Multilayer flex-grid network planning

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***Abstract*— The traffic in metro and core networks is forecasted to grow in volume but also in dynamicity, and the inefficiency of WDM optical networks drove research efforts on flex-grid technologies. Flex-grid networks support variable spectrum connections as a way to increase spectral efficiency and support future transmission rates. In addition, the use of flexible transponders further increases the flexibility of such networks, bringing closer the optical and the IP layers. The joint planning and operation of both layers becomes crucial to reduce the capital and operational costs. To this end, in this paper we examine the planning problem of a multilayer (ML) flex-grid network from the perspective of capital expenditure taking into account modular IP/MPLS routers at the optical network edges along with tunable optical transponders. We propose a concise ILP formulation that jointly solves the ML planning problem. The formulation is quite generic and can be used for flex- and fixed-grid networks employing flexible or fixed transponders.**

***Keywords*— CAPEX; Cost Efficiency; Flex-grid; ILP; IP over WDM; IP over flexible (elastic) optical networks; Planning;**

I. Introduction

The Internet is continuously transforming our reality, increasing productivity, and supporting economic developments across the world. Emerging services such as Video on Demand, tele-conferencing, mobile broadband and cloud applications cause tremendous pressure on network infrastructures. Apart from increased traffic volume, traffic dynamicity is becoming a key challenge. Such requirements have unveiled the inefficiency of single-line-rate Wavelength Division Multiplexing (WDM) optical networks, which are typically used today in core and metro networks. WDM networks 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 account for the physical layer (impairments) and the coarse granularity. 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.

The recent advances in transmission technologies and coherent reception have increased the rate-reach product of WDM networks. Moreover, it has become possible the use of more than one line rates in the same WDM network (employing different types of transponders simultaneously). Mixed-line-rate WDM networks, as such networks are typically referred to, exploit the trade-offs between reach and cost of the different devices to improve the efficiency and decrease the total network cost. However 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. The optical network needs to be dynamic and agile, to become part of the whole network, in order to increase the overall efficiency and enable fast end-to-end service provisioning. The rigid bandwidth and reach granularity of WDM networks make such operation inefficient.

As the next step, flex-grid architectures appear to be a promising technology for meeting the requirements of next generation metro and core networks. A flex-grid network migrates from the fixed-grid 50GHz grid that traditional WDM networks utilize, and has slot granularity of 12.5 GHz, while slots can be combined on demand to create as wide channels as needed [1]. These networks are built using bandwidth variable switches that are configured to create appropriately sized end-to-end all-optical paths (lightpaths) of sufficient spectrum slots. The support of variable spectrum connections increases spectral efficiency, supports future transmission rates, and reduces capital costs. Flexible transponders envisioned for flex-grid networks, also referred to as bandwidth variable transponders (BVTs), allow multiple choices when serving a demand: they can decide the modulation format, baud-rate, spectrum, the FEC, or a subset of these, and choose the parameters that give sufficient performance to reach the required distance. BVTs exploit the finer grid to increase spectrum efficiency and favor grooming data directly at the optical layer instead. Although the advanced optical flex-grid technology might imply higher equipment costs, especially at early stages, its higher efficiency can actually lead to savings when considering the whole network. Moreover, the higher optical network flexibility brings it closer to the IP layer, making their joint planning and operation feasible, a crucial factor to further reduce the capital and operational costs. To this end, in this paper we focus on the multi-layer (ML) planning of flex-grid optical network.

In the general case, the multi-layer (ML) flex-grid network planning problem consists of problems in two layers: the Routing sub-problem at the IP layer (IPR), and the Routing, Modulation Level and Spectrum Allocation (RMLSA) sub-problem at the optical layer. We examine the ML planning problem from a perspective of capital expenditure (CAPEX) and propose a concise ILP formulation to solve it. Our goal is, to analyze and compare different optical network scenarios (fixed- and flex-grid) in terms of the CAPEX needed to deploy the related multilayer architecture. The cost model used in our paper includes equipment in the two examined levels: IP/MPLS routers and optical (both fixed- and flex-grid) switches and transponders, taking as a reference the cost model defined in the framework of the EU project IDEALIST [2]. We

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use realistic network topologies, traffic matrices, and cost parameters of the used components, in an attempt to calculate with high precision the CAPEX of realistic cases.

