A comparison study of joint and sequential multi-layer planning for IP over flexible optical networks

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Abstract: We propose a joint multi-layer planning algorithm for IP over flexible optical networks and use to compare the performance of joint as opposed to sequential multi-layer network planning in terms of spectrum and cost.

1. Introduction

The current planning cycle of IP/MPLS and optical transport networks, which is based on the use of separate planning tools for the IP/MPLS and optical network, cannot meet network operators' needs in terms of flexibility, programmability and dynamic provision of services. The continuous growth of consumers' IP traffic and the provision of new services the majority of which are hosted in the cloud, entail an increase in the traffic volume, but even more importantly an increase in the unpredictability and the dynamic nature of traffic. This has created the need for the design and operation of a truly flexible and programmable multi-layer networking environment. This approach is also favored by Software Defined Networks (SDN) technology, where programmability and flexibility through centralized control is meant to hold for both IP and optical layers [1]. Flexible (or elastic) optical networks [2], solve various inefficiency problems of the traditional WDM optical systems, exhibit increased elasticity that fits quite well to a multi-layer networking environment where the planning and operation of both IP and optical layers is jointly performed.

In this work, we consider an IP over flexible optical network, employing flex-grid optical switches and flexible optical transponders at the optical layer, and modular IP/MPLS routers at the edge of the optical network, and propose an algorithm to solve the joint multi-layer network planning (*JML-NP*). The *JML-NP* problem consists of three subproblems in two layers: the IP-layer Routing (IP-R) sub-problem at the IP layer, the Routing, Modulation Level (RML) and Spectrum Allocation (SA) sub-problems at the optical layer. The RML problem is also referred to as distance-adaptive routing in flexible optical networks. The proposed algorithm solves the problem in two phases: at the first phase we *jointly* solve the IP-R and the RML problems, while in the second phase we solve the SA problem. More specific, given the IP layer end-to-end traffic matrix and the feasible configurations of the flexible optical transponders, we serve demands for their requested rates by selecting the routes in the IP topology, the IP/MPLS modules to install, and the placement of transponders, their configurations, and the paths and spectrum slots in the underlying optical topology. The objective is to serve the traffic and find a solution that is optimal with respect to the total network cost. The proposed *ML-NP* algorithm, differs from previous solutions [3],[4] and extends them in a number of aspects as: (a) it is the first time, to the best of our knowledge, that multi-layer planning is jointly performed at IP and optical layers taking into account distance adaptivity/modulation level decisions for the flexible transponders which affect the IP routing decisions, and (b) the proposed algorithm is generic as: (i) it can be applied to both flexible and fixed-grid mixed or single liner rate (MLR or SLR) networks and (ii) it can be used to sequentially plan the IP and optical layers, a case which we call sequential multi-layer network planning (*SML-NP*).

Using realistic transmission specifications, we compare the performance of the proposed joint multilayer planning (*JML-NP*) solution, as opposed to a sequential (*SML-NP*) solution, and verify that when the algorithms are applied to both flexible and fixed-grid MLR optical networks: (a) *JML-NP* outperforms *SML-NP* in terms of cost both for flexible and fixed-grid MLR networks and (b) *JML-NP* outperforms *SML-NP* in terms of spectrum when applied to flexible networks, while the opposite holds for fixed-grid MLR networks.

2. Problem description and proposed algorithm

We consider a flexible optical network which consists of flex-grid optical switches and flexible transponders which are characterized by transmission tuples [7] that identify the reach at which a transmission is feasible, given the parameters that are under our control. More specific, the configurations of a flexible transponder of a specific cost c_t are indicated by transmission tuples (d_t,r_t,b_t,g_t,c_t), where d_t is the reach for which a transmission of rate r_t (gpbs) using b_t spectrum slots and g_t guardband slots is feasible with acceptable QoT [6]. Note that (a) the definition of a specific rate and spectrum incorporates the choice of the modulation format of the transmission and (b) a fixed transponder can be also expressed by a single tuple in the above form.

