Joint Multilayer Planning of Survivable Elastic Optical Networks

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Abstract: We formulate the joint multilayer planning problem of survivable elastic networks and present two ILP formulations to solve it. Compared to the traditional dual plane planning approach significant cost and energy savings can be achieved.

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1. Introduction

Elastic Optical Networks (EON) use variable spectrum connections to increase spectral efficiency and support variable transmission rates. In addition, flex-rate transponders (with the ability to adapt a number of transmission parameters, such as the modulation format, spectrum, baudrate, and/or FEC) further increase the flexibility and adaptability of such networks. The joint planning and operation of a multilayer (ML) network, that is, considering both the optical network and its IP edges, is key to reducing capital and operational costs in next generation EON transport networks. Apart from savings in planning [1], exploiting reconfigurable optical equipment and an ML control plane, enables planning of a survivable ML networks while avoiding installing a dual network to achieve 1+1 node protection at the IP and optical layer (which is usually referred to as the dual plane approach).

According to today's traditional approach the IP layer is responsible for failure recovery. A common practice used by operators is to build two variants of the network that mutually protect each other (dual plane protection) [2]. Such approach, however, leads to an enormous over-provisioning of IP interfaces, which are largely underutilized, with consequent a high CAPEX that decreases overall network profitability.

ML network survivability is a topic that has received considerable interest by the research community but also by operators. In [3] mathematical programming models are developed for the design of survivable IP/MPLS over a WDM network focusing on CAPEX reduction, while [4] highlights the significance of optimizing the design of IP topology (optical nodes bypass) by considering the cost impact of several ML restoration schemes. Building on advanced optical layer capabilities, [5] presented the ML shared backup router (MLSBR) concept and compared its availability to a traditional dual-plane approach.

In this paper, we focus on the savings that can be achieved by ML restoration. To this end, we proposed two Integer Linear Programming (ILP) formulation variations that jointly plan a ML survivable elastic optical network under single optical link failures (which is the typical survivability level offered) and we compared them to the traditional dual plane approach. Even though ML restoration of EON is a topic that has been extensively researched, since the joint consideration of both layers has shown to yield significant gains, there is no formal description and optimal solution to the joint problem (e.g. given by an ILP formulation), to the best of our knowledge. Our optimization models account for a flexible and modular network in both layers. We apply these models to DT's IP backbone showing that important cost and energy savings can be obtained through the joint consideration of the optical and the IP layers when dimensioning the network to be ML survivable.

2. Network model, survivability policies and mathematical formulation

The network model used in our study was developed in the Idealist project [6], and includes optical as well as IP/MPLS routers models. We evaluate the cost and energy efficiency of the ML resiliency mechanisms assuming an elastic optical network with flex-grid enabled switches and tunable - Bandwidth Variable Transponders (BVTs). The IP/MPLS router model is organized into three component classes: the basic node, the line-cards and the transceivers. The cost P of a multi-chassis router is computed according to Eq (1), derived based on the modular equipment structure of a specific vendor [6]:

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

where, $n_{ch} = \left\lceil C/K \right\rceil$, $2 \le n_{ch} \le 72$, C is the total switching capacity in Tb/s of the router, and K is the capacity of a fully equipped shelf. The reference cost unit (c.u.) used is the 100 Gb/s coherent optical transponder and all other devices are priced with reference to this c.u.

The idea behind multilayer (ML) restoration is to exploit ML communication and coordination to prevent resource inefficiencies created by resilience mechanisms reacting separately on their own layer. For a fair comparison, all planning approaches dimension the network so as to provide the same level of survivability. Three approaches are considered:

Approach I – Dual plane network design: A dual plane network dimensioning scheme consists of building an A and a B variant of the network for mutual protection. Each core router is connected to the optical mesh through different ROADMs.

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Traffic is distributed over the A and B planes using Equal Cost Multipath protocol (ECMP) with 50:50 load sharing. When a failure occurs, the entire link traffic is directed to the other plane, keeping protecting link loads under 100% (Fig. 1.a).

