Multiple-period planning of Internet Protocol-over-Elastic Optical Networks

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ABSTRACT
In view of both the growing dynamic traffic and increasing costs, in future, network operators will have to adopt a multi-period network planning technique that aims to jointly account for the upgrade of both the network, and the optical and the IP edges. In the current work, for an IP-over-Elastic Optical Network, we propose a multi-layer network planning technique that is multi-period in nature, i.e. the approach relies on efficient forecasts for a short-term increase in the volume. We formulate the problem as an integer linear programme with the aim of reducing the (i) capital expenditure (CapEx) – by minimizing the addition of any equipment every period and (ii) operational expenditure (OpEx) – by minimizing any displacement(s) of the equipment and reconfiguration(s) in successive periods. We conduct extensive simulations considering realistic networks to validate the proposed network planning technique. The obtained results demonstrate that the proposed technique is able to trade off the network equipment reconfiguration for the CapEx.

1. Introduction

The increase in volume and dynamicity of Internet traffic has put immense pressure on network infrastructures. To meet the demands of current heterogeneous services which (i) have a high peak-to-average ratio and (ii) vary dynamically in both time and location (Cisco white paper, 2016), network operators have had to deal with the issue of network dimensioning in view of anticipated large volumes of Internet Protocol (IP) traffic and also, simultaneously have had to ensure the same or even minimized costs. The current Optical Transport Networks (OTNs) are based on the fixed-grid technology which assumes the use of a particular transceiver type and in which, only a single demand serving method exists that fixes bit-rate, transmission reach (TR) and spectrum utilization. However, such fixed-grid OTNs are (i) overdimensioned to deal with IP traffic peaks (Singh, Sengar, Bajpai, & Iyer, 2013) and (ii) required to admit all channels within a fixed frequency grid which is not adequate for high-speed channels and also underutilizes the spectrum for low bit-rate requests (Iyer & Singh, 2017a).
Furthermore, in fixed-grid OTNs, the conventional approach of long cycles of upgrade is followed and also, considering a specific traffic forecast, overprovisioning of capacity is enabled to ensure that network can cope with future traffic until the arrival of next cycle of upgrade (Agrell et al., 2016). However, such forecasts are unable to capture dynamism in traffic, and also traffic variations which significantly influence cost-efficiency due to the fact that cost of the equipment lowers with maturation in technology. Furthermore, capacity overprovisioning in such OTNs also results since independent upgrade of optical network and IP edges is conducted. Hence, a consequence of overprovisioning capacity is an underutilization of equipment, and investments which are not required for long network lifecycle periods. Also, with the ever-increasing dynamic traffic, currently, network operators face greater challenges in view of shortening the cycles for upgrade which, in effect, has a major influence on cost-efficiency, and also reduces the investment return (Agrell et al., 2016).

In view of the aforementioned, the new paradigm of Elastic Optical Network (EON) technology has emerged for OTNs in which, (i) on the basis of requirement(s), wider channels are created by combining spectrum units (or frequency slots (FSs)) and (ii) the use of multiple subcarrier(s) provisions increased flexibility in capacity allocation to heterogeneous demands (Napoli et al., 2015). The EONs (i) resort to use of flexi-grid switches and tunable (or flexible) transponders (or bandwidth variable transponders (BVTs)) and (ii) increase network efficiency, reduce network cost, and enable a reconfigurable OTN (Jinno et al., 2009). Furthermore, a mix of EON technology with IP layer re-configurability can alleviate the notion of ‘pay-as-you-grow’ in which, installation, continuous re-optimization, and upgrade in short cycles, of only some equipment are ensured. However, this require its conduction to be accurately co-ordinated between IP and optical segments.

In recent years, algorithms to design IP-over-WDM (IP-o-WDM) and IP-over-EON (IP-o-EON) have received a great deal of attention (Chatterjee, Sarma, & Oki, 2015; Oki & Chatterjee, 2017; Singh et al., 2013). Furthermore, much research has also been focused on multi-layer network optimization (MLNO) (Gerstel et al., 2014; Gkamas, Christodoulopoulos, & Varvarigos, 2015; Velasco, Wright, Lord, & Junyent, 2013) and multi-period network planning (MPNP) (Eira, Pedro, & Pires, 2015; Meusburger, Schupke, & Lord, 2010; Palkopoulou, Meusburger, Schupke, Wosinska, & Bauschert, 2010; Pesic, Zami, Ramantamis, & Bigo, 2016; Rožić, Klonidis, & Tomkos, 2016; Soumplis, Christodoulopoulos, Quagliotti, Pagano, & Varvarigos, 2016) approaches. However, to the best of authors’ knowledge, there exists no study which formally describes, and finds an optimal solution in regard to a mix of the aforementioned planning techniques. Hence, in this article, for an IP-o-EON, we propose a multi-layer network planning technique which is multi-period in nature and relies on efficient forecasts for a short-term increase in volume. The adoption of such a multi-period nature of planning stems from the fact that, with traffic becoming more dynamic and unpredictable, if intermediate periods are considered for complete network lifecycle, then it will become very difficult to assemble any a priori knowledge of exact traffic. Hence, the aim of our proposed technique is the deployment of the least additional network resource(s) amount(s) at every period considering traffic variations from last (previous) period. Thus, our technique optimizes both utilized equipment capital expenditure (CapEx) and operational expenditure (OpEx) which is associated with variations that are enforced due to changeover (transition) between two periods. Lastly, under the consideration of maturation of technology, and decrease in equipment value
(s), the developed model can be used for (i) studies of ‘what-if’ kind and (ii) identifying correct times (periods) when, new technology(s) and implementation of network changes, can be introduced.

