A comparison of elastic and mixed line rate optical slot switching WDM metro rings

Y. Pointurier, B. Ušćumlić, I. Cerutti, J.-C. Antona

***Abstract*—We propose optimal resource allocation techniques for two kinds of optical slot switching metro rings: fixed mixed line rate (fMLR), where the rate of each transponder (TRX) is fixed and set at network planning time, and elastic TRX, which rate may adjust dynamically on a per-slot basis during network operation. We then numerically compare the cost (CAPEX or energy) of fMLR and elastic networks, and investigate the suitability of each of the two considered network technologies for several ring topologies, TRX cost models, and traffic distributions and loads.**

I. Introduction

Optical packet or slot switching has gained attention in the past few years as a technology able to cope with the traffic growth, especially in metro and regional networks. Optical slot switching in synchronous multi-wavelength rings is made possible by the Packet Optical Add-Drop Multiplexers (POADM) proposed in [1]. POADM separates the data channels, which transport data, from the control channel, which carries the header of each synchronous wavelength division multiplexed (WDM) slot. Data channels transit through intermediate nodes transparently, while the control channel is processed electronically at every node. This separation enables POADM to support the statistical multiplexing of slots modulated at different formats and/or rates in the same ring, and potentially even on the same wavelength. Our prior work [2] investigated the problem of optimally designing POADM rings with fixed mixed line rate (fMLR) POADM i.e., each transponder (TRX) can operate at one out of several rates. A dimensioning algorithm was proposed in such a work and the results showed the benefits of fMLR over single line rate in terms of energy efficiency, in fully transparent rings. The concept of *elastic POADM* was introduced for the first time in [3]. In an elastic POADM, each transmitter and receiver is able to change its datarate (and modulation format) on a per-slot basis. The cost comparison (in terms of CAPEX or energy efficiency) between fMLR rings and elastic POADM rings is carried using heuristics in [4] when the transmitters (TX) can tune their emitting wavelength at every slot ("fast wavelength tunable transmitters") whereas receivers are fixed on a pre-determined wavelength ("fixed-wavelength receivers").

Y. Pointurier and J.-C. Antona are with Alcatel-Lucent, Bell Labs, Route de Villejust, 91620 Nozay, France (e-mail: yvan@ieee.org).

B. Ušćumlić is with Institut Mines Telecom, Telecom Bretagne Technopôle Brest Iroise, CS83818, 29238 Brest, Cedex 3, France.

I. Cerutti is with Scuola Superiore Sant'Anna, 56124 Pisa, Italy.

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This paper investigates the following trade-off: the flexibility brought by elasticity (any TRX can communicate with any other TRX — unlike in the fMLR scenario where TRX working at different rates cannot communicate together) decreases the number of TRX in the network, but an elastic TRX is on average more expensive than a fixed-rate TRX. This paper builds on [2] and [4], and provides a three-fold contribution. Instead of heuristics, this paper proposes *optimal techniques* for designing fMLR and elastic POADM rings. Unlike the fully transparent fMLR scenario [2], this paper investigates the impact of the transparent reach limitations, which are dependent on the modulation format. Finally, fast-wavelength tunability is enabled at the TX and also at the RX, leading to a different optimization problem. This work shows that elastic POADM rings can save up to 20% of the total TRX cost (e.g., CAPEX or energy) in optically slotted rings compared with fMLR rings.

The paper is organized as follows. The concept of POADM with an emphasis on elasticity is reviewed in Section II. Then for the first time optimal dimensioning strategies are proposed for elastic POADM and fMLR rings with reach constraints (Section III), and numerically compared in Section IV.

II. Elastic POADM

A POADM node (Fig. 1), can add, drop or let slots transit to the next node on a ring network. The control channel is processed by each node and carries all the headers of the synchronous WDM slots, to enable transparent bypass (no opto-electronic conversion) in the intermediate nodes and dropping at the destination. After a slot is dropped, it can be erased by a fast slot blocker (i.e. an optical gate) so that a new optical slot can be added in the same time-slot, on the same wavelength. Hence, client data is processed in the electronic domain only twice (i.e., at the source and destination node), but still POADM can leverage statistical multiplexing. The POADM node is equipped with fast wavelength-tunable TX [5] and RX. Fast wavelength-tunable RX have received

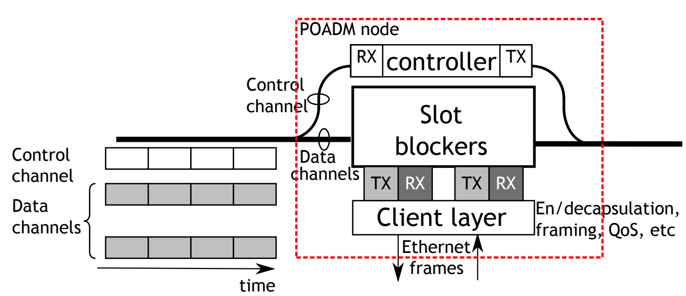

Fig. 1. Optical slot switching POADM node description.