Our simulation results showed that flex-grid networks, although assumed to have 30% higher equipment cost, become more cost-efficient over fixed-transponder systems after a point. In particular, the flex-grid network is shown to outperform networks deploying fixed-grid or flex-grid optical switches and fixed optical transponders, for medium and high loads, while it always achieves the lowest spectrum utilization. We also observed that the IP layer equipment is the major contributor to the total network cost, and we analyzed it further in its constituents.

The rest of the paper is organized as follows. In Section II we report on the related work. Section III presents the network architecture and the used CAPEX model. In Section IV we describe the proposed multilayer network planning algorithm. Simulation results are presented in Section V. Our conclusions follow in Section VI.

II. RELATED WORK

Multilayer network optimization has been an active research subject in the last few years. More and more efforts focus on the design of CAPEX-aware algorithms that consider both the optical network and its electronic edges. We classify these algorithms into two subcategories: algorithms (i) that consider only the flexible optical network [3]-[6], and (ii) that consider both the optical network and the electronic edges (also referred to as traffic grooming) [7]-[10].

The problem for planning a flexible optical network has been investigated with various objectives ([3]-[6]). Algorithms for planning flexible optical networks under physical layer constraints are proposed in [4]. In [5] the authors address the offline RSA problem with dedicated path protection in elastic optical networks and they provide an Integer Linear Programming (ILP) formulation to solve it. A distance-adaptive RSA algorithm for dynamic flexible networks is proposed in [6], in order to select the proper modulation format according to the transmission reach.

We now turn our attention to the multilayer network optimization problem, a problem inextricably linked to the available optical transport technology. For example, in [7], the authors deal with the survivable multilayer IP/MPLS-over-WDM optimization problem. In [8] the authors provide a perspective on how the capital costs and energy consumption of optical WDM networks scale with increasing network capacity. They conclude that using traffic grooming to maximize the utilization of lightpaths and optical bypass to minimize the number of grooming ports is the most cost-effective technique. More recently, in [9], the authors develop a Integer Linear Programming (ILP) formulation and a metaheuristic procedure to analyse the cost implications that a set of frequency slot widths have on the capital expenditure investments required to deploy a multilayer network. In [10] the authors proposed a new architecture to design national IP/MPLS networks, to conclude that significant savings at the flex-grid core network as well as the IP/MPLS area networks can be obtained when the core network extends toward the edges.

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 [2] and [11]), which are given in the form of feasible transmission configurations of the transponders used. So, it can be used for both flexible and fixed-grid optical networks, using fixed or flexible transponders. Second, in contrast to previous works, we consider a flexible and modular CAPEX model covering different layers in our optimization formulation. In particular, we consider more accurately the IP layer, by using a detailed model for the IP/MPLS routers deployed at the edges of the optical network. Thirdly, our algorithm, accounts for tunable optical transponders and for distance adaptive in the optical flexible network. This makes the routing at the optical layer to affect the spectrum allocation but also the routing at the MPLS layer, interrelating all these subproblems.

III. PROBLEM STATEMENT

A. IP/MPLS-over-Flex-grid network architecture

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). The IP/MPLS router is connected to the ROADM via a grey or a colored transceiver. In the case of a short reach gray transceiver additional flexible (tunable) transponders plugged to the ROADMs are needed to regenerate the incoming signal for optical long-haul transmission. 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 on 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 (Fig. 1). 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 only performed electronically and in particular at the IP/MPLS routers, while optical switches function as transparent pipes between IP/MPLS router end-points.

