On the Benefits of Elastic Transponders in Optical Metro Networks

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Abstract: We investigate the benefits of using elastic transponders with distance-adaptive data-rate in optical metro networks: experimental results show a significant reduction in terms of number of transponders and spectrum utilization.

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1. Introduction

The metro network is the section of the telecommunication network that bridges the core segment to the access segment of the network. It typically spans a metropolitan region, covering distances of a few tens to a few hundreds of kilometers and is traditionally based on ring topologies exploiting the deep-rooted technology of SONET/SDH, or, more recently, Metro Ethernet and RPR. Due to the increasing amount of content generated by real-time mobile broadband services (such as VoD, live streaming, P2P applications), the metro segment is facing a sheer increase of the traffic, mainly driven by the raising demand for mobile backhauling, and metro optical spectrum is becoming scarce.

In the last decade, the introduction of the wavelength-division multiplexing (WDM) technology in metropolitan rings has allowed to rapidly and cost-efficiently upgrade metro network capacity to face traffic growth. Using WDM, the optical fiber spectrum is divided into separate channels with fixed spectrum spacing (namely 50 GHz or 100 GHz, as specified by ITU-T standards). The optical signal is then transmitted over each channel by transponders that support fixed line rates (typically 10, 40 or 100 Gbps).

Recently, new trends in optical transmission technologies, such as coherent detection and digital signal processing, are enabling new "elastic" transponders capable of tuning their rates according to the network state (typically choosing the best modulation format, or the best coding rate, or the best spectrum width, similarly to what happens in wireless systems) [1].To fully exploit the capabilities of these elastic transponders, the conventional fixed spectrum grid (spaced, e.g., at 50GHz) has to be removed or at least replaced with a minigrid of narrower spectral intervals (spaced, e.g., at 10 or 5 GHz) to support more scalable and flexible optical circuits that can use just as much spectral resources as requested to serve the client demand. Enabling technologies and sub-systems to switch these bandwidth-variable optical circuits, such as bandwidth-variable transponders and OXCs, have been already demonstrated [4].

The investigation of the impact and effective use of such elastic transponders on the design and control of optical core networks has already started, and possible gains in terms of CAPEX, OPEX, flexibility and survivability [5] have been demonstrated. However, to the best of our knowledge, no study has still analyzed the benefits of elastic transponders in metro networks. Here we try to address, under a networking perspective, some basic questions: are elastic transponders a suitable technology for optical metro rings? What are the gains achievable in terms of spectrum occupation and transponder utilization? In particular, we analyze the impact of grid flexibility and of the usage of distance-adaptive modulation techniques in the metro ring network. To do so, we recast a classical design problem in metro networks, referred to as "traffic grooming in optical WDM rings" (see e.g., [6]), in the *traffic grooming in optical rings with elastic transponders*.

The remainder of the paper is structured as follows: Section 2 provides a description of the metro network architecture . Section 3 shows how to formalize the problem through an Integer Linear Programming model. Some illustrative numerical results are discussed in Section 4.

2. Metro Network Architecture with Elastic Transponders

In our work, we model the metro-network physical topology as a bidirectional ring network with N nodes. The fiber links are deployed in both clockwise and counterclockwise direction between every pair of nodes. The fiber spectrum is divided into a so-called minigrid of S spectral intervals (SIs), each of them supporting a baud rate of C Gbaud/s and regularly spaced along the spectrum with granularity of F GHz, for a total spectrum width of SF GHz. Together with the physical topology, the electronic traffic demands among the various nodes are also given and need to be aggregated over sequences of one or more optical paths connecting some of the metro nodes.

An optical path is formed by one or more adjacent minigrid SIs and it is originated by an elastic transponder with a maximal spectral width of T GHz, i.e., supporting at most T/F SIs. The spectral efficiency of each of these SIs can be varied by modifying the modulation format

