Evaluating Flexibility Degrees in Optical Networks

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Abstract: We consider an IP over flexgrid network and present a joint IP routing, distance-adaptive routing and spectrum allocation formulation. We evaluate the performance of fixed- and flex-grid switches, fixed transponders, single- and multi-flow bandwidth-variable transponders.

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1. Introduction

The continuous growth of consumers' IP traffic and the provision of new services, the majority of which are hosted in the cloud, increase not only the volume but also the unpredictability and the dynamicity of traffic. This motivates the design of a new truly flexible and programmable multi-layer networking environment. The Wavelength Switched Optical Networks (WSON) used today in core and metro networks are typically designed with an overprovisioning factor, while the IP and physical layers are operated statically and independently, without taking into account short- or mid-term traffic dynamics at their edges. Recently flexible (or elastic) optical networks have emerged to alleviate the inefficiency problems of the traditional WDM approach [1][2]. Flexible networks are based on (i) flex-grid technology that slice the spectrum according to the actual traffic needs, removing the rigid granularity of WDM, but also on (ii) flexible transponders (aka bandwidth-variable transponders, BVTs) that can tune their transmission parameters, trading off transmission reach for spectrum and/or rate. Even more advanced BVTs, called multi-flow or Sliceable-BVTs (S-BVTs), that are able to split the traffic to many destinations are also envisioned. All these features increase the efficiency of resource allocation when planning a network, but also the complexity of the algorithms [3]. Finally apart from the advantages in planning the network, compared to typical WDM systems, the increased network's elasticity fits quite well with the dynamic multi-layer network operation that is actually needed.

In this paper we present a formulation that incorporates traffic grooming at the edges of the flexible optical network (assuming e.g. IP/MPLS, MPLS-TP or OTN routers) and serves the demands in the optical layer by exploiting the tuning capabilities of the BVT or S-BVT transponders. So the proposed formulation solves the joint IP routing (IPR) and Distance Adaptive Routing (DAR) and Spectrum Allocation (SA) problem (IPR+DAR+SA), cross-optimizing layers 3 and 1. The objective is to minimize a weighted combination of the transponders cost and spectrum used. The proposed formulation is quite generic and can be used to allocate resources when Sliceable transponders (S-BVTs) are used, but also for fixed transponders of single- (SLR) or mixed-line-rate (MLR), and also cater for fixed-grid switches. We use the proposed formulation to examine the cost evolution of various optical network scenarios of increased degrees of flexibility (fixed- to flex-grid and fixed- to BVT and S-BVT transponders). Both long-term evolution and short-term fluctuations of traffic are examined: CAPEX comparisons are carried out on biyearly basis, but the network is also allowed to re-optimize and adapt to daily traffic changes to save on energy.

2. Joint IP routing and Distance Adaptive Routing and Spectrum Allocation Formulation

We consider a flexible optical network consisting of flex-grid optical switches and flexible (BVT) transponders that are characterized by transmission tuples [4] identifying the reach d at which transmission is feasible with acceptable quality, for a given transmission rate r (Gpbs) and number of spectrum slots used b. The definition of a specific rate and spectrum incorporates the choice of the modulation format of the transmission, while a fixed transponder can be also expressed by a single tuple of the above form.

We are given a traffic matrix describing the IP traffic aggregated from the access networks at (IP/MPLS, MPLS-TP, OTN) routers at the edges of the optical network and need to be forwarded over it. We want to establish lightpaths, and route the traffic over these lightpaths and possibly through intermediate electronic routers, to the end-router destination, and optimize some parameter of interest, e.g. the cost of the transponders or their energy consumption or the number of slots used, etc. As discussed in the introduction, the multi-layer resource allocation problem in the studied IP over flexible network consists of three sub-problems: the IPR, DAR and SA sub-problems. In the IPR problem we decide on the modules to install at the IP/MPLS routers, how to map traffic onto lightpaths, and the intermediate routers used to reach the domain destination. In the DAR problem (also referred to as routing and modulation level selection-RML), we decide on how to route the lightpaths and we also select the transmission configurations of the flexible transponders used. In the SA problem, we allocate spectrum to optical connections. The use of flexible transponders, where the rate, reach, and spectrum are under our control, makes DAR decisions affect the two other sub-problems, significantly complicating the solution. The network is described by graph $G=(V,E)$ and supports F spectrum slots. The entry Λ_{sd} of traffic matrix Λ denotes the traffic from IP edge s to d. A BVT is

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characterized by a set T of feasible transmission tuples, 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 (including guardband) using that transponder of type (cost) c_t.