The rest of the paper is structured as follows. In Section 2, related studies are presented. Section 3 details multi-period planning problem in IP-o-EON. In Section 4, we detail mathematical formulation of the ILP model to solve the multi-period IP-o-EON problem. Section 5 presents and discusses the various simulation results obtained. Finally, the study is concluded in Section 6.

2. Related works

In recent years, many studies have focused on the MLNO approaches. For an IP-o-EON, Gerstel et al. (2014) have considered a multi-layer capacity planning approach which builds on existing planning methods. The authors have computed savings which are achievable considering two realistic networks and it is observed that the resulting savings are the same for both the networks.

Velasco et al. (2013) have proposed a new network architecture which consists of many IP/multiprotocol label switching (MPLS) areas to perform routing and aggregating flows to the desired level and a flexi-grid-based core network that connects the areas among them. The authors have formulated mixed-ILP (M-ILP) and biased random-key genetic algorithm-based heuristics to solve the optimization problem. The results show that by extending the core towards edges leads to significant savings in both the core and IP/MPLS networks.

Gkamas et al. (2015) have considered the multi-layer network planning problem for IP-o-EON comprising a routing problem at IP layer (IPR), routing, modulation level (RML) and the spectrum allocation (SA) problems at the optical layer. The authors have proposed a novel algorithm that follows a multi-cost approach to solve the aforementioned sub-problems jointly and have also compared a flexible network to a mixed line rate (MLR) network.

We refer the reader to the survey by Rožić et al. (2016) in which, the authors have provided an overview of the recent studies on the multi-layer networks and have also provided a classification, followed by the identification of open issues study areas.

In a longer frame of time, with an eye towards optimizing network cost for the OTNs, the obvious way ahead is the adoption of MPNP approaches which can (i) assume traffic knowledge for all periods (Meusburger et al., 2010; Palkopoulou et al., 2010) or (ii) rely on efficient forecasts for short-term increase in volume (Eira et al., 2015; Pesic et al., 2016; Soumplis et al., 2016). For an IP-o-WDM network, Palkopoulou et al. (2010) have studied the effect of joint consideration of MLNO and MPNP approaches using linear programming. The resulting case studies show that more than 20% cost savings are achievable, if the forecast knowledge is included within the multi-layer optimization.

Meusburger et al. (2010) have studied this migration from a networking view point to optimize migration strategy in terms of CapEx. It is shown that migration optimization significantly impacts from forecast knowledge to cost optimality, channel mix, and aggregation decisions. It is observed that for long-term migration under traffic growth, optimal network cost is obtained by early investments in 40G-only equipment.

Considering sliceable-BVTs (S-BVTs) which are composed of line cards with many transceiver ports, Eira et al. (2015) have used an MPNP approach to investigate the pros and
cons of using fixed-rate and/or flexi-rate technology in line cards, as well as transceivers. The results show that an initial investment in flexi-rate line cards and transceivers is beneficial only in small- and medium-sized networks where an upgrade to the higher bit-rates does not require extra-regeneration.

Soumplis et al. (2016) have presented an algorithm that provisions lightpaths considering actual physical performance. It is observed that the aforementioned yields savings when compared to current provisioning practice of end-of-life margins. Considering 10-year life of a core WDM network enabled by elastic transponders, Pesic et al. (2016) have shown that, compared to the use of margins which grow progressively with ageing of networks, directly accounting for end-of-life margins leads to major reduction in network costs.

2.1. Key contributions

Our study is novel in three ways: (i) we propose a novel optimization model that jointly considers multi-layer and the multi-period network planning, (ii) our model ensures that a penalty is incurred upon reconfiguration of existing lightpaths in view of keeping a check on number(s) of modification(s) that are conducted between periods and (iii) defined problem and proposed optimization model is general and can be utilized to plan an IP-o-OTN (both flexi- and fixed-grid). Overall, our proposed model requires realistic transmission specifications as input and further, it accurately considers the IP layer through a detailed model for IP/MPLS routers which are deployed at optical network edges.