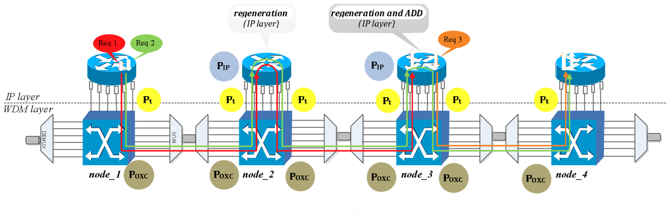


Fig. 1. Architecture of IP over flexible optical network

B. *CAPEX Model*

CAPEX refers to the costs pertaining to the ownership of the network equipment. The CAPEX model used in our studies takes as reference the model developed in the Idealist project [2], and includes equipment of IP/MPLS and optical technology areas, the last one in two versions: fixed and flex-grid. We present the building blocks of our CAPEX model in Fig. 2. Following Idealist model the reference cost unit (c.u.) that we use is the 100 Gb/s coherent transponder, as nowadays this is the state-of-the-art in transponders technology. All other devices are priced with reference to this c.u.

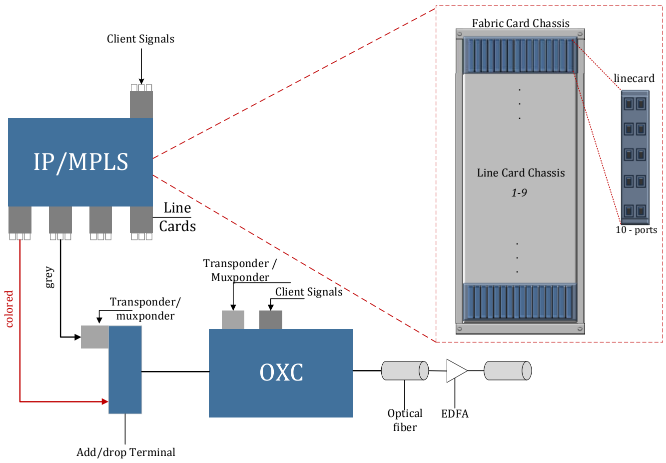


Fig. 2. Building blocks of our CAPEX model

IP/MPLS Layer

The IP/MPLS model is organized into three classes: the basic node, the line-cards and the transceivers. The basic node includes the chassis (single-chassis router for metro nodes, scalable multichassis router for large core nodes) the physical and mechanical assembly, the switch, power supplies, cooling, and control and management plane hardware and software. A chassis provides a specified number of slots with a nominal transmission speed (slot capacity). Into each slot, a line-card (LC) of the corresponding (or lower) speed can be installed. Each line-card provides a specified number of ports at a specified speed. The adopted cost model takes into account the number and kind of the line-cards used, the number of line-cards fitted in a shelf, also called a line-card chassis (LCC), and the number of LCCs fitted in a fiber-card chassis (FCC). Core routers are capable of a minimum of 16 (one shelf - LCC) to a maximum of 1152 (72 shelves - LCCs) slots for hosting line-cards. The cost P of multi-chassis core routers (routers that require two or more shelves) is computed according to the formula (1), derived according to the modular structure of equipment supplied by a specific vendor and presented in [2].

$$P = 6.02 \cdot n_{ch} + 1.76 \cdot \left\lceil \frac{n_{ch}}{9} \right\rceil + 9.11 \cdot \left\lceil \frac{n_{ch}}{3} \right\rceil \quad (1)$$

where, $n_{ch} = \left\lceil C/K \right\rceil$, $2 \le n_{ch} \le 72$, C is the total switching capacity in Tb/s required to the router, and K the capacity of a fully equipped shelf.

In TABLE I we present the cost of the equipment of the IP layer that we take into account in our study.

TABLE I

Cost of IP layer equipment

Line-cards			*Chassis*	
Port density	Port capacity	Cost (*c.u.*)	Type	Cost (c.u.)
10	40	2.56	LCC	6.02
4	100	2.88	FCC	9.11
2	200	2.88	Metro router chassis (16 slots, 400 G capacity per slot)	4.30
1	400	2.76		

Optical Layer: Fixed & Flex grid

For the fixed-grid optical layer we assumed the use of fixed transponders with line rates of 40, 100 and 400 Gb/s, and the maximum transparent reach for each type as shown in TABLE II. In our studies we did not consider 10 Gb/s and 1Tb/s transponders, since the former use incoherent reception and need special dispersion compensation strategies (not considered here), and the latter are not expected to appear in the near future.

