented in Fig. 4, where in Fig. 4(a), three lightpaths ($A \leftrightarrow C$, $B \leftrightarrow C$, and $C \leftrightarrow D$) and three IP-LSPs ($R_A \leftrightarrow R_B$, $R_B \leftrightarrow R_C$, and $R_C \leftrightarrow R_D$) have been established at the optical and the IP layer, respectively. In this example, we demonstrate that choices made for one connection in the early planning periods, e.g., to serve it over a specific path by placing regenerators at specific nodes so as to avoid congestion over another path, could be changed in subsequent periods, when the chosen path becomes congested while the avoided path turns out to be relatively empty. More specifically, the optical connection $B \leftrightarrow C$, which is already established at network period t_{N-1}, requires intermediate

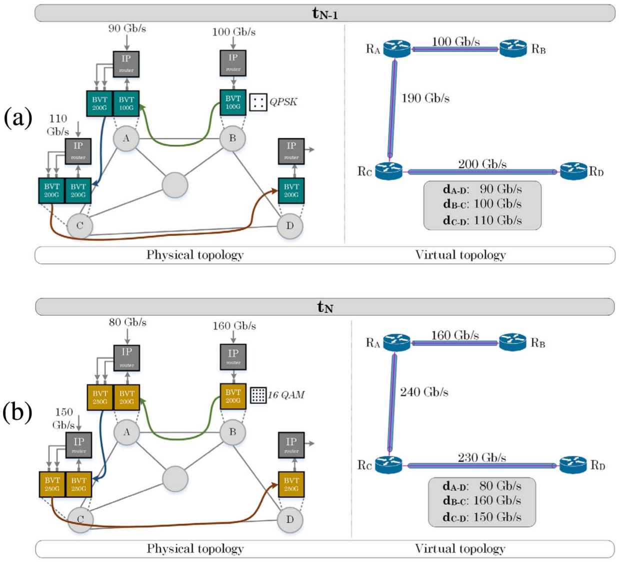

Fig. 3. Example of optical layer reoptimization in an incremental planning scenario: (a) previous network state (t_{N-1}) and (b) current network state (t_N).

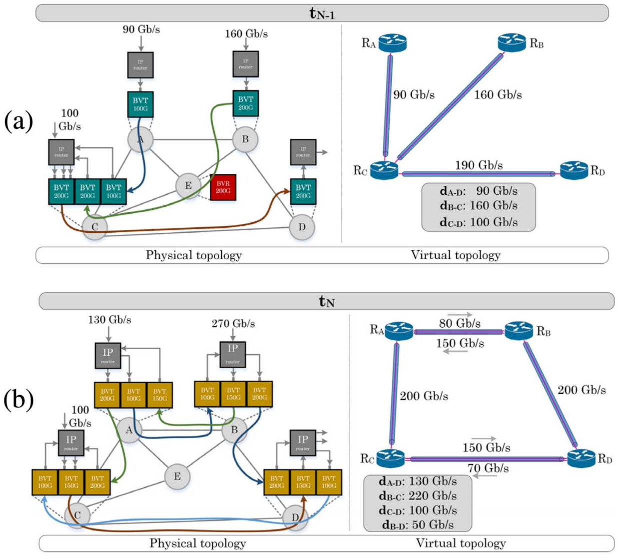

Fig. 4. Example of joint multilayer reoptimization in an incremental planning scenario: (a) previous network state (t_{N-1}) and (b) current network state (t_N).

BVR (node E). The growth of the traffic demands and the addition of a new demand ($d_{B\text{–}D}$) (in period t_N) triggers the JMR technique, which combines traffic grooming and the reconfigurability of the BVTs to reroute lightpath $B\leftrightarrow C$ and eliminate regeneration. The establishment of four low-rate optical connections ($A\leftrightarrow B$, $B\leftrightarrow A$, $B\leftrightarrow D$, and $D\leftrightarrow C$) facilitates the rerouting of the increased demands to remove bottlenecks and avoid network congestion. Figure 4(b) presents the regrooming of demands $d_{A\text{–}D}$ and $d_{B\text{–}C}$, where part of the demand $d_{A\text{–}D}$ (50 Gb/s) and demand $d_{B\text{–}C}$ (150 Gb/s) are groomed and allocated to a 200 Gb/s BVT (lightpath $A\leftrightarrow C$). In node C, grooming demand $d_{C\text{–}D}$ (100 Gb/s) and part of demand $d_{A\text{–}D}$ (50 Gb/s) leads to a 150 Gb/s BVT (lightpath $C\leftrightarrow D$). The rest of the $d_{A\text{–}D}$ demand (80 Gb/s) and $d_{B\text{–}C}$ demand (70 Gb/s) and the demand $d_{B\text{–}D}$ (50 Gb/s) are groomed and allocated to lightpaths $A\leftrightarrow B$, $B\leftrightarrow D$, and $D\leftrightarrow C$, with a capacity of 100, 200, and 100 Gb/s, respectively.