3. Multi-period planning for IP-o-EON

In the current study, we adopt the EON architecture from our previous study (Iyer & Singh, 2017b) in which the EON is assumed to consist of (i) fibre links comprising single-mode fibre spans, and Erbium Doped Fiber Amplifiers (EDFAs) and (ii) optical switches which operate as Reconfigurable Optical Add Drop Multiplexers (ROADMs) that employ flexi-grid technology, and also support lightpaths of individual or multiple contiguous 12.5 GHz slots of spectrum. The IP/MPLS routers comprise optical domain edges, and it may occur that no, single or multiple such routers are connected to an optical switch. The IP/MPLS router and ROADM connection occur via a short TR grey transceiver, and to achieve long-haul transmission, BVTs are plugged into ROADMs so that the client signal can be transformed. It must be noted that in our current study, we do not consider deployment of flexible coloured transceivers (coloured transceivers can generate signals that can directly enter optical domain) to be plugged into IP router ports since, in terms of cost and functionality, such transceivers perform similarly to transponders (BVTs) (IDEALIST Project, 2014). Furthermore, we assume that the transponders perform as transmitters and receivers simultaneously. As a transmitter, transponder’s main function is to convert arriving electrical packets from the IP/MPLS source router into the optical domain and then to route traffic which enters the ROADM over the optical network in the form of lightpath connections. The lightpath can pass intermediate ROADM either as a transparent or as a translucent (in our study we assume that multiple transmission parameters of BVTs and regenerators are under our control, and, they are ‘flexible’ and affect TR and bit-rate at which they can transmit) lightpath, and reach its destination.
ROADM where it is dropped which, in this domain, may correspond to final destination or an intermediate hop. As a receiver, the transponder converts optical signal back into the electrical type at the destination of lightpath. Then, the packets are forwarded and handled by IP/MPLS router which, for some packets, can be either a destination or an intermediate hop. If router is the destination for a packet(s), then such packet(s) are forwarded towards their corresponding final destination via the lower hierarchy level networks which are connected to the router, else, if the router is an intermediate hop for a packet, then the packet re-enters optical network, and eventually, is forwarded to its destination.

We also assume that there is a bi-directional connection of lightpaths which implies that, for every lightpath, there is installation of an opposite directed lightpath. Furthermore, every bi-directional route, which is built from a unidirectional route pair, has the capability to support traffic in both the directions. Also, similar to transponders, grey transceivers and router ports are assumed to be capable of simultaneously performing as transmitters and receivers. It must also be noted that from an optimization view point, the network consists of IP and optical layer, and further, lightpaths are installed accounting for optical topology, and then IP topology is created, on top of which, installation of IP/MPLS connections occurs.

In view of network planning, in the current study, we assume that process of upgrade in IP-o-EON is periodically performed and further, based on the network’s current state; it is decided as to how traffic will be supported in the following period of planning. Also, it is assumed that having knowledge of only next period’s traffic (and strictly no further future knowledge), for every period, the aforementioned process is consecutively and separately performed. Next, we describe conduction of network planning.

At the start of network planning, in period $t_0$, we use the algorithm detailed in Papanikolaou, Christodouloupolos, and Varvarigos (2015) to simultaneously optimize both IP and optical layers for network cost reduction. Further, with an assumption of a current period $t_N$, input to the proposed model is new traffic and network’s previous state corresponding to period $t_{N-1}$. The aforementioned includes (i) resource(s) state, i.e. lightpaths which are established and IP tunnels and (ii) physical resource(s) information, i.e. installed or available equipment with location information. The proposed model’s optimization process jointly considers previous network state, and both layers of network for reducing (i) network equipment which are added (CapEx) and (ii) equipment which are displaced and re-configured between two consecutive states of network (OpEx).

The working of the proposed multi-period planning technique is shown in Figure 1. As shown in Figure 1(a), the proposed model is able to exploit the BVT’s flexible nature which is useful in multiple varied configurations for carrying the client traffic and further, also allows for a scalable design due to the fact that the increase in port rate of the client can be ensured by (i) increasing (if and when available) the optical carriers amount(s) or (ii) utilizing advanced (higher order) modulation formats. The aforementioned is then applicable in the following (subsequent) periods, and can then be combined with the possibility of the (i) regenerator(s) addition (with the use of advanced (higher order) modulation formats, there occurs a decrease in TR) and (ii) already installed regenerator(s)’s displacement. Furthermore, as shown in Figure 1(b), by resorting to the previous network state’s re-optimization which, in turn, leads to the exploitation of the IP grooming capability, spare capacity utilization can be enabled, in turn, ensuring the availability of the network resources.
Hence, our proposed model jointly considers MLNO and MPNP approaches and also accounts for maturation in technology and minimizations in prices. However, it must be noted that in order to achieve cost savings through the proposed model it is required that there is an adoption of short network cycles which have the capability of (i) capturing traffic dynamicity effects and (ii) avoiding any overprovisioning, by virtue of incorporation of small, but frequent updates in network. Hence, the overall challenge is to optimize changes that are conducted, and cost reductions which are incurred over the entire network lifecycle period. We address the aforementioned by formulating ILP for the planning problem.