TABLE I
SIGNAL REACH AND COST FOR FIXED RATE AND ELASTIC TRANSPONDERS IN A 4-RATE NETWORK ($\mathcal{R} = \mathcal{R}_4$).

Capacity (m) (Gb/s)	Baud-rate (Gbaud)	Reach ℓ_m (km)	Sample Modulation	TRX cost	
				Fixed rate ($C_{f,m}$)	Elastic (C_e)
3R	R	ℓ	PDM 64-QAM	$1+2\ \alpha$	$1+2\ \alpha$
2R	R	4ℓ	PDM 16-QAM	$1+\alpha$	
1.5R	R	8ℓ	PDM 8-QAM	$1+0.5\ \alpha$	
R	R	20ℓ	PDM QPSK	1	

attention only recently thanks to the advent of coherent modulation formats in optical transmission. The fast-wavelength tunability in a RX is achieved by fast-tuning its local oscillator, as done for the laser at the TX [6] This paper focuses on rings with coherent modulation formats. Coherent equipment also enables elastic POADM, where the modulation format used by a TRX can easily be changed through digital signal processing [3]. The use of more complex modulation formats leads to higher channel capacity, but limits the maximum transparent reach of the signal. In this paper, four modulation formats are considered as indicated in Table I [7], [8]. Hence, in the absence of opto-electronic regeneration (as in the case in POADM rings) the maximum rate achievable between 2 nodes depends on the distance between the nodes. In the following, CAPEX or energy consumption is the optimization metric. Considering a fMLR network and an elastic network where the same datarates are available, elastic TRX have the same cost independently of the modulation format while the cost of a fixed-rate TRX grows linearly (with parameter α) with the datarate. Other cost models could easily be considered.

III. RESOURCE ALLOCATION ALGORITHMS

This section presents the optimal TRX allocation strategies for the fMLR and the elastic scenarios; specifically, fMLR rings are dimensioned by solving a Mixed Integer Linear Programme (MILP) proposed in Section III-A, and elastic rings are dimensioned using a polynomial-time algorithm proposed in Section III-B. Without loss of generality the following algorithms are given for unidirectional rings, but can be easily adapted to bidirectional rings after a routing strategy (e.g. shortest path, least hops, etc.) is used to determine on what direction slots are sent. Slot scheduling and stability issues are not considered in this paper.

A. MILP formulation for reach-dependent fMLR POADM ring

Parameters:

$G = (V, E)$: graph with vertices V and unidirectional edges E, that models the unidirectional ring network of interest;
$\mathcal{T}$: matrix indicating the demands of client frame streams, $T_{s,d}$, from node s to node d, expressed in b/s;
$\pi_{s,d}$: set of the links used by the path from s to d;
$\mathcal{R}$: set of transmission rates that the ring can support, i.e., $\mathcal{R} = \{m_1, \ldots, m_{|\mathcal{R}|}\}$, expressed in b/s;
W: maximum number of wavelength channels;
B_m: capacity (in b/s) of wavelength channels at rate m;
$L_{s,d}$: length of the route from s to d;
ℓ_m: reach of a signal modulated at rate m;
$C_{f,m}$: cost of a WDM fixed-rate TRX at rate m.

Variables:

$p_{s,d}^{w,m}$: indicates the amount of traffic of the demand $T_{s,d}$ carried on wavelength w at modulation (rate) m;
u_k^m: variable indicating the number of TRX at node k at rate m on node k;
$x_{s,d}^{w,m}$: binary variable indicating whether the demand $T_{s,d}$ is assigned to wavelength w and rate m.