V. MATHEMATICAL FORMULATION

In the ILP model to be presented in this section, multilayer and incremental planning are jointly considered in a single optimization step. For each period, both network layers are simultaneously optimized (see Subsection IV.C, JMR) by taking into account not only equipment cost (CAPEX) but also the cost of changes from the previous network state (OPEX). The extent to which the current state will commit to the previous one (equivalently, the trade-off between CAPEX and OPEX for the optical and the IP layer) is controlled through parameters W_o and W_f, passed as input to the model.

The network is represented by a graph $G(V,L)$, with V being the set of nodes and L the set of bidirectional fiber links connecting nodes. The nodes of the graph correspond to the optical and IP nodes of the network where we account for the cost of both layers. We assume that we are given the traffic matrix Λ, where Λ_{sd} corresponds to the IP demanded capacity between source-destination pair (s, d).

We are also given the models of the BVT transponders and BVR regenenerators. We represent by B the set of BVT, and we also assume that for each BVT $b\in B$ there is an equivalent BVR, represented by r_b. The transmission option of a BVT or BVR are described in what are called transmission tuples. Each transmission tuple t represents a specific configuration of the BVT (rate, spectrum) and is related to a specific transmission reach, using a QoT estimation model (e.g., [18]). To be more specific, transmission tuple $t = (D_t, R_t, S_t)$ represents a feasible transmission at distance D_t, with rate R_t (Gpbs), using S_t spectrum slots. The network designs are based on precalculated paths. In particular, we assume that for each pair of nodes (i, j) we precalculate k paths from i to j, which define the set P_{ij}. The algorithm decides to serve connections using a specific BVT (and if needed BVR), a tranmission tuple, and a path. This is represented by a feasible path-transmission tuple pair (p, t), where the BVT transponder is represented by its related transmission tuple (t). If the length of path p is higher than the reach of tuple t, we assume that we place BVR (with the same configuration t as the BVT) over the path at the node before QoT becomes unacceptable. The term “feasible” is used to indicate that QoT is accounted for. We denote by C_{pt} the cost of the path-transmission tuple pair (p, t), which includes the cost of the BVT and BVR (if required).

Finally, we are also given a model for an IP/MPLS router. We assume that a router is a modular device, built out of (single or multi-) chassis. A chassis provides a specified number of bidirectional slots with a nominal transmission speed. A line card of the corresponding speed can be installed into each router slot. Each line card provides a specified number of client ports at a specified speed and occupies one slot of the IP/MPLS router. A client port is connected with an equivalent BVT, and we assume that for every BVT there is an available tunable line card type. The scalable multichassis core router has up to N_{LCC} line card chassis, and there are N_{FCC} router slot capability per chassis.

A problem instance is described by the following inputs:

- the network topology, represented by graph $G(V,L)$;
- the maximum number Z of available spectrum slots (of 12.5 GHz);
- the traffic, described by the traffic matrix Λ;
- the sets of paths P_{ij} for all pairs of nodes (i, j);
- the sets B and R of available transponders (BVTs) and regenerators (BVRs);
- the set T of available transmission tuples for all transponders (the set T_b represents transmission tuples of transponders $b\in B$);
- the set of feasible path-transmission tuple pairs (p, t) and their cost C_{pt}, which includes the cost of the BVT transponder and BVR regenerator(s) (if required);
- the set of line cards represented by H, where the line cards for transponder $b\in B$ are represented by the set H_b [a line card $h\in H_b$ is represented by tuple $h = (N_h, C_h)$, where N_h is the number of transponders of type b that the line card supports and C_h is the cost of the line card);
- the IP/MPLS router cost model (we assume that an IP/MPLS router consists of line card chassis of cost C_{LCC}, that supports N_{LCC} line cards each, and fabric card chassis of cost C_{FCC}, that supports N_{FCC} line card chassis);
- the weighting coefficient, W_C, taking values between 0 and 1 (setting $W_C = 1$ minimizes solely the CAPEX, whereas setting $W_C \approx 0$ minimizes the maximum spectrum used);
- weighting coefficients W_o and W_f, taking values between 0 and 1 [setting $W_o = W_f = 1$ minimizes solely the current state cost, ignoring the previous network state, whereas setting $W_o \approx 0$ maintains the previous state's lightpaths (optical layer equipment), whereas setting $W_f \approx 0$ maintains the previous state's IP-LSPs (IP layer equiment); thus, W_o (or W_f) controls the trade-off between CAPEX and OPEX for the optical layer (or the IP layer, respectively)].