4. ILP model for multi-period planning for IP-o-EON

In this section, in view of network planning problem, we formulate an ILP to jointly consider multi-layer and multi-period planning in a single step of optimization. In every period, ILP aims to simultaneously optimize both the network layers by accounting for the previous network state. As a novelty, in the ILP model, the extent to which current state commits to the previous state is controlled by introduction of the parameter $Y_{D_i}$ which is passed as input to the ILP model.

The network is assumed to be represented by a graph $G(V, L_i)$ in which $V$ and $L_i$ denote the set of nodes and bi-directional links which connect two locations, respectively. It must be noted that the nodes of the graph denote the network optical nodes on which there also occurs cost account of the connected IP/MPLS router. It is assumed that an a priori traffic matrix $\Lambda$ is given, and $\Lambda_{s-d}$ denotes the IP requested capacity between a source-destination $(s-d)$ node pair. Following (IDEALIST Project, 2014), the IP/MPLS router model assumed in the current study is that of a modular type which is constructed by

Figure 1. Proposed multi-period planning of the IP-o-EON by (a) reconfiguration of the BVT and (b) re-optimization of the network.
using one or many chassis, and further, within every slot in the router, a linecard is also installed, whose speed corresponds to that provided by the chassis. Within the optical layer, it is assumed that the tuples of transmission detail the capability of transmission of the transponders (Iyer & Singh, 2017b). Every tuple \( T \) (i) is used to specify a certain transponder configuration in terms of the bit-rate and the spectrum and (ii) has a relation to a certain TR which accounts for the optical physical layer model. The pre-evaluated routes form the basis of solutions for the dimensioning process, and further, it is assumed that a route-transmission tuple \( (r, T) \) is permissible only if tuple's \( (T) \) TR is greater than that of route's \( (r) \) length. The following form inputs to problem:

- the graph \( G(V, Li) \) which represents the network topology;
- the maximum amount of frequency slots, \( FS \) of 12.5 GHz, which are available;
- the matrix \( L \) which describes the traffic;
- the BVTs set, \( BVT \), which denotes the available transponders (BVTs);
- the permissible transmission tuples set \( TU \) characterizing the alternatives for transmission of transponders (or BVTs) which are available. The tuple \( T = (DT, BT, ST, CT) \) indicates transmission permissibility at a distance \( DT \), with a bit-rate \( BT \) (in Gpbs), using \( ST \) slots of the spectrum, for the transponder of cost \( CT \). Furthermore, \( TU_{bvt} \) represents transmission tuples of the transponder \( bvt \in BVT \);
- the linecards set which is represented by \( LCR \). A linecard for the transponder \( bvt \in BVT \) is represented by a tuple \( lcr_{bvt} = (N_{lcr}, C_{lcr}) \), where \( N_{lcr} \) is the amount of transponder of type \( bvt \) which are supported by the linecard;
- the cost of an IP/MPLS router which is assumed to consist of (i) linecard chassis whose cost is \( C_{LC} \), and which supports \( N_{LC} \) linecards each, and (ii) fabriccard chassis whose cost is \( C_{FC} \), and which supports \( N_{FC} \) linecard chassis;
- the coefficient for weighting which is denoted as \( Y_C \). Furthermore, \( Y_C = 1 \), when aim is to minimize only cost, whereas \( Y_C = 0 \), when only spectrum needs to be minimized and
- the coefficient for weighting which is denoted as \( Y_D \). Furthermore, \( Y_D = 1 \), when the aim is to minimize only current state cost while ignoring previous network state, whereas \( Y_D = 0 \), when previous state lightpaths are to be maintained, and also, any additional cost that is incurred to maintain the previous state’s lightpath needs to be minimized.

The following variables are also used in the ILP:

- \( f_{sd}^{r} \) are real (float) variables that equal the IP tunnel rate from the IP source \( s \) to the destination \( d \) passing over a lightpath utilizing the route \( r \).
- \( x_{rT} \) is an integer variable that represents the route-transmission tuple pairs \( (r, T) \) belonging to lightpath numbers which are utilized.
- \( z_{nLcr} \) is an integer variable that denotes the linecard(s) number(s) of type \( LCR \) at a node \( n \).
- \( q_{nLC} \) is an integer variable that denotes the linecard chassis numbers at a node \( n \).
- \( o_{nFC} \) is an integer variable that denotes the fibrecard chassis numbers at node \( n \).
- \( s \) is an integer variable which equals the maximum indexed slot of the spectrum.
- \( \xi_{nbvt} \) is an integer variable which equals the number(s) of used transponder(s) of type \( bvt \) at a node \( n \).
• $\omega_{n\text{bvt}}$ is an integer variable which equals the number(s) of deployed transponder(s) of type bvt at a node $n$.