TABLE II

Cost of fixed transponders

Capacity *(Gb/s)*	Reach *(km)*	Data slots *(12.5 GHz)*	Cost (c.u.)
40	2500	4	0.48
100	2000	4	1
400	500	6	1.36

Cost of BVTs

Capacity *(Gb/s)*	Reach *(km)*	Data slots *(12.5 GHz)*	Cost *(ICU)*	Capacity *(Gb/s)*	Reach *(km)*	Data slots *(12.5 GHz)*	Cost *(ICU)*
40	2500	3	1.76	**200**	1900	6	1.76
	1900	2	1.76		750	5	1.76
100	2500	4	1.76	**400**	900	10	1.76
	600	2	1.76		700	8	1.76
					450	6	1.76

In flex-grid networks the traffic is served by BVTs. We assume that the BVTs can control the following features: (i) the modulation format and (ii) the spectrum (in contiguous spectrum slots) that they utilize. By adapting these features, a BVT of cost C can be tuned to transmit R Gb/s using bandwidth of B spectrum slots (including guardband) resulting in a total energy consumption V to transmit at reach D km with acceptable Quality of Transmission (QoT). Thus, $t=(R_t,D_t,B_t,C_t)$ is what we call a transmission tuple of the transponder [4]. TABLE II presents the transmission tuples considered in our study.

C. Multilayer Network Planning

As stated above, 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.

IV. Mathematical Formulation

We assume that the network is represented by a graph $G(V,E)$, with V being the set of nodes and E the set of bidirectional fiber links connecting two locations., where the nodes of the the graph correspond to the optical nodes of the network on which we also account for the cost of the IP/MPLS connected router. We are also given the traffic matrix Λ, where Λ_{sd} corresponds to demand (s,d), and the model of the IP/MPLS routers and the transmission tuples of the transponders. To solve the multilayer network optimization problem we propose the following ILP formulation. We precalculate a set P_{ij} of k paths for each pair of nodes (i,j) in graph G. A path-transmission tuple pair (p,t) is feasible only when the reach with acceptable Quality of Transmission, D_t is higher than the length of p. A feasible path-transmission tuple (p,t) identifies the route of the lightpath and the configuration of the used transponder. Spectrum allocation is performed using channel variables of contiguous spectrum slots: channel (f,w) starts at slot f and has w slots width, i.e., it uses slots $[f,f+w-1]$.

The problem of multilayer network planning can be stated as follows.

Input:

- The network topology is represented by a graph $G(V,E)$.
- The maximum number F of available spectrum slots.
- The traffic is described by the traffic matrix Λ.
- A set T of feasible transmission tuples, which characterize a BVT, with tuple $t=(D_t,R_t,B_t,C_t)$ indicating feasibility of transmision at distance D_t, with rate R_t (gpbs), using B_t spectrum slots using that transponder of type (cost) C_t.
- A set of line-cards represented by L, where a line-card for transponder of type C_t is represented by a tuple $l_{Ct}=(N_l, R_l, C_l)$, where N_l, is the number of transponders with rate R_l that the line-card supports, and C_l is the cost of the line-card.
- The IP/MPLS chassis cost, specified by a modular cost model. We assume that an IP/MPLS router consists of line-card chassis of cost C_{LCC} that suport N_{LCC} line-cards each, and fabric card chassis of cost C_{FCC} that suport N_{FCC} line-card chassis, each.
- The weighting coefficient W, taking values between 0 and 1. Setting $W = 0$ ($W = 1$) minimizes solely the cost (the maximum spectrum used, respectively).