Formulation:

Objective function:

$$\min \sum_{m\in\mathcal{R}} \sum_{k\in V} C_{f,m} u_k^m \tag{1}$$

Subject to:

$$\sum_{m\in\mathcal{R}} \sum_{w=1}^{W} p_{s,d}^{w,m} = T_{s,d} \qquad \forall s,d \in V \tag{2}$$

$$\sum_{w=1}^{W} \sum_{d\in V} p_{s,d}^{w,m} \le B_m u_s^m \qquad \forall s \in V, \forall m \in \mathcal{R} \tag{3}$$

$$\sum_{w=1}^{W} \sum_{s\in V} p_{s,d}^{w,m} \le B_m u_d^m \qquad \forall d \in V, \forall m \in \mathcal{R} \tag{4}$$

$$\sum_{m\in\mathcal{R}} \sum_{(s,d):(i,j)\in\pi_{s,d}} \frac{p_{s,d}^{w,m}}{B_m} \le 1 \qquad \forall (i,j)\in E, \forall w \tag{5}$$

$$p_{s,d}^{w,m} \le B_m x_{s,d}^{w,m} \qquad \forall s,d \in V, \forall w, \forall m \tag{6}$$

$$\sum_{m\in\mathcal{R}} x_{s,d}^{w,m} \le 1 \qquad \forall s,d \in V, \forall w \tag{7}$$

$$p_{s,d}^{w,m} = 0 \qquad \forall s,d \in V, \forall w, m \text{ s.t. } L_{s,d} > \ell_m \tag{8}$$

The objective function (1) aims at minimizing the cost for TRX in the network. Constraint (2) defines how demands are split across the wavelengths and assigned different rates. Constraints (3) and (4) ensure that at any given node there are enough TRX at rate m for transmitting (receiving) data from (to) such node. Constraint (5) ensures that the wavelength capacity is not exceeded. Constraint (6) assigns a binary variable to each traffic stream. Each traffic stream is forced to be assigned a single rate, for any given wavelength in constraint (7). The signal reach constraint (8) ensures that signals at some rate m do not propagate on a route that is longer than the maximum transparent reach ℓ_m.

B. Algorithm for an elastic POADM ring

The same notation as in Section III-A is used here to describe a resource allocation algorithm in the elastic case. Note that, with elastic TRX, the resource allocation consists in allocating at each node a number of identical TRX, such that traffic T can be carried; cost minimization in this case is strictly equivalent to TRX number minimization. We propose the following polynomial algorithm to allocate elastic TRX, which can be easily proved to be optimal.

The proposed algorithm uses the notion of "resource utilization", which is the average fraction of the time that a resource is utilized (at any rate), as a metric. For each demand $T(s,d)$ the utilization $U(s,d)$ of a TX on node S and a RX at node d is computed as follows: $U(s,d) = T(s,d)/B_{s,d}$, where $B_{s,d} \in \mathcal{R}$ is the maximum achievable rate given the transmission length from s to d. Note that using a resource at its maximum available datarate for a demand ensures maximum availability of the resource for other demands. In terms of resource utilization, this means that each elastic TX deployed at s and each elastic RX deployed at d is used during time fraction $U(s,d)$ to carry demand $T(s,d)$. Since all TX and RX are wavelength tunable, the whole ring capacity is available to any TX and RX. The amount of transmitting hardware needed to support demand $T(s,\cdot)$ from node s to any other node is $\lceil \sum_d U(s,d) \rceil$, and the amount of receiving hardware needed to support demand $T(\cdot,d)$ to node d from any other node is $\lceil \sum_s U(s,d) \rceil$. Thus, the number of elastic TRX required in the ring is $\sum_k \max\{\lceil \sum_d U(k,d) \rceil, \lceil \sum_s U(s,k) \rceil\}$.

IV. Simulation results

We consider fMLR and elastic bidirectional POADM rings with N nodes; for simplicity, we assume that the distance between 2 adjacent nodes is constant and equal to D km. The model can easily be extended to networks where fiber lengths are arbitrary. The baseline rate is R=100 Gb/s. The considered modulation formats and the corresponding transparent reaches and TRX costs are given in Table I (setting ℓ=100 km). We set $W = 80$ channels. A single rate scenario ($\mathcal{R} = \mathcal{R}_1 = \{R\}$) is compared with mixed rate scenarios at 2 rates ($\mathcal{R} = \mathcal{R}_2 = \{R, 1.5R\}$), 3 rates ($\mathcal{R} = \mathcal{R}_3 = \{R, 1.5R, 2R\}$) or 4 rates ($\mathcal{R} = \mathcal{R}_4 = \{R, 1.5R, 2R, 3R\}$). Recall that an elastic TRX supporting rates $\mathcal{R}$ is as expensive as a fixed-rate TRX supporting the same maximum rate. If the highest available rate is used on very few routes/supports little traffic, then expensive TRX are deployed in the elastic case while in the fMLR case only a few expensive TRX working at the maximum rate are deployed. In this case a fMLR network is bound to be less expensive than an elastic network. Elastic networks can be cost-effective only if there is a diversity of the maximum achievable rates over the set of routes.