• $\gamma_{rT}$ is an integer variable which equals the number(s) of $(r, T)$ tuples which have been removed from the previous state.

• $c$ is a float variable which equals the network equipment cost.

The following constants are also used in the ILP:

• $F_{sd}^*$ are integer constants which are equal to the IP traffic of the end nodes to $d$ which is transferred over the router in the previous network state.

• $X_{rT}^*$ are integer constants which are equal to lightpath(s) number(s) of route-transmission tuple pairs $(r,T)$ which is used in the previous network state.

• $\beta_{rT}^*$ are integer constants which are equal to the number(s) of transponder(s) of type bvt at a node $n$ which is utilized in the previous network state.

The objective for the ILP is defined as

$$\text{Minimize}((Y_c \cdot c + (1 - Y_c) \cdot s)) \quad (1)$$

The objective in (1) is subjected to the following constraints:

• Cost calculation

$$c = \sum_{n \in V} \left( \sum_{\text{bvt} \in \text{BVT}} C_{\text{bvt}} \cdot \omega_{n\text{bvt}} + \sum_{n \in V} \sum_{\text{LCR}} C_{\text{LCR}} \cdot z_{n\text{LCR}} + \sum_{n \in V} C_{\text{CH}} \cdot o_{n\text{FC}} \right)$$

$$+ (1 - Y_d) \cdot \sum_{r \in R} \sum_{T \in TU(r,T)} \gamma_{rT} \quad (2)$$

• IP flow continuity

$$\sum_{r \in R_i} \sum_{T \in TU} f_{sd}' - \sum_{j \in V} \sum_{r \in R_{ij}} f_{sd}' = \begin{cases} -\Lambda_{sd}, & n = s \\ \Lambda_{sd}, & n = d \\ 0, & n \neq s, d \end{cases} \quad \forall (s, d) \in V^2, n \in V \quad (3)$$

• Assignment of route-transmission tuple

$$\sum_{sd \in V^2} f_{sd}' \leq \sum_{r \in R_i} \sum_{T \in TU(r,T)} (B_{T}, x_{rT}), \quad \forall (i, j) \in V^2 \quad (4)$$

• Previous state for the optical layer

$$\gamma_{rT} \geq X_{rT}^* - x_{rT}, \quad \forall \text{feasible } (r, T) \quad (5)$$

• Transponders which are utilized

$$\xi_{n\text{bvt}} = \sum_{r \text{ starts at } n} \sum_{T \in TU_{\text{bvt}}} x_{rT}, \quad \forall n \in V, \text{bvt} \in \text{BVT} \quad (6)$$
Transponders which are deployed

\[ \omega_{nbt} \geq \xi_{nbt}, \quad \forall n \in V, bvt \in BVT \]  

\[ \omega_{nbt} \geq \beta_{nbt}^*, \quad \forall n \in V, bvt \in BVT \]  

Previous state for the IP layer

\[ f_{sd}^r > F_{sd}^{sr}, \quad \forall (s, d) \in V^2, (i, j) \in V^2, r \in R_{ij} | F_{sd}^{sr} > 0 \]  

- Maximum numbers of frequency slots used

\[ s^* = \sum_{r \in R_{ij}} \sum_{l \in T \in \exists (r, T)} (S_T \cdot x_{rT}), \quad \forall l \in Li, (i, j) \in V^2 \]

\[ s = \max (s^*), \quad \forall l \in Li, (i, j) \in V^2 \]

\[ s \leq FS, \quad \forall l \in Li, (i, j) \in V^2 \]  

In (10), \( s^* \) is equal to maximum indexed frequency slot which is utilized in every bi-directional fibre link.

- Number of linecards per node

\[ z_{nlcr} \geq \sum_{lcr} \omega_{nbt} \frac{N_{lcr}}{supports bvt}, \quad \forall n \in V, lcr \in LCR \]  

- Number of linecard chassis per node

\[ q_{nlc} \geq \sum_{lcr} \frac{z_{nlcr}}{N_{lcr}}, \quad \forall n \in V \]  

- Number of fibrecard chassis per node

\[ o_{nfc} \geq \frac{q_{nlc}}{N_{lcr}}, \quad \forall n \in V \]  

Using the formulated ILP, IP-o-EON can be dimensioned for normal operation. The ILP model jointly addresses multi-layer and multi-period problems by virtue of (3) and (4), and (10)–(13), respectively. The ILP’s objective is to reduce a weighted sum of maximum equipment cost and spectrum that is utilized in both layers which is given by (1). The cost function in (2) is a weighted sum of variables which (i) capture equipment (used in both layers) CapEx in current state and (ii) represent the removed \((r, T)\) path-transmission tuples numbers from previous state, given by (6), so as to capture OpEx associated with displacement of transponders or reconfigurations. The algorithm creates solution to problem by selecting among \(k\) pre-evaluated optical routes \(R_{ij}\) between the optical nodes \(i, j\). The ILP model captures costs of IP/MPLS routers through variables \(z_{nlcr}, q_{nlc}\) and \(o_{nfc}\).