At each optical switch, one or more modular IP/MPLS routers, consisting of multiple chassis and linecards, are connected through flexible transceivers plugged to the routers' ports or using transponders at the optical switch add-drop ports. We are given the traffic matrix, that corresponds to the IP traffic from the domains adjacent to the routers to be forwarded over the optical domain and our goal is to establish lightpaths, and route the traffic over these lightpaths and through possibly intermediate IP/MPLS routers, to the end IP/MPLS router destination. As discussed in the introduction, the *ML-NP* of an IP over flexible network consists of three sub-problems: the IP-R, RML and SA sub-problems. In the IP-R problem, we decide on the modules to install at the IP/MPLS routers, how to map traffic onto the lightpaths, and the intermediate routers to use to reach the domain destination. In the RML problem, we decide on how to route the lightpaths and also we select the transmission configurations of the flexible transponders to be used. In the SA problem, we allocate spectrum to optical connections. The use of flexible transponders, where the rate, the reach, and spectrum are not fixed, is the reason which makes the RML decisions to affect the two other sub-problems, and significantly complicates the *JML-NP*. At the proposed *JML-NP* algorithm, the IP and optical layers are jointly planned, that is the demands of the given traffic matrix are groomed taking into account the distance constraints and thus the RML decisions. This does not hold in case of sequential planning (*SML-NP*), where the two layers are sequential planned.

The optical network topology and the IP/MPLS router edges are represented by a directed graph *G*, which consists of two types of nodes, IP nodes and optical nodes, and two layers, the IP layer and the optical layer. An IP node represents an IP/MPLS router, while an optical node represents a flex-grid optical switch. In the graph, we define also three types of links, inter-layer, optical and virtual links: (a) an inter-layer link connects an IP node with an optical node and represents the use of a (flexible or fixed) transponder (we define inter-layer links at both directions), (b) an optical link corresponds to a fiber and connects two optical switches, and (c) a virtual link corresponds to a lightpath that connects two IP/MPLS routers.

2.1 Description of JML-NP algorithm

The proposed algorithm serves the demands one-by-one, and is applied sequentially to serve all demands of the traffic matrix. We assume that the node where the algorithm is executed, knows the network topology, the current state of the network (established lightpaths, used router modules) and the feasible transmission configurations of the available transponders. The algorithm runs for a specific demand with source and destination being virtual nodes of the network graph *G* and a demanded rate. In the case where a demand requires rate bigger than that supported by the transponders, then it is splitted to sub-demands of the supported rates, and the algorithm is executed many times. The algorithm constructs a reduced graph G_A from *G*, which includes all nodes and all links expect from the virtual links (established lightpaths) that have remaining capacity lower than the demanded.

The proposed *JML-NP* algorithm is executed in two phases. At the first phase, we jointly solve the IP-R+RML problems according to a multi-cost routing algorithm [5]. The multi-cost routing algorithm runs at graph G_A and creates for each type of link (inter-layer, optical and virtual) a cost vector, that incorporates information regarding both layers, optical and IP. More specific, the cost vector of each link incorporates information concerning the length of the link, the use of a transponder, the cost of a transponder, the additive cost of a router, the feasible transmission tuples and the virtual links. Note, that the value of each parameter of link cost vector, is different depending on the type of link, e.g. transponder and router costs are non-zero for inter-layer links, but these links have zero length, while optical links have zero transponder and router cost and non-zero length. Then the algorithm carries out two steps. In the first step, it calculates the cost vectors of non-dominated paths from the source to the destination by combining the cost vectors of links, using an associative operator, which is different for each type of link. The algorithm used to compute the set of non-dominated paths is a generalization of Dijkstra's algorithm that only considers scalar link costs. Other optimization function can be defined, according to the QoS requirements of the connections. Finally, at the second phase of the *JML-NP* algorithm, the SA problem is solved, using a variation of the heuristic proposed in [6].

3. Performance results

We used the 12-node DT network [8] and starting with a realistic traffic matrix, we scaled it up assuming a uniform increase of 35% per year to obtained matrices for years 2014 to 2024. We examine the following network cases: (a) flexible network with *JML-NP* (*flex-JML-NP*), (b) fixed-grid MLR network with *JML-NP* (*fixed-JML-NP*), (c) flexible network with *SML-NP* (*flex-SML-NP*) and (d) fixed-grid MLR network with *SML-NP* (*fixed-SML-NP*) and compared their performance in terms of spectrum, transponder cost and router cost. We assumed that the MLR system utilizes fixed transponders with the following (rate-reach-spectrum-cost) characteristics: (40 Gbps-2500 km-50 GHz-0.48), (100 Gbps-2000 km-50 GHz-1), (400 Gbps-500 km-75 GHz-1.36), and utilizes flex-grid switches to accommodate 400 Gbps transmission. Also, we assumed that in the flexible network we have a single type of flexible transponder with 400 Gbps maximum rate and cost 1.76. The transmission tuples of flexible transponders were based on [7], [8]: (40 Gbps-4000 km-75 GHz-1.76), (40 Gbps-2500 km-50 GHz-1.76), (100 Gbps-3500 km-75 GHz-1.76), (100 Gbps-2000 km-50 GHz-1.76), (100 Gbps-600 km-37.5 GHz-1.76) (400 Gbps-600 km-100 GHz-1.76), (400 Gbps-600 km-75 GHz-1.76). The cost of transponders, linecards and routers used in our simulations are derived from the CAPEX model defined in the context of the EU project IDEALIST [8].