Variables:

- f_{sd}^{ij} : real variable, representing the flow from source s to destination d that passes over a lightpath between i-j.
- x_{pt}: integer variable, representing how many lightpaths of path-transmission tuple pairs (p,t) are used.
- u_{pfw}: Boolean variable, equal to 1 if channel (f,w), i.e. slots $[f,f+w-1]$, is used over path p, and 0 otherwise.
- z_{nl}: integer variable, number of line-cards l at node n.
- u_n: integer variable, number of line-card chassis at node n.
- h_n: integer variable, number of fiber-card chassis at node n
- y: integer variable, equal to the maximum indexed spectrum slot that is used in the network.
- c: Cost of utilized transponders, line-cards and chassis.

ILP formulation:

$$\text{Minimize } (1-W)\cdot c+W\cdot y$$

Subject to the following constraints:

- Cost function definition:

$$c=\left(\sum_{p\in P}\sum_{t\in T|\exists(p,t)} C_t\cdot x_{pt}+\sum_{n\in V}\sum_{l\in L}C_l\cdot z_{nl}+\sum_{n\in V}C_{LCC}\cdot u_n+\sum_{n\in V}C_{CH}\cdot h_n\right), \quad (2)$$

For all $l\in E$, for all $f=\{1,...,F\}$ and $w=\{1,...,F-f+1\}$

$$y\geq (f+w-1)\cdot \sum_{p\in P|l\in p} u_{pfw}, \quad (3)$$

- Flow Constraints:

For all $(s,d)\in V^2$

$$\sum_{i\in V} f_{sd}^{in}-\sum_{j\in V} f_{sd}^{nj}=\begin{cases}\Lambda_{sd},\ n=s\\ -\Lambda_{sd},\ n=d\\ 0,\ \ n\neq s,d\end{cases}, \quad (4)$$

- Path-transmission tuple assignment constraints:

For all $(i,j)\in V^2$

$$\sum_{sd\in V^2} f_{sd}^{ij}\leq \sum_{p\in P_{ij}}\sum_{t\in T|\exists(p,t)} (r_t\cdot x_{pt}), \quad (5)$$

- Data slot assignment constraints:

For all feasible (p,t), where, b_t is the number of slots required for transmission of tuple t.

$$x_{pt}=\sum_{f=\{1...F\}} u_{pfb_t}, \quad (6)$$

- Non overlapping slot assignment constraints:

For all $l\in E$, and $m=\{1,..,F\}$,

$$\sum_{p\in P|l\in p}\sum_{f,w|m\in[f,f+w-1]} u_{pfw}\leq 1, \quad (7)$$

- Number of line-cards per node constraints

For all $n\in V$ and $l\in L$

$$z_{nl} \geq \sum_{p\, start\, at\, n} \sum_{t|l\, supports\, C_t} x_{pt} / N_l \text{ , (8)}$$

- Number of line-card chassis per node constraints
  For all $n \in V$

$$u_n \geq \sum_l z_{nl} / N_{LCC} \text{ , (9)}$$

- Number of fabric card chassis per node constraints
  For all $n \in V$

$$h_n \geq u_n / N_{FCC} \text{ , (10)}$$

In the above ILP formulation $x_{p,t}$ identifies the number of path-transmission tuple pairs (p,t) are used. So it identifies the number of transponders and their configurations. The slot allocation problem solution is indicated by the related u_{pfw} variables. The cost of the IP/MPLS routers is captured through variables z_{nl}, u_n, h_n. The objective is to minimize a weighted sum of the maximum spectrum and the cost of the equipment used in both layers.

The proposed algorithm is general and can be used for planning flex- or fixed-rid networks, employing fixed or flex-grid transponders, and can work with other router models as well. These different network cases are captured by appropriately defining the transmission tuples of the related transponders used in each case.

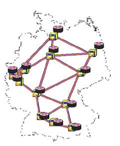
V. Illustrative Results

In this section, we solve the multilayer network planning problem considering a set of realistic network and traffic instances. In particular, we assume that the network under study is deployed using fixed-grid WDM (in the form of MLR) or flex-grid technology. In particular, we use the proposed algorithm which is quite generic, in order to analyze and compare the performance of the following cases of networks.