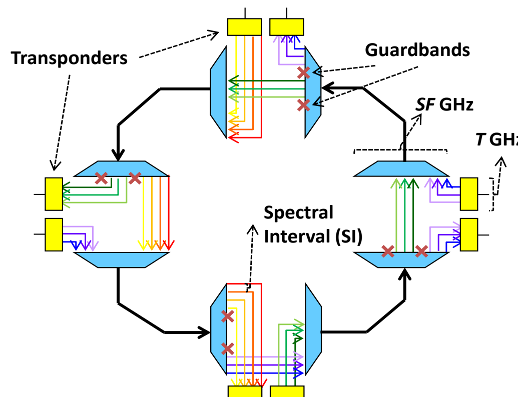


Fig. 1: The network architecture

(MF) and depends on the length of the optical path (distance adaptive MF): shorter paths will benefit of higher spectral efficiency. One additional requirement is the presence of spectrum guardbands [5] that must be placed to separate different optical paths sharing the same link to allow filtering of the optical-path spectrum. All the nodes are equipped with Bandwidth Variable Optical Cross-Connects (BV OXCs) that can vary the number of SIs reserved for the optical paths. Note that, along a single optical path, spectrum continuity has to be ensured, therefore in all the traversed links the same spectrum intervals must be reserved. (These optical paths, once established, will form the so-called logical topology). Note also that grooming several requests over the same optical path leads to an effective capacity utilization, because *i*) optical paths bandwidth is filled up more effectively *ii*) less optical paths, and consequently less guardbands, will be needed.

3. MILP formulation for traffic grooming in elastic networks

The following ILP model formalizes the traffic grooming in minigrid-based optical metro rings with elastic transponders stated in the previous Section. It has been derived through a non-trivial combination of the ILP models in [6] and [5].

Parameters
- $G(N,L)$: oriented graph of the ring network with $|N|$ nodes and $|L|$ physical links (m,n)
- $K=\{1,2\}$: direction (1=clockwise, 2=counterclockwise)
- S: number of available spectral intervals on each link
- C_s: capacity of a spectral interval (Gbps)
- F_s: spacing between consecutive spectral intervals (GHz)
- G: number of spectral intervals used as guardband
- $T^{s,d}$: traffic between source-destination pairs (Gbps)
- L_{ijk}: number of links traversed by the lightpath between node i and node j in direction k
- T^{max}: maximum number of admissible adjacent spectral intervals without intermediate guardbands
- R_{ijk}: Transmission rate along the lightpath between node i and node j in direction k
- $D_k(m,n)$: set of lightpaths in direction k that, if established, would traverse link (m,n)
- $E_k(i,j)$: set of physical links traversed by lightpath (i,j) in direction k (if established)

Variables
- x^{sd}_{ijk}: boolean variable, indicates whether a lightpath established between (i,j) node pair in direction k is used to serve the connection request between (s,d)
- b_{ijk}: integer variable, indicates the number of adjacent spectral intervals required between (i,j) node pair in direction k
- y_{ijk}: boolean variable, is 1 if a lightpath is established between (i,j) node pair in direction k
- f_{ijk}: integer variable, indicates the starting spectral interval used on the lightpath between (i,j) node pair in direction k
- g_{ijk}: integer variable, indicates the total number of guardbands (external and possible intermediate guardbands) for the lightpath between (i,j) node pair in direction k
- $d_{ijki'j'k'}$: boolean variable, is 0 if $f_{i'j'k'} < f_{ijk}$, 1 otherwise

Objective function

$$\min \alpha_1 \sum_{i,j\in N,k\in K: i\neq j} 2g_{i,j,k} + \alpha_2 \sum_{i,j\in N,k\in K: i\neq j} L_{i,j,k}(b_{i,j,k}+g_{i,j,k}G)F_s \quad (1)$$

The objective function is the sum of two separate components: the first summation computes the number of transponders that need to be installed, while the second summation calculates the overall spectrum occupation. The parameters α_1 and α_2 are weights that can be varied in order to privilege the minimization of one of the two components.