Variables:

f_{psd}	Float variable, equal to the capacity of the IP-LSP from IP source s to destination d that passes over a lightpath (virtual link) that uses path p.
x_{pt}	Integer variable, equal to the number of lightpaths with path-transmission tuple pair (p, t) used.
y_{nh}	Integer variable, equal to the number of line cards of type h at node n.
θ_{nb}	Integer variable, equal to the number of used transponders of type b at node n.
v_{nb}	Integer variable, equal to the number of deployed transponders of type b at node n.
q_n	Integer variable, equal to the number of line card chassis at node n.
o_n	Integer variable, equal to the number of fabric card chassis at node n.
d_{pt}^{O}	Integer variable, equal to the number of torn down lightpaths from the previous state, counted as the number of removed (p, t) path–transmission tuple pairs.
d_{psd}^{F}	Boolean variable, identifying if the IP-LSP from IP source s to destination d that passes over a lightpath that uses path p was affected by the transition between the two network states.
z	Integer variable, equal to the maximum indexed spectrum slot.
z^{l}	Integer variable, equal to the total number of spectrum slots used in bidirectional fiber link l.
c	Float variable, equal to the CAPEX of the added network equipment.
ω	Integer variable, equal to the number of lightpaths torn down in the transition between the previous and the current state.
φ	Integer variable, equal to the number of affected IP-LSPs in the transition between the previous and the current state.

Constants:

F_{psd}	Float constant, equal to the IP traffic of end nodes s to d that is transferred over optical path p in the previous network state.
X_{pt}	Integer constant, equal to the number of lightpaths of path-transmission tuple pairs (p, t) used in the previous network state.
Θ_{nb}	Integer constant, equal to the number of transponders of type b at node n used in the previous network state.
M	Float constant, a big number that is used to form big-M constraints [e.g., $M > \max(\Lambda_{sd})$].

The objective is

$$\min(W_o \cdot W_f \cdot (W_C \cdot c + (1 - W_C) \cdot z) + (1 - W_o) \cdot \omega + (1 - W_f) \cdot \varphi). \quad (1)$$

- The CAPEX calculation constraints are

$$c = \left(\sum_{i\in V} \sum_{j\in V} \sum_{p\in P_{ij}} \sum_{t\in T|(p,t)\text{feasible}} C_{pt} \cdot x_{pt} + \sum_{n\in V} \sum_{h\in H} C_h \cdot y_{nh} + \sum_{n\in V} C_{\text{LCC}} \cdot q_n + \sum_{n\in V} C_{\text{FCC}} \cdot o_n \right). \quad (2)$$

- The OPEX calculation constraints are

$$\omega = \sum_{i\in V} \sum_{j\in V} \sum_{p\in P_{ij}} \sum_{t\in T|(p,t)\text{feasible}} d_{pt}^{O},$$
$$\varphi = \sum_{s\in V} \sum_{d\in V} \sum_{i\in V} \sum_{j\in V} \sum_{p\in P_{ij}} d_{psd}^{F}. \quad (3)$$

- The IP flow continuity constraints are

$$\forall\ (s,d) \in V^2,\ n \in V,$$
$$\left(\sum_{i\in V} \sum_{p\in P_{in}} f_{psd} - \sum_{j\in V} \sum_{p\in P_{nj}} f_{psd} \right) = \begin{cases} \Lambda_{sd}, & n = s \\ -\Lambda_{sd}, & n = d \\ 0, & n \neq s, d \end{cases}. \quad (4)$$

- The path-transmission tuple assignment constraints are

$$\forall\ (i,j) \in V^2,$$
$$\sum_{p\in P_{ij}} \sum_{sd\in V^2} f_{psd} \le \sum_{p\in P_{ij}} \sum_{t\in T|(p,t)\text{feasible}} (R_t \cdot x_{pt}). \quad (5)$$

- The previous state constraints (optical layer) are

$$\forall\ \text{feasible}(p,t), \qquad d_{pt}^{O} \ge X_{pt} - x_{pt}. \quad (6)$$

- The used transponder constraints are

$$\forall\ n \in V,\ b \in B, \qquad \theta_{nb} = \sum_{i\in V|p\in P_{ni}} \sum_{t\in T_b} x_{pt}. \quad (7)$$