To better understand when elastic networks have a potential to be more cost-effective than fMLR networks, Fig. 2 reports the proportion of the routes (assuming that traffic is uniformly distributed over all pairs of nodes) of the network that support each available rate, for several network scenarios (varying number of nodes N and link length D), and when the maximum available rate in the network varies between 1 rate ($\mathcal{R}_1$) and all 4 rates ($\mathcal{R}_4$; x-axis of each subfigure). Each bar of each subfigure of Fig. 2 depicts a separate network scenario. For instance, for N=10 nodes and D=25 km, if a network designer is willing to deploy TRX up to rate $2R$ (third bar of Fig. 2(d)), all routes could use $2R$ TRX, but if D=100 km (keeping N=10 nodes and $\mathcal{R} = \mathcal{R}_2$; Fig. 2(s)), then only 80% of the routes could use $2R$ TRX while the remaining 20% would be restricted to TRX working at rate of (at most) $1.5R$. Overall, elastic rings can be more cost-efficient than fMLR only in the scenarios corresponding to non-plain bars in Fig. 2. Indeed in a scenario corresponding to a plain bar

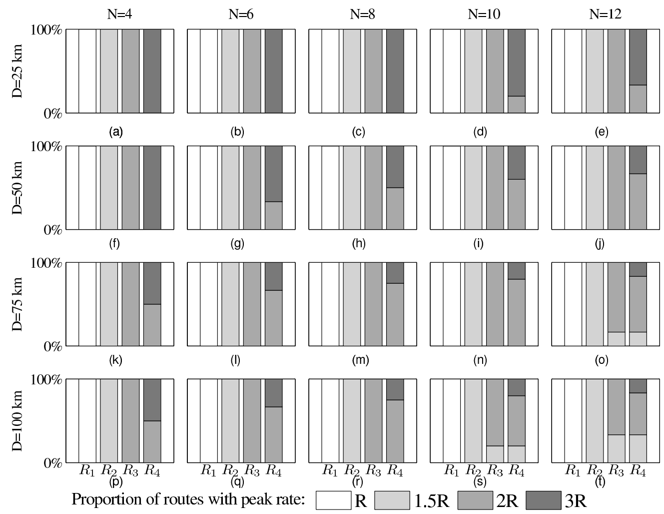

Fig. 2. Distribution of the maximum usable rates across all network routes, assuming uniform traffic demand over all pairs of network nodes; each subfigure corresponds to a different network sizes (N, D); each bar corresponds to a set of available rates: $\mathcal{R}_1$, $\mathcal{R}_2$, $\mathcal{R}_3$, or $\mathcal{R}_4$.

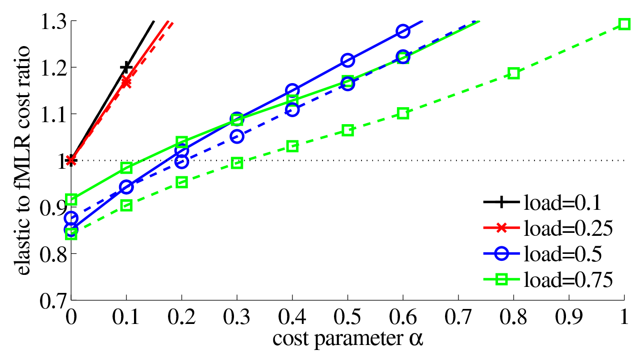

Fig. 3. Cost of elastic vs. fMLR networks for N=6 nodes, D=50 km, 4 rates ($\mathcal{R} = \mathcal{R}_4$). Plain lines: uniform traffic, dashed lines: gravity traffic. There is no difference between uniform and gravity cost ratios for load=0.1.

the elastic TRX can be replaced with a less expensive fixed-rate TRX working at peak rate yielding a fMLR dimensioning at a lower cost: in most optical slot switching metro network scenarios, fMLR networks are actually more cost-efficient than elastic networks.