Constraints

$$\sum_{k\in K} x^{s,d}_{ijk} \leq 1 \qquad \forall i,j,s,d\in N: i\neq j, s\neq d \quad (2)$$

$$\sum_{s\in N,d\in N:s\neq d} x^{sd}_{ijk}\frac{t^{s,d}}{R_{ijk}} \leq b_{ijk}C_s \quad \forall i,j\in N,k\in K: i\neq j \quad (3)$$

$$x^{sd}_{ijk} \leq y_{ijk} \qquad \forall i,j,s,d\in N,k\in K: i\neq j, s\neq d \quad (4)$$

$$f_{ijk}+b_{ijk}+g_{ijk}G \leq S \qquad \forall i,j\in N,k\in K: i\neq j \quad (5)$$

$$b_{ijk} \leq g_{ijk}T^{max} \qquad \forall i,j\in N,k\in K: i\neq j \quad (6)$$

$$\sum_{k\in K,j\in N:i\neq j} x^{sd}_{ijk} - \sum_{k\in K,j\in N:i\neq j} x^{sd}_{jik} = \begin{cases} 1 \text{ if } s=i \\ -1 \text{ if } d=i \\ 0 \text{ otherwise}\end{cases} \qquad \forall i\in N, s,d\in T^{s,d}: s\neq d \wedge t^{s,d}>0 \quad (7)$$

$$f_{i'j'k'}-f_{ijk} \leq F_sSd_{i'j'k'ijk} \quad (8) \qquad f_{ijk}-f_{i'j'k'} \leq F_sSd_{ijki'j'k'} \quad (9) \qquad d_{ijk,i'j'k'}+d_{i'j'k'ijk}=1 \quad (10)$$

$$f_{ijk}+b_{ijk}+g_{ijk}G-f_{i'j'k'} \leq (F_sS+G)(1-d_{i'j'k'ijk}+2-y_{ijk}-y_{i'j'k'}) \quad (11)$$

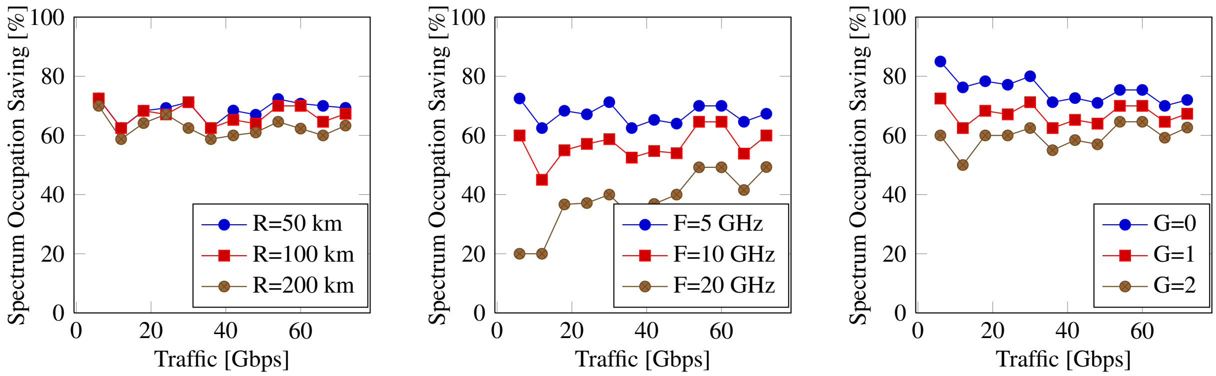
$$f_{i'j'k'}+b_{i'j'k'}+g_{ijk}G-f_{ijk} \leq (F_sS+G)(1-d_{ijki'j'k'}+2-y_{ijk}-y_{i'j'k'}) \quad (12)$$

$\forall i,j,i',j' \in N, k,k' \in K: E_k(i,j) \cap E_{k'}(i',j') \neq \oslash$ (Applied to Eq. [8-12])

Equation (2) ensures that no bifurcation of traffic flows occurs, while Eqn. (4) imposes coherence of the values of y_{ijk} and x^{sd}_{ijk} variables by forcing the lightpath indicator y_{ijk} to 1 if the lightpath (i,j) in direction k is used to serve at least one traffic request. Flow conservation is imposed by Eqn. (7) while Eqn. (3) considers the capacity constraints and eventually allows traffic grooming. Limitations due to physical impairments on the maximum number of adjacent spectral intervals are introduced by Eqn. (6). As proposed in [5], the correct ordering of the starting frequencies of the lightpaths having at least one common link is guaranteed by Eqns. (8,9,10) by ensuring that either $f_{ijk} < f_{i'j'k'}$ or $f_{ijk} > f_{i'j'k'}$. Moreover, the starting frequencies are forced to assume a value in the available range of spectrum by Eqn. (5). The correct placement of the guardbands between adjacent spectrum paths is imposed by Eqns. (11,12): these are activated only in case x_{ijk} and $x_{i'j'k'}$ are both set to 1 and are mutually excluding, depending on the value of $d_{ijki'j'k'}$. Results from this model have been compared with results from the model in [6], which solves the traffic grooming problem in a traditional WDM ring.