(a) MLR optical network employing fixed-grid 50 GHz optical switches and fixed 40 Gbps and 100 Gbps transponders (*fixed-grid/fixed-TSP*),
(b) MLR optical network employing 12.5 GHz flex-grid optical switches and fixed 40 Gbps, 100 Gbps and 400 Gbps 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 Gbps transponders is that such devices are expected to require 75 GHz spectrum, which does not fit in traditional 50 GHz fixed-grid WDM systems.

In the fixed-grid network case, a maximum per-link capacity of 80 wavelengths with the 50 GHz ITU-T grid is assumed. For the flex-grid network cases, the width of the spectrum slot is considered to be 12.5 GHz, and 320 slots are available. The available transmission configuration of the fixed-grid and BVTs are presented in TABLE II.



Operator	Segment Covered		
DT	**Core**		
Nodes	Links	Link length *(km)*	
		average	max
12	**40** ***bidirect.***	**243**	**459**

Fig. 3. DT national backbone network.

The topology used in our simulations is the Deutsche Telekom (DT) shown in Fig. 3. The traffic matrix of the DT network used in our simulations is realistic as provided by the operator (DTAG) participating in the Idealist project. The traffic load for year 2014 is equal to 3494.33 Gbit/s and we assumed that traffic increases uniformly by 35% per year. We graph our results for 10 years span with a step of 2 years. Note that each time we plan the whole network from zero, meaning that we do not take the previous solution as existing and incrementally add more equipment. We do this in an attempt to locate the point that each of the examined technologies is more efficient and would make sense for the network to switch to that technology.

A. Capital Expenditure

In this section we present the total network cost for the DT network (Fig. 4). The *flex-grid/flex-TSP* case is shown to exhibit the lowest cost, at heavy load. At medium load the cost of the flex-grid network is quite close to that of the *flex-grid/fixed-TSP*, with the *flex-grid/fixed-TSP* being slightly more efficient at light load. 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. As load increases, the *flex-grid/fixed-TSP* network becomes less efficient, giving an advantage to the *flex-grid/flex-TSP* network that exploits the higher number of transmission options it has at its disposal. The point that this happens is year 2018.

The performance of the *fixed-grid/fixed-TSP* case is inferior to the other two network cases in all traffic scenarios examined. This is expected, since the *fixed-grid/fixed-TSP* is unable to use the cost-efficient 400 Gbps for certain connections that need them. Note that we stop presenting the performance for the *fixed-grid/fixed-TSP* case after the year 2022, as it was blocked (could not be served with the available spectrum).

Note that in this study we didn't assume any decrease in prices of the components cost over time. Our study is comparative and we considered that the components used will follow similar learning curves and therefore the cost changing through time will not affect our comparison. Note however, that the cost of BVTs was assumed to be 30% higher than equal rate fixed TSP. If this difference is lower, even higher savings could be obtained for the flex-grid/BVT network.

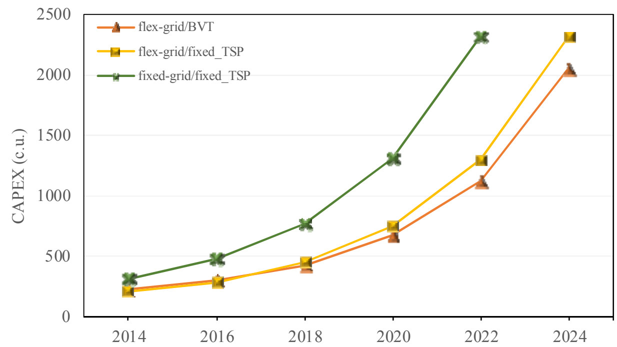


Fig. 4. Capital Expenditure for the DT network.

B. Maximum Spectrum Used

We now present the results obtained regarding spectrum utilization for the DT reference network and the three different network cases (Fig. 5).