Approach II – Failure driven network design: In this approach we initially dimension both IP and optical layer for normal operation. Then, we take this as input and formulate an ILP model that considers all the possible (single) optical link failures, capturing their impact on the IP links to re-dimension (add capacity to) the network, assuming the optical layer restores the IP link by rerouting the corresponding optical lightpath (Fig.1.b).

Approach III – Integrated ML survivable network design: in this approach we jointly dimension both layers and consider all the single optical link failures, allowing re-direction of traffic at both the IP and the optical layers.

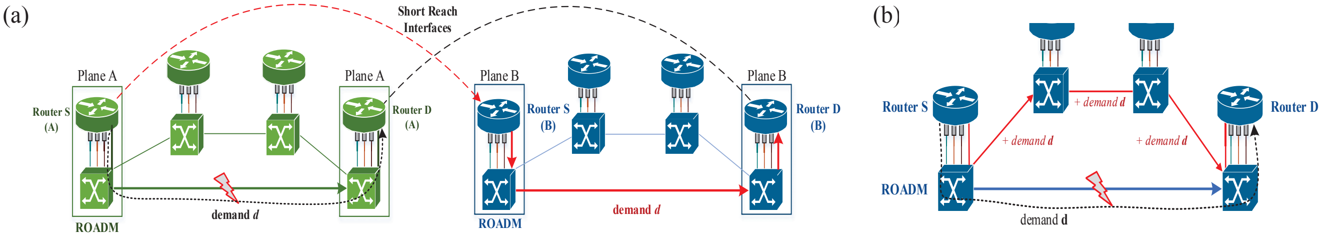

Fig. 1. (a) Example of a ML network with dual plane design (b) Optical restoration restores wavelength connectivity in the optical layer.

We implemented three ILP models, one for each of the above approaches. The optimization objective is set to the minimization of a weighted sum of (i) the maximum spectrum, (ii) the energy consumed and (ii) the cost of the equipment used in both layers. Different choices of the weighting coefficients give different importance to the 3 aforementioned criteria (the Pareto front under these 3 criteria can be found, but for brevity we avoid presenting the corresponding results). Also, due to space limitation we only present the ILP formulation for the integrated ML survivable network (approach III).

Input:

- The network topology represented by graph $G(V,L)$.
- The maximum number F of available spectrum slots (of 12.5 GHz).
- The traffic described by the traffic matrix Λ.
- A set T of feasible transmission tuples, which characterize the available BVTs, with tuple t=(D_t,R_t,B_t,E_t,C_t) indicating feasibility of transmision at distance D_t, with rate R_t (Gpbs), using B_t spectrum slots, consuming E_t power, using the transponder of type (cost) C_t.
- A set of line-cards represented by H, where a line-card for transponder of type C_t is represented by a tuple h_{Ct}=(N_h,R_h,E_h,C_h), where N_h, is the number of transponders with rate R_h that the line-card supports, E_h is the power consumption and C_h the cost of the line-card.
- The IP/MPLS router cost, specified by a modular cost model. We assume that an IP/MPLS router consists of line-card chassis of cost C_{LCC}, power consumption E_{LCC} that suport N_{LCC} line-cards each, and fabric card chassis of cost C_{FCC}, power consumption E_{LCC},that suport N_{FCC} line-card chassis.
- The weighting coefficient, W_E and W_C, taking values between 0 and 1. Setting $W_C = 1$ *and* $W_E = 0$ ($W_E = 1$ *and* $W_C = 0$) minimizes solely the cost (the power consumed, respectively), while setting $W_C = W_E = 0$ minimizes the maximum spectrum used.

Variables:

- $f_{A_{sd}}^{in}, f_{B_{sd}}^{in}$ real variables, representing the primary and backup IP flow from IP source s to destination d that pass over a lightpath between i and j.
- x_{pt}: integer variable, representing the number of lightpaths of path-transmission tuple pairs (p,t) 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_{nh}: integer variable, number of line-cards of type h at node n.
- q_n: integer variable, number of line-card chassis at node n.
- o_n: integer variable, number of fiber-card chassis at node n.
- y: integer variable, equal to the maximum indexed spectrum slot.
- c: total cost of utilized transponders, line-cards and router chassis.
- e: total power consumed by transponders, line-cards and router chassis.