- The deployed transponder constraints are

$$\forall\ n \in V,\ b \in B, \qquad v_{nb} \ge \theta_{nb}, \qquad v_{nb} \ge \Theta_{nb}. \quad (8)$$

- The previous state constraints (IP layer) are

$$\forall\ (s,d) \in V^2,\ (i,j) \in V^2,\ p \in P_{ij},$$
$$M \cdot d_{psd}^{F} \ge F_{psd} - f_{psd}. \quad (9)$$

- The number of line cards per node constraint is

$$\forall\ n \in V,\ b \in B,\ h \in H_b, \qquad y_{nh} \ge \sum_{h} v_{nb}/N_h. \quad (10)$$

- The number of line card chassis per node constraint is

$$\forall\ n \in V, \qquad q_n \ge \sum_{h\in H_b} y_{nh}/N_{\text{LCC}}. \quad (11)$$

- The number of fabric card chassis per node constraint is

$$\forall\ n \in V, \qquad o_n \ge q_n/N_{\text{FCC}}. \quad (12)$$

- An estimation of maximum spectrum slot used constraints:

$$\forall\, l \in L,\ (i,j) \in V^2,$$
$$z^l = \sum_{p\in P_{ij}|l\in p}\ \sum_{t\in T|(p,t)\text{feasible}} (S_t \cdot x_{pt}), \tag{13}$$

$$\forall\, l \in L, \qquad z \geq z^l, \tag{14}$$

$$z \leq Z. \tag{15}$$

The joint multilayer planning ILP formulation presented dimensions the network for the next period. An IP demand between s and d is served by a single lightpath (when $s = i$ and $d = j$) or by a series of lightpaths that compose the IP-LSP. The IP-LSP paths are identified by the values of the IP flow variables f_{psd}, showing the amount of IP traffic of end nodes s to d that is transferred over optical path p. Variables x_{pt} represent the lightpaths; a lightpath between source-destination optical nodes i, j is chosen among k (precalculated) optical paths P_{ij} [Eq. (5)]. Note that some transponders that were deployed in a previous period might remain unused in the current period. To account for this, we use two types of variables, v_{nb} that corresponds to the deployed transponders [Eq. (8)], including idle ones, and θ_{nb} that corresponds only to the used ones in the current period [Eq. (7)]. Because line cards and subsequently chassis are matched and calculated based on deployed transponders v_{nb}, such variable distinction is not required for that equipment [Eqs. (11)–(13)].

The cost of the IP/MPLS routers is captured through variables y_{nh}, q_n, and o_n. The objective [Eq. (1)] is to minimize a weighted sum of the maximum spectrum used in the network, the CAPEX of the equipment used in both layers [Eq. (2)], and the reconfigurations of lightpaths and IP-LSPs [Eq. (3)]. Constraints (4) and (5) and (11)–(13) deal with the joint multilayer (optical and IP) planning problem, Constraints (6)–(10) address the incremental planning problem, and Constraints (13)–(15) address the spectrum usage.

To reduce the model complexity and obtain optimal results for realistic network sizes, the ILP does not perform spectrum assignment. It calculates an estimation of the slots used per link z^l, by summing the spectrum of the lightpaths that cross the link, thus neglecting the spectrum continuity constraint (requiring the use of the same spectrum slots over all links of the lightpath). Based on those it minimizes the estimation of the maximum spectrum used in the network z [Eq. (1)], which is constrained to be within the available spectrum slots range Z [Eq. (15)]. The model can be extended to jointly perform spectrum allocation as well, but the gains in the objective were observed to be significantly small. For the purposes of simplicity and to enable running the ILP model for large network instances, the spectrum assignment was performed, with respect to the spectrum continuity constraint, in a subsequent step using a modified Hungarian method [19].

VI. ILLUSTRATIVE RESULTS

In this section, we evaluate the performance of the incremental multilayer planning techniques presented in Section IV. In particular, we distinguished the following three scenarios:

- The planning from scratch scenario (denoted as *ML*), where the whole network is designed at each period without taking into account the previous network state. This scenario provides the optimal benchmark for the comparisons because planning the network from scratch without considering the previous network state obviously leads to the optimum (lowest) CAPEX; it is not, however, a realistic approach because it maximizes OPEX and disruption [$W_o = W_f = 1$ in Eq. (1)].
- The static incremental scenario (denoted as *Inc*), where the network is incrementally planned without being able to perform any change from the previous network state, thus fully respecting it. This restriction applies to both layers of the network, limiting the BVT reconfiguration and IP grooming capabilities, and this scenario provides the pessimistic benchmark for the comparison [$W_o = W_f = 0$ in Eq. (1)].
- The joint multilayer incremental planning scenario, where both layers of the network are upgraded in a coordinated manner. The objective of this scenario is to optimize both the added equipment (CAPEX) at each period and the number of changes made (OPEX) using the proposed techniques (Section IV). We examined three scenario variations by varying the parameters W_o and W_f that control the ability to deviate from the previous network state: $W_o = 0$ and $W_f = 1$ (denoted as VTR, Subsection IV.A), $W_o = 1$ and $W_f = 0$ (denoted as OLR, Subsection IV.B), and $W_o = 0.5$ and $W_f = 0.5$ (denoted as JMR, Subsection IV.C). When $W_o = 0$ and $W_f = 1$ (VTR), the reoptimization model is based solely on the grooming capabilities of the IP layer and is not able to perform any change in the established lightpaths of the previous network state. When $W_o = 1$ and $W_f = 0$ (OLR), the reoptimization process exploits only the reconfigurability of the optical layer equipment. When $W_o = 0.5$ and $W_f = 0.5$ (JMR) the reoptimization incremental planning technique utilizes both IP grooming capabilities and BVT flexibility to equally minimize both the CAPEX of the added equipment and the OPEX associated with the transition changes between the two states.

In our simulations, we used two reference network topologies with different characteristics in terms of number of nodes, link lengths, and load—the Deutsche Telekom (DT [20]) and the Telefónica (TID [20]) topologies—so that the results obtained are representative of real networks. For these networks we also used realistic traffic matrices. The traffic matrices of the DT and TID networks used in our simulations were based on input by the related operators reported in the IDEALIST project [20] for past years. We projected the traffic of these networks for 10 years, with a step of 2 months. To emulate the dynamic evolution of traffic, we assume random growth rates for every

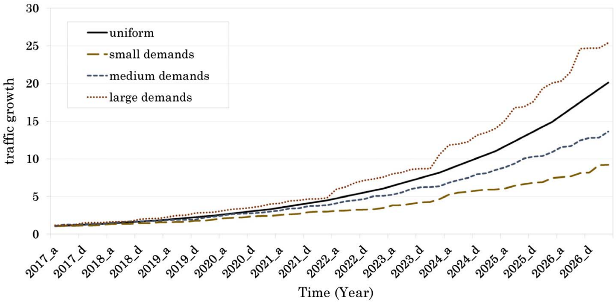

Fig. 5. Illustration of the traffic demand profile of the DT topology used in our study.

demand/entry of the traffic matrix. More specifically, for both networks, we categorized each demand into three groups consisting of small, medium, and large demands. For every demand of each group, a set of traffic growth parameters is randomly generated per year. For the DT topology, the yearly scaling factor of the large demands varies between 1.35 and 1.4, while for the medium demands it varies between 1.3 and 1.35 and for the small demands between 1.25 and 1.3. For the TID topology, the yearly scaling factors vary between 1.15 and 1.3. Following [20], the average yearly increase of the total traffic for the DT network is 1.35, while for TID it is 1.25.

In Fig. 5 we present the traffic growth for three random demands of each group and the uniform traffic growth for the DT network (1.35 yearly traffic growth). Our main goal through the aforementioned traffic patterns is to emulate dynamic traffic evolution and provoke network congestion.

We assume two types of BVTs (and equivalent BVRs), the first with maximum rate of 400 Gbps and the second of 1 Tbps, with the latter being made available after year 2020. The transmission configurations (tuples) of the BVTs are presented in Table I. We assume that for every BVT there is an available tunable line card type. We also consider a scalable multichassis core router, with up to 72 chassis (N_{FCC}), and a 16 router slot capability per chassis (N_{LCC}). The costs of BVTs and of the IP/MPLS routers are based on cost models defined by the IDEALIST project [20]. The reference cost unit (c.u.) is defined as the cost of a 100 Gb/s coherent transponder. In our study, we account for equipment cost erosion over the network lifecycle, assuming a cost erosion of 10% per year for all types of equipment.

TABLE I
Bandwidth Variable Transponders

BVT 1				BVT 2[a]			
Capacity (Gb/s)	Reach (km)	Data Slots	Cost (c.u.)	Capacity (Gb/s)	Reach (km)	Data Slots	Cost (c.u.)
100	2000	4	1.76	500	950	7	2
150	1350	4		600	800	8	
200	1050	5		700	700	9	
250	950	5		800	650	11	
300	700	6		900	550	12	
350	600	6		1000	450	14	
400	450	6					

[a] Available from 2020.