It must be noted that the following two assumptions hold in regard to the formulated ILP model: (i) solution to the ILP includes values for the IP flow variables \(f_{sd}^r\) that identify the IP traffic amount of the end nodes \(s\) to \(d\) which is transferred over a router and (ii) \(x_{rT}\) may
correspond to a lightpath \((r, T)\) which, is used to serve (a) an end-to-end demand transparently between a given source \(s (=i)\) and destination \(d (=j)\) or (b) a lightpath series that comprises a translucent connection.

Lastly, it must be noted that in the current study, in view of minimizing proposed model’s complexity, and to obtain optimal results for realistic medium- to large-sized networks, through (10), the developed ILP only ensures that maximum frequency slots \(s\) used in the network is within available spectrum slots \((FS)\) range. Hence, no spectrum assignment is performed by the ILP model; however, formulated ILP model can be extended to jointly perform the aforementioned, which will be the focus of our future research. In the current study, for assignment of spectrum in the next step, we use the method detailed in Schrijver (2003).

5. Simulation results and discussion

In the simulations, we compare the following three cases:

1. When the entire multi-layer network, in every period, is jointly planned from the start, however, with no account of the previous network state. This technique is referred to as Multi-layer-Joint (ML-J). Furthermore, in our simulations, ML-J is used as the benchmark for comparisons as this technique results in the least (optimum) CapEx. However, it must be noted that the ML-J technique is not realistic.

2. When the network is planned by relying on efficient forecasts for a short-term increase in volume, however, no change from previous network state is permitted. The aforementioned is applicable to both IP and optical layer, and hence, there occurs a limit on reconfiguration of transponder(s) and the capability(s) of IP grooming. This technique is referred to as a short-term increase (STI). Furthermore, in all periods, the STI method is not able to exploit IP and optical equipment re-configurability completely.

3. When the multi-layer network is planned jointly using the proposed algorithm, and considering the efficient forecasts for the short-term increase in the volume so as to optimize both the CapEx in every period and the OpEx. In this case, two case-variations are investigated in which, \(Y_D\) is varied. In the first instance, \(Y_D = 0\) and hence, no changes in the lightpaths of the previous network state are permitted. In the second instance, \(Y_D = 0.5\), which implies that the CapEx due to added equipment, and the OpEx due to any transition(s) between the two states are equally optimized. The two techniques are referred to as ML-STI and ML-J-STI, respectively. Furthermore, the ML-J-STI technique introduces a penalty on the existing lightpath(s) reconfiguration, and by adjusting this penalty, we intend to investigate the CapEx and the OpEx trade-off.

For simulations, following our previous studies (Iyer, 2017), we use two realistic network topologies, namely Deutsche Telekom (DT) and Telefónica (TID) as shown in Figure 2, with their various dimension values shown in Table 1.

It is assumed that in DT topology all optical nodes are interconnected with IP routers, whereas in TID topology, many optical (transit) nodes are not connected to IP routers, and further, no traffic terminates or originates at these nodes. In regard to traffic, for considered networks, we use their corresponding realistic traffic matrices as detailed in
Palkopoulou et al. (2012) which report that, for the year 2012, traffic loads were 1917.33 and 834.94 Gbps for DT and TID network topologies, respectively. Assuming that the traffic increases uniformly by 35% per year (Palkopoulou et al., 2012), for the year 2017, we evaluated traffic matrices for the two topologies which correspond to 8624.11 and 3744.13 Gbps for DT and TID topologies, respectively. The simulation results considering DT and TID topologies are presented starting from the year 2017 for the following 10 years with a step of 1 year, again assuming a uniform traffic increase of 35% per year. In the considered networks, every link consists of one fibre in which 12.5 GHz wide 320 spectrum slots are available.