We precalculate a set P_{ij} of k paths for each pair of nodes (i,j), and define $P=\cup P_{ij}$. A path-transmission tuple pair (p,t) is feasible only when 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 $[f,f+w\text{-}1]$. The algorithm optimizes a weighted combination (through coefficient a) of the transponders' cost and spectrum used. The problem is formulated as an ILP with the following 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 $[f,f+w\text{-}1]$, is used over path p, and 0 otherwise.

y: integer variable, equal to the maximum indexed spectrum slot that is used in the network.

$$\text{Minimize: } \alpha\cdot\sum_{p\in P}\sum_{t\in T|\exists(p,t)} c_t\cdot x_{pt}+(1-\alpha)\cdot y$$

- Flow constraints:

$$\sum_{i\in V} f_{sd}^{in}-\sum_{j\in V} f_{sd}^{nj}=\begin{cases}\Lambda_{sd},\ n=s\\ -\Lambda_{sd},\ n=d\\ 0,\quad n\neq s,d\end{cases},\ \text{for all } (s,d)\in V^2$$

- Path-transmission tuple assignment constraints:

$$\sum_{sd\in V^2} f_{sd}^{ij}\leq\sum_{p\in P_{ij}}\ \sum_{t\in T|\exists(p,t)}(r_t\cdot x_{pt}),\ \text{for all } (i,j)\in V^2$$

- Data slot assignment constraints:

$$x_{pt}=\sum_{f=\{1\ldots F\}} u_{pfb_t}$$, for all feasible (p,t), where b_t is the number of slots required for transmission of tuple t

- Non overlapping slot assignment constraints:

$$\sum_{p\in P|l\in p}\ \sum_{f,w|m\in[f,f+w-1]} u_{pfw}\leq 1,\ \text{for all } l\in E, \text{ and } m=\{1,\ldots,F\}$$

- Maximum slot used constraints:

$$y\geq(f+w-1)\cdot\sum_{p\in P|l\in p} u_{pfw},\ \text{for all } l\in E, \text{ for all } f=\{1,\ldots,F\} \text{ and } w=\{1,\ldots,F\text{-}f+1\}$$

2.1 Generality of the model and extensions to the proposed formulation

The proposed formulation is quite generic and can be used in a variety of problems. First, by properly defining the set T of feasible transmission tuples we can model both flexible transponders (BVTs) and fixed transponders of single- (SLR) or mixed-line-rates (MLR). Flexible or fixed transponders can be used in a flex-grid or fixed-grid system, and the only distinction from the algorithm's perspective is on the definition of T. Thus, we can use the same model to include fixed 40, 100, and 400 Gbps MLR transponders in a fixed- or flex-grid network. With simple extensions, we can also include Sliceable BVTs (S-BVTs): a sliced connection is represented by a tuple whose cost is the corresponding portion of the cost of the whole transponder and the ILP formulation is extended with an extra variable per node that enumerates the integer number of transponders at the node, and is carried to the objective.

The formulation presented above plans the network assuming all transponders are installed from scratch. It can be also extended to account for an evolving network scenario, where previously used transponders are present (at the same nodes or moved), or some connectiosn are torn down (similar to [6] but focusing on BVTs). To do so, we use the previous solution, as described by the related variables $\bar{f},\bar{x},\bar{u}$, and add constraints in the above formulation to meet the required specifications. For example, if the traffic increases and we need to keep the previously established optical connections (and thus only IP rerouting is allowed) we add the constraints: $x_{pt}\geq\bar{x}_{pt}$ for all $\bar{x}_{pt}>0$, and $u_{pfw}\geq\bar{u}_{pfw}$ for all $\bar{u}_{pfw}=1$, or when we are allowed to reroute the optical connections we add the constraints: $\sum_{j\in V}\sum_{p\in P_{sj}}\sum_{t\in T|\exists(p,t)}x_{pt}\geq\sum_{j\in V}\sum_{p\in P_{sj}}\sum_{t\in T|\exists(p,t)}\bar{x}_{pt}$, for all $s\in V$. Note that this approach is for hard constraints, but we can also define soft constraints that would penalize but allow changes in the previous solution. An extension that seems quite interesting is when we examine the performance of the network in short term traffic variations, e.g. following the daily traffic cycle (it has been observed that traffic on a daily basis has a well-structured cycle with a peak during daytime and a valley at nighttime, and almost all network connections are synchronized in this cycle [2][5]). To follow such traffic we plan the network for the peaks and re-optimize the network at certain intervals, e.g. every hour. Depending on the requirements, e.g. no or limited re-routings, we can define appropriate constraints so as to move to the next state and switch-off or re-configure transponders so as to save, e.g., on energy.

3. Comparison Study

We used the proposed formulation to evaluate various optical network scenarios of increasing flexibility:

1. fixed-grid (50 GHz) switches and fixed mixed-line-rate (40 and 100 Gbps) transponders (fixed-grid/MLR-TSP)
2. flex-grid (12.5 GHz) switches with fixed mixed-line-rate (40, 100, 400 Gbps) transponders (flex-grid/MLR-TSP)
3. flex-grid (12.5 GHz) switches with Bandwidth Flexible Transponders (flex-grid/BVT)

4. flex-grid (12.5 GHz) switches with Sliceable Bandwidth Flexible Transponders (flex-grid/S-BVT)