A. Cost Evaluation and Spectral Impact

In this section, we compare the different planning techniques with respect to the resulting CAPEX (Fig. 6) and spectral resource utilization (Fig. 7) for the two reference networks. We use the planning from scratch (ML) technique as an optimal benchmark for the comparison, while the static incremental planning (Inc) technique is used as a pessimistic benchmark, because it is unable to exploit the reconfigurability of the IP and optical equipment, exhibiting in all periods the worst performance. The joint multilayer incremental planning (JMR, Subsection IV.C) technique leverages the flexibility provided by both network layers to achieve noteworthy CAPEX and OPEX savings. VTR (Subsection IV.A) and OLR (Subsection IV.B) techniques achieve limited savings by focusing solely on the reoptimization of the virtual and optical layer, respectively.

More specifically, Fig. 6 depicts the cost evaluation of the entire network assuming incremental planning with 12-month increments. In both network topologies, JMR marginally underperforms the optimal benchmark (ML), while it exhibits significantly higher efficiency (ranging between 10% and 48%) when compared to the pessimistic benchmark (Inc). The increased efficiency results from the limited reconfiguration capabilities of the Inc technique at both layers of the network. In the DT network, VTR performs similarly to OLR, while it clearly underperforms

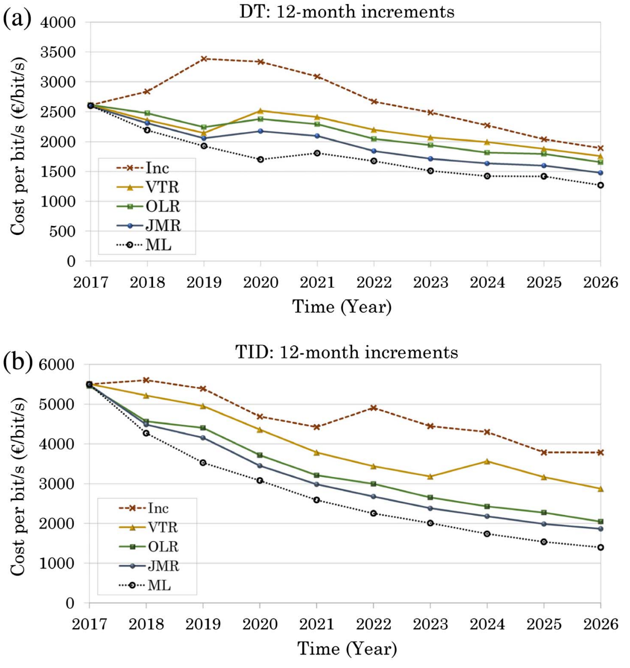

Fig. 6. CAPEX of (a) DT and (b) TID topology for different optimization options and 12-month network planning periods.

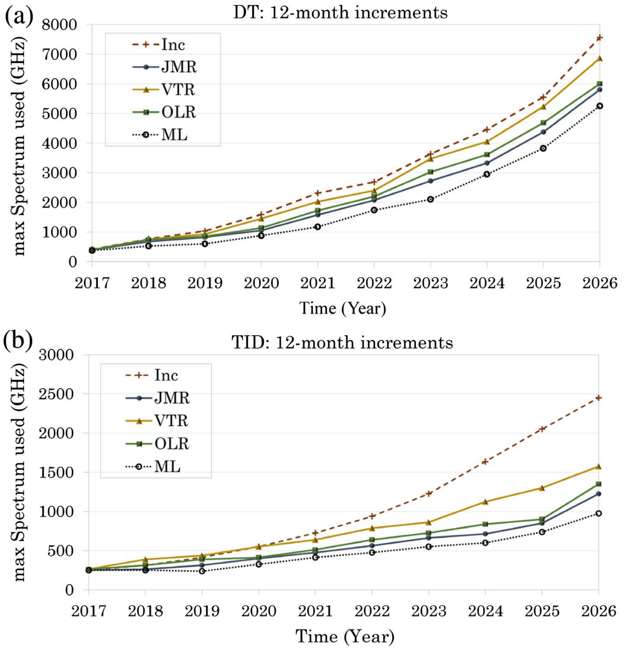

Fig. 7. Maximum spectrum used for the (a) DT and (b) TID topology for 12-month planning periods.