The model for cost in our study considers 100 Gbps coherent transponder cost as reference Unit Cost (U.C.), i.e. all devices are priced with reference to U.C since current scenario in the technology of transponders is the coherent 100 Gbps transponder (IDEAL-IST Project, 2014). The optical nodes (OXCs) are assumed to be ROADM with colourless/directionless/contentionless (C/D/C) feature, since such an OXC has been shown to demonstrate the best lightpath blocking probability performance (Li, Gao, Shen, & Peng, 2012). The ROADM utilize EDFAs and $1 \times 20/20 \times 1$ type add-drop Wavelength Selective Switch (WSS) whose relative costs correspond to 0.1 and 0.68 U.C, respectively (Pesic et al., 2016). It must be noted that our cost model also accounts for inline EDFAs, and we assume 80 km length spans, with every span being followed by an inline EDFA that is assumed to completely compensate the loss. In regard to BVTs, we assume the availability of two BVT types, namely one with 400 Gbps maximum rate, and the other

![Figure 2. Network topologies used in the simulations (a) DT and (b) TID.](image)

| Network topology | Location | Number of nodes | Number of bi-directional links | Average length of the link (km) | Maximum length of the link (km) |
|------------------|----------|-----------------|-------------------------------|-------------------------------|-------------------------------|
| DT               | Germany  | 12              | 40                            | 243                           | 459                           |
| TID              | Spain    | 30              | 56                            | 148                           | 313                           |
with 1 Tbps maximum rate which is assumed to be available only after the year 2020. Following studies in Iyer and Singh (2017b) and IDEALIST Project (2014), in Table 2, we present various other parameters in regard to BVTs. In regard to IP routers, cost model which is adopted accounts for utilized number(s) of (i) linecard(s), (ii) linecard chassis and (iii) linecard chassis fitted into a fibrecard chassis, with a cost of 6.04 U.C., 9.3 U.C. for (i) and (ii), respectively (Iyer & Singh, 2017b). Furthermore, for hosting linecards, core routers have a slot capability that ranges between 16 and 1152 slots; and a single linecard type of cost 2.58 U.C. is assumed to drive a single BVT. In addition, for an accurate estimation of increase in equipment cost for the entire lifecycle of the network, it is imperative that maturation in technology and equipment depreciation be considered. In view of the aforementioned, in the current study, for all equipment, we assume a depreciation of 15%.

Finally, it must be noted that in the current study, since we focus on solutions for an offline (static) issue, running times are not considered to be a constraint; however, to avoid searching of solutions which are intractable, in the simulations, we fix a time limit for the ILP model execution to 6 hours. The CPLEX solver (ILOG CPLEX optimizer, 2015) used for finding the ILP solutions returned a 4% and 8% optimality bound for the lower and the higher traffic, respectively.

5.1. Cost (CapEx)

In this sub-section, we present comparison results for various planning techniques in view of cost. Considering DT network, from Figure 3(a) it can be observed that (i) compared to STI technique, ML-J-STI technique is able to achieve saving between 14% and 37% and (ii) compared to ML-STI technique, ML-J-STI technique achieves savings between 4 and 20%. Next, considering TID network, from Figure 3(b) it can be observed that (i) compared to STI technique, ML-J-STI technique is able to achieve saving between 14% and 38%, and (ii) compared to ML-STI technique, ML-J-STI technique achieves savings between 5 and 21%. The reason is that the capability(s) of reconfiguration provisioned is limited, by (i) STI technique at both the layers and (ii) ML-STI technique at only the optical layer. It can also be observed that there occurs an increase in savings obtained by ML-J-STI technique as the years increase owing to poor selections which are made by STI technique and ML-STI technique that collect, and further, with an advance in time (years), these choices are not corrected.

Table 2. Various parameters of the BVTs.

| Capacity (Gbps) | Transmission reach (km) | Data slots | U.C. |
|----------------|-------------------------|------------|------|
| 100            | 2400                    | 4          | 1.96 |
| 200            | 1250                    | 5          | 1.96 |
| 300            | 840                     | 6          | 1.96 |
| 400            | 560                     | 6          | 1.96 |
| 500            | 1050                    | 7          | 2.20 |
| 600            | 900                     | 8          | 2.20 |
| 700            | 800                     | 9          | 2.20 |
| 800            | 750                     | 10         | 2.20 |
| 900            | 650                     | 12         | 2.20 |
| 1000           | 550                     | 14         | 2.20 |
Furthermore, when required, ML-STI technique has the capability of adding equipment hence, being able to take advantage of depreciation(s) in the equipment price(s). In this regard, it must be noted that the major difference between STI and ML-STI techniques is that the IP layer reconfiguration (i.e., grooming) is permitted by ML-STI technique. Also, with reference to ML-J technique using which the optimal CapEx is achievable, it can be observed that the proposed ML-J-STI technique is able to achieve a CapEx which is very close to the optimal CapEx. Furthermore, ML-J-STI technique also offers a trade-off between the CapEx and reconfiguration of the equipment by virtue of the weighting parameter $Y_D$. In regard to the aforementioned, in Section 5.3, we show that by the appropriate choice of $Y_D$, solutions can be found with CapEx ranging from highest (achievable by STI technique with a wide network reconfiguration) to lowest (achievable by ML-J technique with a limited network reconfiguration) values.