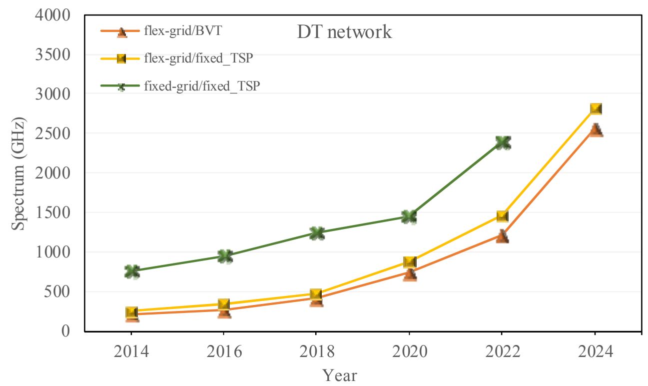
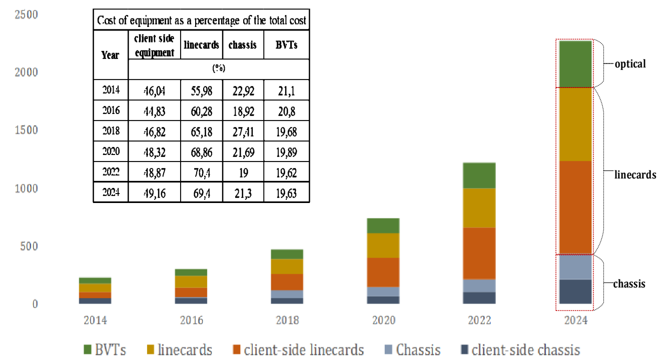


Fig. 5. Maximum spectrum used for the DT network.

The *flex-grid/flex-TSP* solution, due to the intrinsic characteristic of finer granularity and many transmission options, achieves in all cases the lowest spectrum utilization. Second comes the *flex-grid/fixed-TSP* that also takes advantage of the different transmission modes, which are however less than those available in the *flex-TSP* case. The *fixed-grid/fixed-TSP* network achieves very low maximum spectrum utilization, since it does not use the spectrum efficient 400 Gbps transponders.

C. CAPEX profile of the network

In this section we report on the contribution of every component of the *flex-grid/flex-TSP* network case in the total cost for the DT topology. Fig. 6 shows that line-cards are the major CAPEX contributor for a fully flexible network for every traffic scenario. The percentage of cost of line-cards is over 55% of the total cost for every year of our study, and increases through the years. On the other hand the percentage of cost of BVTs is about 20% and decreases through years. This is expected as the IP layer equipment is more expensive, and as traffic increases the large number of line-cards creates a need for more chassis, which leads to a further cost increase of the IP/MPLS routers. From Fig. 6 we can also observe that the cost due to the pre-installed IP layer (client side – for aggregating the traffic to be served over the optical domain) equipment is about 50% for every year of our study.



Cost of equipment as a percentage of the total cost

Year	client side equipment (%)	linecards (%)	chassis (%)	BVTs (%)
2014	46,04	55,98	22,92	21,1
2016	44,83	60,28	18,92	20,8
2018	46,82	65,18	27,41	19,68
2020	48,32	68,86	21,69	19,89
2022	48,87	70,4	19	19,62
2024	49,16	69,4	21,3	19,63

Fig. 6. CAPEX profile of a multilayer network

VI. Conclusions

In this paper we address the design of a multilayer IP/MPLS-over-flex-grid network and study its capex under realistic network topologies and traffic scenarios. For this purpose, we proposed a concise ILP formulation. Our joint multi-layer network planning ILP algorithm 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. Through numerical experiments, we examined the cost implications that the use of different technologies has on the multilayer network planning problem. Using realistic transmission specifications, our results verified that flex-grid optical networks outperform fixed-grid in terms of maximum spectrum used. Our results also showed that CAPEX savings are dependent on the traffic under which the network operates. Whilst investments in costly BVTs are very well motivated under medium or heavy load they do not seem profitable in the short term, where a low-cost/low-rate fixed transponders are sufficient to serve the traffic.

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