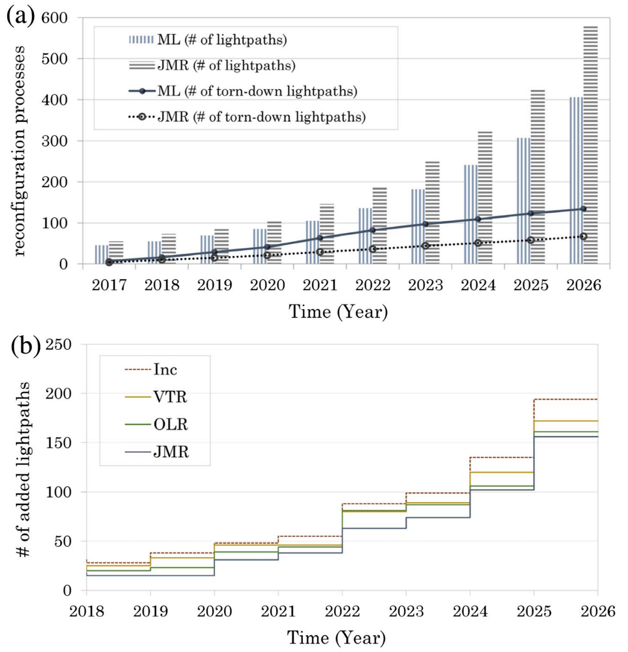

Fig. 8. (a) Reconfiguration overhead in the optical layer and (b) number of added lightpaths per period for different incremental planning techniques (12-month period).

the latter for the TID network. This is indicative of the impact each layer has in the reoptimization process of the network and comes as a result of the different traffic profiles (higher traffic growth for DT) and topologies (in the DT topology all optical nodes are interconnected with IP routers, whereas in TID topology, there are several optical transit nodes not connected to IP routers with no traffic terminating/initiating at those nodes).

Figure 7 presents the results regarding spectrum utilization for the two reference networks. All planning approaches perform similarly with respect to spectrum utilization as to the CAPEX metric, even though we observe slightly lower spectrum savings for the DT network, due to the deployment of more regenerators for the DT topology, which provide wavelength conversion possibilities. In contrast, TID topology is characterized by lower traffic demands leading to the deployment of lower-order modulation format BVTs that are able to exploit the trade-off between spectral efficiency and reach. In cases where the link lengths of the network are small enough, we are utilizing modulation formats that increase the spectral efficiency of the network. In cases where the available spectrum is consumed [Fig. 7(a)], we assume that extra fibers are installed. The cost of the fibers and the equipment required for the installation of new fibers is included in the calculation of the network cost.

B. Lightpath Reconfiguration Analysis

In this subsection, we focus on the trade-off between CAPEX minimization of the equipment used in the current state and the minimization of OPEX associated with the optical equipment displacements and reconfigurations between network states. Figures 8(a) and 8(b) present the number of reconfigured and added lightpaths per period (considering a 12-month period), respectively. As already stated, ML is agnostic to the previous state of the network, leading to the optimum CAPEX achieved through an extensive reconfiguration of already established lightpaths. Figure 8(a) shows that the proposed joint incremental multilayer (JMR) approach limits the number of lightpath reconfigurations and establishing of new lightpaths, and consequently controls the corresponding OPEX. The JMR technique achieves a significant reduction, of the order of 50%, of the reconfiguration processes, while maintaining a relatively small number of added lightpaths per period, which is only 18% larger than the one achieved by the benchmark planning technique [ML; see Fig. 8(b)].

C. Cost Breakdown and Impact of Each Layer in the Total CAPEX

In Fig. 9(a), we present the cost breakdown for four planning techniques examined in our study. As expected, the JMR technique exhibits the best performance because it exploits the flexibility of both network layers to minimize the cost of the network equipment. The static incremental approach (Inc) increasingly underperforms, due to its inability to use the reconfiguration capabilities of the network equipment. As time advances the bad choices made by Inc aggregate and are not corrected at any point of the network lifecycle.