We have modeled the fixed transponders with the following (rate-reach-spectrum-cost) characteristics: (40 Gbps-2500 km-50 GHz-0.48 CU), (100 Gbps-2000 km-50 GHz-1 CU), (400 Gbps-500 km-75 GHz-1.36 CU), and thus the 400 Gbps transponder is not suitable for fixed 50 GHz grid (fixed-grid/MLR-TSP scenario). We have taken the cost of a 100 Gbps transponder as the relative Cost Unit (CU). Also, we assumed a single type of bandwidth variable transponder (BVT) with 400 Gbps maximum rate and cost 1.76 CU and transmission tuples based on [2], [7]: (100 Gbps-3500 km-75 GHz-1.76 CU), (100 Gbps-2000 km-50 GHz-1.76 CU), (100 Gbps-600 km-37.5 GHz-1.76 CU) (400 Gbps-600 km-100 GHz-1.76 CU), (400 Gbps-500 km-75 GHz-1.76 CU). The S-BVT transponder was assumed to cost 2 CU and has the BVT's tuples with the addition of tuples that split 400 Gbps traffic to 200 and 100 Gbps at the same reach requiring the relative percentage of spectrum plus one spectrum slot (extra guardband).

In our comparison we used the 12 node DT network and projected traffic until year 2024 assuming a uniform increase of 35% per year for all connections [2]. We set a=0.95, that is, the cost was the main optimization parameter, while spectrum utilization had much lower importance. Fig. 1a presents the (relative) transponders' costs for the different network scenarios, while Fig. 1b the resulting spectrum utilization. The fixed-grid scenario exhibits the worst cost and spectrum performance, while it is not able to serve traffic for year 2024 (for a network of 4000 GHz in total). The flex-grid/MLR-TSP is cheaper than the flex-grid/BVT until year 2020, harvesting the capacity/cost tradeoff of the MLR transponders, while at heavy load the BVTs become efficient, thanks to the many transmission options and yield cost reductions (note that calculations already include a 30% increased cost for the BVT as opposed to a 400 Gbps fixed transponder). The flex-grid/S-BVT scenario has the lowest cost until year 2020, but after that it becomes more expensive than the (single-flow) BVT scenario. At low load, the multi-flow feature is quite efficient but as the load increases the S-BVTs are eventually used to serve a single destination, at an increased cost (2 CU as opposed to 1.76 CU for a BVT). The S-BVTs result also in higher spectrum utilization than the BVT option, due to the extra guardband required when serving multiple flows. Note that the presented results are for planning the target networks from scratch at each year. An evolution scenario, where previously used transponders remain, increases the gains of using the BVT and S-BVT when compared to the fixed MLR scenarios. Also note that this study assumes the use of up to 400 Gbps transponders, neglecting the introduction of 1 Tbps that could be available at some future point.

Fig. 1c shows the energy consumption for three different years assuming that the network is planned for the target peak traffic and adapted during the day to follow the traffic fluctuations. We plot the energy consumption for two time instants where traffic is 75% (evening) and 50% (nighttime) of the peak. At low load (for early years and low traffic utilization, e.g. at nighttime), S-BVT achieves the highest energy savings, while it has almost the same performance with the BVT case at heavy load, the reason being that the multi-flow feature can be exploited at light loads.

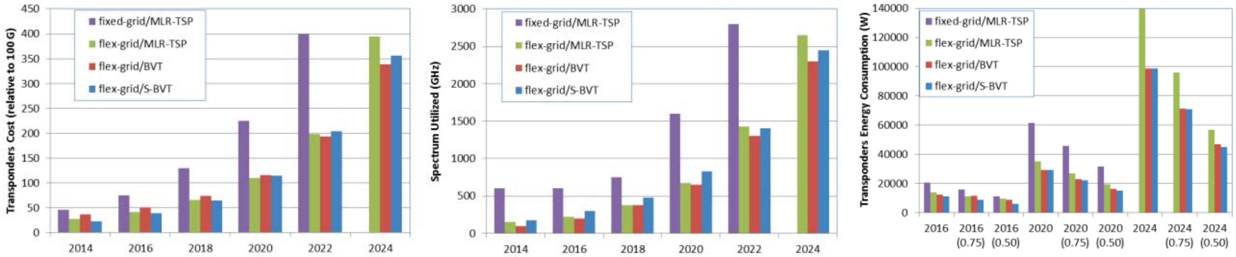

Figure 1 (a) Relative cost and (b) spectrum utilization for the different scenarios for reference years from 2014 to 2024. (c) Relative cost for three years assuming network planned for peak traffic and adapted when traffic is 75% and 50% of the peak.

4. Conclusions

We presented an algorithm for the distance adaptive routing and spectrum allocation problem that incorporates traffic grooming at the optical network edges. We used it to examine the cost evolution of various optical network scenarios with increased flexibility degrees (fixed- to flex-grid and fixed to BVT and S-BVT transponders). A definite advantage is shown for moving from fixed- to flex-grid switches, while the use of BVTs becomes efficient at later stages. The use of S-BVTs seems efficient at an early network stage or at low traffic utilization, e.g., at nighttime.

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