$$\min\left(W_e\cdot e+W_c\cdot c+(1-W_E-W_c)\cdot \mathrm{y}\ \ ,\ \ where\, W_E+W_c=1\right)$$

$$c=\left(\sum_{p\in P}\ \sum_{t\in T|\exists(p,t)} C_t\cdot x_{pt}+\sum_{n\in V}\sum_{l\in L}C_h\cdot z_{nh}+\sum_{n\in V}C_{LCC}\cdot q_n+\sum_{n\in V}C_{CH}\cdot o_n\right)$$

$$e=\left(\sum_{p\in P}\ \sum_{t\in T|\exists(p,t)} E_t\cdot x_{pt}+\sum_{n\in V}\sum_{l\in L}E_h\cdot z_{nh}+\sum_{n\in V}E_{LCC}\cdot q_n+\sum_{n\in V}E_{CH}\cdot o_n\right)$$

Flow constraints:

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

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

Path-transmission tuple assignment constraints:

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

node disjoint constraints:

$$g_{nsd}=1\ \ if\left(\sum_i f_{A_{sd}}^{in}+\sum_j f_{A_{sd}}^{nj}\right)>0\ ,\forall(s,d)\in V^2,\forall n\in V,n\neq s,d$$

$$\left(\sum_i f_{A_{sd}}^{in}+\sum_j f_{A_{sd}}^{nj}\right)\geq bigM\cdot q_{nsd}\ ,\forall(s,d)\in V^2,\forall n\in V,n\neq s,d$$

$$\left(\sum_i f_{B_{sd}}^{in}+\sum_j f_{B_{sd}}^{nj}\right)\geq bigM\cdot g_{nsd}\ ,\forall(s,d)\in V^2,\forall n\in V,n\neq s,d$$

$$g_{nsd}+q_{nsd}=1\ ,\forall(s,d)\in V^2,\forall n\in V,n\neq s,d$$

Data slot assignment constraints:

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

Non overlapping slot assignment constraints:

$$\sum_{p\in P|l\in p}\ \sum_{f,w|m\in[f,f+w-1]}u_{p\,f\,w}\leq 1,\ \forall\ l\in L,\ and\ m=\{1,\ldots,F\}$$

Number of linecards per node constraints:

$$z_{nh}\geq\sum_{p\ starts\ at\ n}\ \sum_{t|h\ supports\ C_t}(x_{pt}+1)/N_h\ ,\ \forall\ n\in V\ and\ h\in H$$

LCC per node constraints:

$$q_n\geq\sum_h z_{nh}/N_{LCC}\ ,\forall n\in V$$

FCC per node constraints:

$$o_n\geq q_n/N_{CH}\ ,\forall n\in V$$

Maximum slot used constraints:

$$y\geq(f+w-1)\cdot\sum_{p\in P|l\in p}u_{p\,fw}\ ,\ \forall\ l\in L,\ f\in[1,F]\ and\ w\in[1,F-f+1]$$

4. Illustrative results

To study the cost and energy efficiency of the proposed resiliency mechanisms compared to the traditional overprovisioning approach (dual plane), we evaluated the energy consumption and the CAPEX cost for the DT network assumed to be deployed using flex-grid technology. The width of the spectrum slot was set to 12.5 GHz, and 320 slots were assumed to be available, while the available transmission configuration of the BVTs, the energy consumption, the spectrum used, and the cost of the IP and optical layer equipment are presented in [1,6]. The traffic matrix of the DT network used in our simulations is realistic as provided by the operator (DTAG) for year 2012, and is projected in the future assuming that traffic increases uniformly by 35% per year. We graph our results for a 10 years span, from 2014 (total traffic 3494.33 Gbps) with a step of 2 years, and each examined year we plan the whole survivable network from scratch, without taking into account the solutions for previous years. Our primary goal is to minimize the cost and energy consumed, so in the objective function we used the following weighting coefficients $W_E = W_C = 0.45$ (with the remaining 0.1 to be the weight of the spectrum used).