Year	fixed-JML-NP			flex-JML-NP			fixed-SML-NP			flex-SML-NP		
	Spectrum	Tsp cost	Router cost	Spectrum	Tsp cost	Router cost	Spectrum	Tsp cost	Router cost	Spectrum	Tsp cost	Router cost
2014	550	73,12	63,08	387,5	56,32	87,68	575	60,19	117,72	387,5	56,32	87,68
2016	950	106,48	111,25	400	77,44	139,17	900	85,06	180,17	412,5	77,44	139,17
2018	1125	149,92	173,63	612,5	112,64	199,99	1000	128,03	271,51	650	116,16	205,47
2020	2075	226,88	329,93	812,5	183,00	323,97	1125	187,18	479,92	900	196,06	365,25
2022	2800	401,36	637,86	1487,5	302,72	634,74	1800	315,52	856,79	1537,5	332,29	684,06
2024	3950	656,70	1091,67	2725	545,00	1045,50	3200	562,22	1424,21	3075	572,88	1102,23

Table 1 - Spectrum, transponders (tsp) cost and router cost for each case of network and reference years from 2014 to 2024

Table 1 shows the spectrum, transponders cost and router cost for each case of network and reference years from 2014 to 2024. Note that the objective used in all cases was the minimization of the total network cost and thus the spectrum minimization is a subsidiary. Concerning the *fixed-JML-NP* and *fixed-SML-NP* cases, we observe that in terms of spectrum, expect for year 2014, the *fixed-SML-NP* network outperforms the *fixed-JML-NP* network. This is explained as follows: in the case of *SML-NP*, the connections are groomed (IP-R problem) without taking into account the reach constraints at the optical layer, resulting in the use of more 400 Gbps transponders, compared to the *JML-NP* case, which are more spectrum efficient but have higher cost. Concerning the *flex-JML-NP* and *flex-SML-NP* cases, we observe that in terms of spectrum at low loads (year 2014) the performance of two networks is the same, and as the load increases, the joint planned (*flex-JML-NP*) network uses less spectrum compared to the *flex-SML-NP* network. This is contrary to the fixed network case, and is due to the single type of tunable transponder used in the flex case as opposed to three different types in the fixed case. Also, we observe that in terms of spectrum regardless the planning solution applied (*JML-NP* or *SML-NP*), the flexible network outperforms the fixed-grid MLR network.

Concerning the total network cost we observe that the *fixed-JML-NP* network outperforms the *fixed-SML-NP* network for the whole examined period, since the SML uses mainly 400 Gbps transponders at the IP-R phase while the JML selects the most cost-efficient combination of available transponders. Also we observe that the *flex-JML-NP* network outperforms the *flex-SML-NP* network in terms of both transponders and routers cost and thus total network costs. Regardless the planning solution applied (joint or sequential), we observe that in terms of total network cost the flexible network outperforms the fixed-grid MLR network, except from year 2014, where the fixed-grid MLR network has a slightly smaller. This is because at light loads, lower cost/low-rate fixed transponders are sufficient to serve the traffic, while flexible transponders are not fully utilized. Although IP-R decreases this problem, through appropriate traffic grooming, still at low load (year 2014) the fixed-grid MLR network is slightly better than flexible network. As traffic increases, the utilization of flexible transponders increases, and yielding a better performance for the flexible network at medium and high loads.

4. Conclusions

We proposed a joint multilayer network planning (*JML-NP*) algorithm for IP over flexible optical networks that is quite generic and can be used for fixed grid and sequential multilayer planning. Using realistic network and transmission specifications, we verified the gains that can be obtained by a joint as opposed to a sequential (*SML-NP*) network planning solution, when applied both at flexible and fixed-grid MLR optical networks.

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6. References

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