Lastly, in view of multi-period planning, since the majority (approximately 70–75%) of total CapEx is comprised IP layer equipment, it can be inferred that IP layer savings are of more significance.

### 5.2. Maximum amount of spectrum utilization

In this sub-section, we present comparison results for the various planning techniques in view of the maximum spectrum utilization. Considering DT network, from Figure 4(a), it can be observed that (i) compared to STI technique, ML-J-STI technique is able to achieve savings between 14% and 37% and (ii) compared to ML-STI technique, ML-J-STI technique achieves savings between 4 and 20%. Next, considering TID network, from Figure 4(b) it can be observed that (i) compared to STI technique, ML-J-STI technique is able to achieve saving between 14% and 38% and (ii) compared to ML-STI technique, ML-J-STI technique achieves savings between 5 and 21%.

In comparison to savings that are achieved in CapEx by the proposed ML-J-STI technique, spectrum savings are observed to be slightly lesser due to the fact that STI and ML-STI techniques deploy more number of regenerators for longer routes which in turn also provision the possibility of wavelength conversion.
5.3. Lightpath establishment analysis

In this sub-section, our focus is to capture trade-off between the reduced CapEx for equipment which is utilized in the current state, and the minimized OpEx owing to the displacement(s) and reconfiguration(s) of the equipment that occurs between the network states. In regard to this, in Figures 5 and 6, considering DT and TID network, we present the overhead due to reconfiguration in optical layer, and the added numbers of lightpaths in every period, respectively.

From Figure 5, it can be observed that proposed ML-J-STI technique is able to control OpEx due to the fact that it achieves limitation on lightpath reconfiguration(s) and establishment of new lightpath(s) Furthermore, ML-J-STI technique achieves a substantial minimization of processes for reconfiguration which is observed to be in the order of (i) 50% in DT network and (ii) 55% in TID network, respectively.

From Figure 6, it can be observed that ML-J-STI technique is able to achieve the aforementioned substantial reduction of reconfiguration processes simultaneously with

Figure 4. Utilization of the maximum spectrum amount in every period for the years 2017–2027 for (a) DT network and (b) TID network.

Figure 5. For the ML-J and ML-J-STI techniques, the overhead due to reconfiguration in the optical layer for (a) DT network and (b) TID network.
maintenance of few number(s) of added lightpath(s) in every period. Compared to ML-J technique, number of lightpaths which are added by ML-J-STI technique is only (i) 20% larger for DT network and (ii) 18% larger for TID network.

Lastly, ML-J technique is uncertain on the previous network state, and hence, extensively reconfigures lightpaths which are already established in turn achieving the optimum CapEx.

5.4. Cost breakdown

In this sub-section, we present cost breakdown for considered techniques. In regard to cost, it must be noted that IP port(s) number utilized in network is a significant metric since transponder(s) number and IP chassis module(s) which are utilized are directly correlated to the core-facing IP port(s) numbers(s).

Considering both the networks, for ML-J, STI, ML-STI and ML-J-STI techniques, in view of breakdown of cost, no significant differences can be observed from Figure 7. This

Figure 6. Added numbers of lightpaths in every period for (a) DT network and (b) TID network.

Figure 7. For the ML-J, STI, ML-STI and ML-J-STI techniques, the breakdown of the cost for (a) DT network and (b) TID network.
occurs owing to the assumption of a uniform decrease in cost in all the layers. However, for the proposed ML-J-STI technique an increase in the regenerator(s) cost is observed due to the fact that in the ML-J-STI case, more numbers of translucent routes are deployed which in turn lead to a minimization of the IP ports. It is also interesting to note that for STI technique, for medium and high traffic, there occurs an increase in router chassis cost, since the transponder(s) number(s) increase and consequently, IP port(s) number(s) also increase which in turn results in multi-chassis configurations being deployed in network.

6. Conclusion

In the current study, for an IP-o-EON, we proposed a multi-layer network planning technique that is also multi-period by virtue of its reliance on the efficient forecasts for short-term increase in the volume. We formulated the multi-layer multi-period planning problem as an ILP which aims at reducing the (i) CapEx, by minimizing the addition of any equipment at every period and (ii) OpEx, by reducing any displacement(s) of the equipment, and reconfiguration(s) in successive periods. We also conducted extensive simulations considering realistic networks to validate the proposed network planning technique. The obtained results demonstrate that the proposed network planning technique trades off the network equipment reconfiguration for the CapEx.

As a scope for future research, we plan to investigate the power (energy) consumption in the IP-o-EON using the proposed technique considering dynamic conditions.

Disclosure statement

No potential conflict of interest was reported by the authors.

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