4. Results and Discussion

We consider a topology with $N=8$ nodes. For the traditional WDM ring, we consider a 1THz spectrum divided into 20 wavelengths (50 GHz channel spacing), and 100G transponders (we assume PDM-DQPSK modulation with spectral efficiency $\eta = C/F = 2$ and no reach limitation in a metro area).



(a) Dependence on the ring dimension ($F = 5$ GHz, $G = 1$)

(b) Dependence on grid granularity ($G = 1, R = 100$ km)

(c) Dependence on the number of guardbands ($F = 5$ GHz, $R = 100$ km)

Fig. 2: Spectrum Savings (in percentage) of elastic vs. fixed spectrum metro networks

For the elastic metro ring, the same spectrum of 1 THz is divided in the basic case in 200 SIs of 5GHz each. Elastic transponders have a maximum spectral width of 100 GHz (i.e. can support up to 20 SIs). The values of C, S and F for this basic case and other two scenarios are reported in Table 3. The possible modulation formats in the elastic transponders are BPSK, QPSK and n-QAM (with $n = 8, 16, 32, 64, 128$) and all of them are polarization multiplexed in order to have a fair comparison with PDM-DQPSK modulation in the fixed grid case. The maximum reach for an elastic (coherent) transponder using BPSK modulation format is considered to be 3000 km [5] and it is halved every time the number of bit per symbol is increased by 1 according to the logarithmic law in [7].

The traffic requests are defined by a static traffic matrix, which can be both uniform or one-to-all, the latter meaning that one of the nodes of the network is elected as gateway and all the traffic is either originated or terminated by that node.

	C (Gbps)	S	F (GHz)
Scenario A	10	200	5
Scenario B	20	100	10
Scenario C	40	50	20

Fig. 3: Grid parameters

	Traffic per Request (Gbps)											
Traffic Matrix	6	12	18	24	30	36	42	48	54	60	66	72
One to All	0	0	11.11	11.11	20	27.27	27.27	27.27	42.86	42.86	42.86	42.86
Uniform	20	42.86	60	56.52	57.14	68.42	63.16	60.53	73.21	71.43	71.43	71.43

Fig. 4: Reduction of the number of installed transponders (%, Scenario A)

We start considering the case of minimization of spectrum utilization ($\alpha_1 \ll \alpha_2$). Figure 2a shows the reduction of the overall spectrum occupation using a distance-adaptive modulation techniques with respect to the classic WDM approach, for different values of the ring radius R (and for F=5 and G=1). Spectrum savings are very significant (from 60% to 75%) in all cases, with larger reductions for smaller rings, where more advanced modulation formats can be used. Figure 2b depicts the the spectrum occupation reduction as a function of the dimension of the minigrid spectral interval: as expected, smaller SIs are more desirable, but spectrum gains tend to converge for higher traffic, since less traffic grooming is applied. Finally, Fig. 2c considers the effect of the number of guardbands needed to separate optical paths (0, 1 or 2 guardbands needed). Also in this case, other than the expected decrease in spectrum reduction for larger bandwidth, we can notice that for larger traffic load the difference among the various cases become less relevant.

Table 4 reports the reduction on the number of transponders, when the number of transponders is the objective of the minimization ($\alpha_1 \gg \alpha_2$): the savings increase for higher traffic, as it becomes more convenient to have long optical paths that avoid OEO conversion at the intermediate nodes.

In conclusion, the application of elastic (distance-adaptive) transponders in metro area results in significant gains in terms of spectral occupation and number of transponders, since the limited geographical dimension of the network enables the utilization of complex modulation formats, with high spectral efficiency. Considering that the development and deployment of coherent transponders is a Hobson's choice in future core networks in order to preserve a high capacity-reach product (e.g. for 400G and 1T equipment), we expect this technology to mature and become more affordable in the next years. So, considering the strong increase in network capacity enabled by these technologies over the short metro reaches, we envision a possible application for coherent/elastic technologies also in the metro area.

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