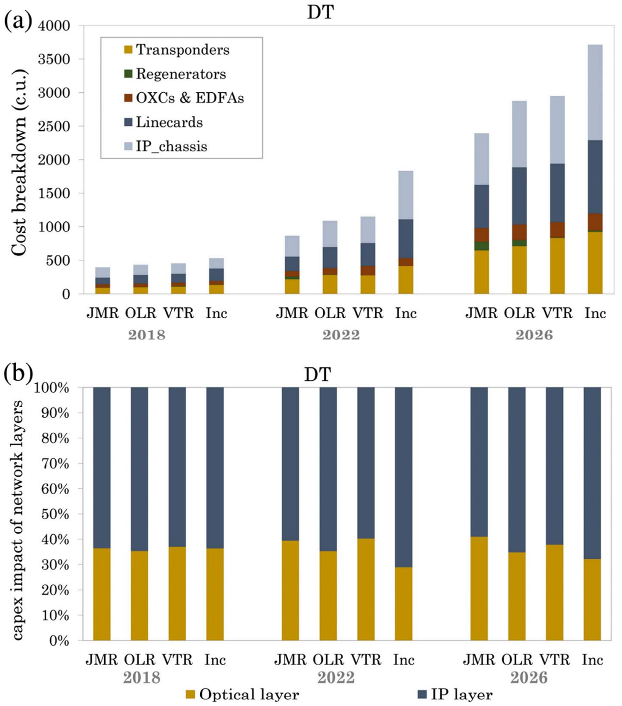

Fig. 9. (a) Network equipment cost breakdown and (b) impact of each network layer in the total cost of the network for different planning techniques.

Figure 9(b) illustrates that under medium (2022) and heavy (2026) traffic load, JMR balances the cost contributions of both network layers to achieve a cost-efficient solution, whereas the performance of OLR and VTR is affected by the single-layer reoptimization capabilities. In particular, OLR exhibits significant increase in the IP layer costs, and VTR's inability to exploit the reconfigurability of the optical layer equipment affects the savings that can be achieved through traffic grooming.

D. Duration of Network Planning Periods

The duration of the network planning periods determines the required investment to be made to ensure that the resulting network design can cope with future traffic until the next upgrade period. By adopting short network planning periods, we are able to avoid the deployment of unnecessary equipment and benefit from technology maturation and corresponding price reductions.

This becomes evident in Fig. 10(a), where we use the JMR technique assuming upgrade periods of different duration. The 60-month upgrade period leads to 77% higher CAPEX when compared to the 2-month network period, in the beginning of each network planning period (2017a and 2022a). We obtain similar results when comparing with the 12-month (28%–39% higher CAPEX) and 24-month (42%–48% higher CAPEX) upgrade periods. The same pattern emerges when examining the TID network topology [Fig. 10(b)].

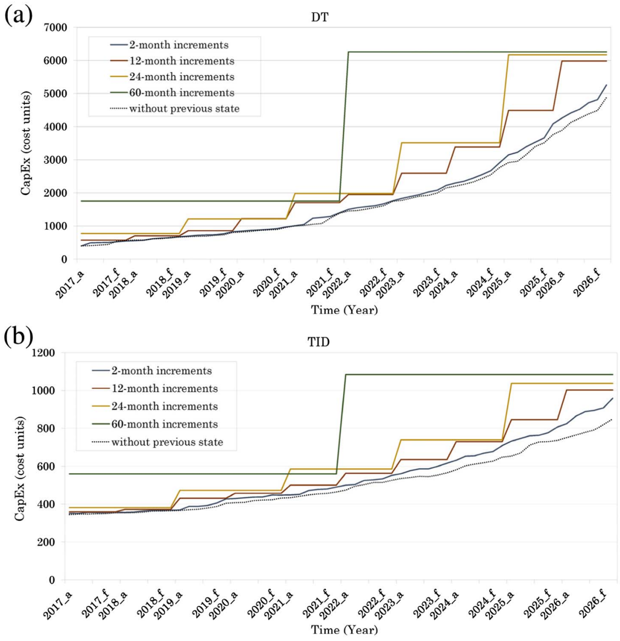

Fig. 10. Impact of the duration of the network planning periods to the CAPEX of the (a) DT and (b) TID topology, using the JMR incremental planning technique.

It is noteworthy that by adopting short network planning periods we not only delay equipment deployment but we also improve cost efficiency over the entire network lifecycle. From Figs. 10(a) and 10(b), and especially when examining the end of the 60-month period (2021_f and 2026_f), it becomes evident that we can obtain significant savings by closely capturing traffic evolution and exploiting technology maturation through short network planning periods.

VII. CONCLUSION

The inevitable growth of the traffic to be transported by optical transport networks, which may also be nonuniformly directed, accentuates the need for planning methods that have the ability to repurpose existing network equipment. In view of this, we proposed planning techniques that account jointly for the upgrade of the optical and the IP edges of the network in an incremental manner. Through an ILP formulation we optimally exploited the reconfigurability of optical and IP equipment, with the objective being the minimization of the equipment added at each period (CAPEX) and the equipment reconfigurations (OPEX) required between two consecutive periods. We evaluated incremental planning performance under realistic network scenarios and quantified the impact of the reconfiguration capabilities of each layer on the total network cost over the entire network lifecycle. Additionally, we verified that short network periods are able to closely capture the effects of traffic dynamicity and technology maturation, resulting in significant cost savings.

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