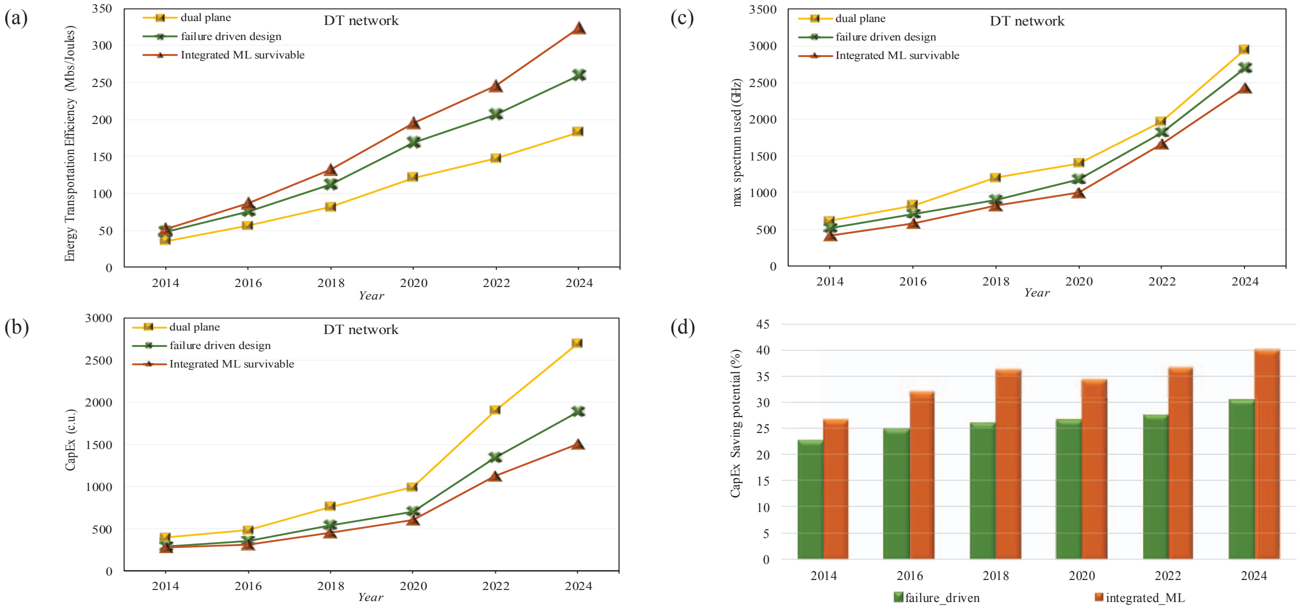

Fig. 2 (a) Energy transportation efficiency, (b) CapEx, (c) Maximum spectrum used, (e) CapEx saving potential compared to dual plane.

The cost is measured in c.u. (see discussion in Section 2), while for energy we used the *energy transportation efficiency* metric, defined as the ratio of the total network traffic over the corresponding energy consumption (Mbits/joule). From Fig 2.a it becomes evident that the dual plane approach exhibits the worst energy efficiency. This was expected, since this approach copes with failures by over-provisioning. The integrated ML strategy outperforms the other two approaches, exhibiting the lowest power consumption and being slightly more efficient than the failure driven approach. The two proposed approaches have very close performance for the two other metrics (spectrum and CAPEX) used in our comparison (Fig.2.b and Fig.2.c), with the integrated ML planning being slightly more cost efficient and achieving the lowest spectrum utilization. The maximum spectrum used metric illustrates the poor utilization of transponders (equivalent to lambdas on the optical layer) under the dual plane approach, where lambdas may be filled only up to 50% in an error-free network. The last graph shows that by considering optical link failures in joint ML network planning (approaches II and III) we obtain cost savings of 22-40% compared to the traditional dual plane approach (similar are the results for the energy consumption not presented here for brevity).

5. Conclusions

In this paper we focused on the inherent inefficiencies of the dual plane resiliency strategy. We considered the planning of a survivable multilayer (ML) IP/MPLS-over-elastic optical network, and presented two ILP models to solve it in a jointly manner. For realistic network scenarios, our simulation results indicated that we can achieve important energy and cost savings by including the analysis of the optical link failures in the joint ML planning phase of the network.

6. References

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