Hence, we focus on scenarios where the peak achievable rate is not the same for all routes, i.e. scenarios corresponding to non-unicolor bars in Fig. 2. Two traffic distributions are considered: uniform ($T(s,d)$ over all (s,d) pairs) and gravity in which the traffic $T(s,d)$ is inversely proportional to the square distance, measured in terms of hops, between s and d. The load of the network is defined as the average demand between two nodes and normalized by rate R, that is, a unit demand corresponds to an average demand between 2 nodes s and d of $T(s,d) = R$ b/s. Each reported datapoint is the average of 20 independent simulations.

Fig. 3 reports the cost ratio between an elastic and a fMLR 6-node ring for uniform (plain lines) and gravity traffic (dashed lines) for several loads, D=50 km, and when all 4 rates (R, 1.5R, 2R, 3R) are available. Points below the $y = 1$ horizontal line correspond to networks where elasticity brings

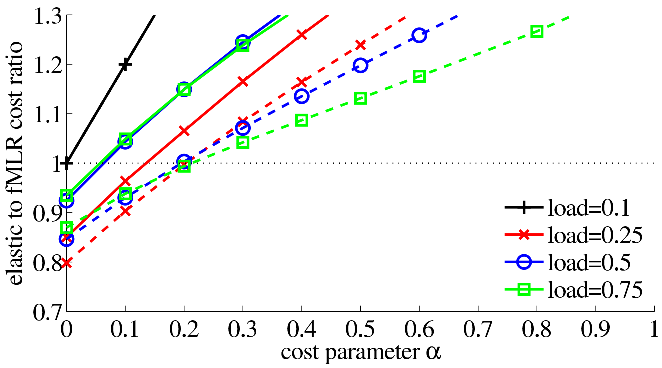

Fig. 4. Cost of elastic vs. fMLR networks for N=10 nodes, D=100 km, 4 rates ($\mathcal{R} = \mathcal{R}_4$). Plain lines: uniform traffic, dashed lines: gravity traffic.

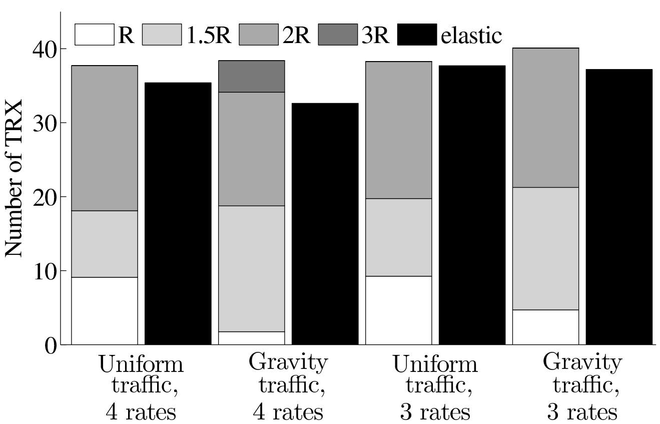

Fig. 5. Number of transponders (N=10 nodes, D=100 km) when the number of available rates is either 3 or 4, for cost factor α=0.2.

a cost advantage. If the dependence of the TRX cost with its maximum rate is weak (α closer to 0), the elasticity can lead to saving of up to a 15% cost gain w.r.t. fMLR. When the load is low (load=0.1 or 0.25) there is no benefit in deploying an elastic network: the load can be supported with fixed TRX working at a low rate. In [4] we reported the existence of a value of the load that maximizes the gains in cost of the elastic ring. This "optimal" load, where elastic has the highest gain over fMLR depends on α and the traffic distribution.

Fig. 4 reports the elastic vs. fMLR cost ratio for an N=10-node ring and shows that the elastic network is less expensive than the fMLR network (by up to 20%) for very few scenarios. In the left part of Fig. 5 we show for a given cost factor $\alpha = 0.2$ and load=0.5R the number of TRX deployed in the fMLR case for each of the 4 available rates, and in the elastic case, for uniform and for gravity traffic. In the fMLR case, very few of the expensive 3R TRX are deployed, while the elastic network by construction deploys only TRX with highest cost $1+2\alpha$. In the right part of Fig. 5 the number of deployed TRX are reported when only 3 rates are allowed ($\mathcal{R} = \mathcal{R}_3$). Now all modulation formats are used more evenly in the fMLR network, hinting at higher potential savings in elastic networks, in which the TRX cost is now only $1 + \alpha$ (cost of a fixed TRX working at the highest available rate). This is confirmed in Fig. 6, where network costs are given when only 3 rates

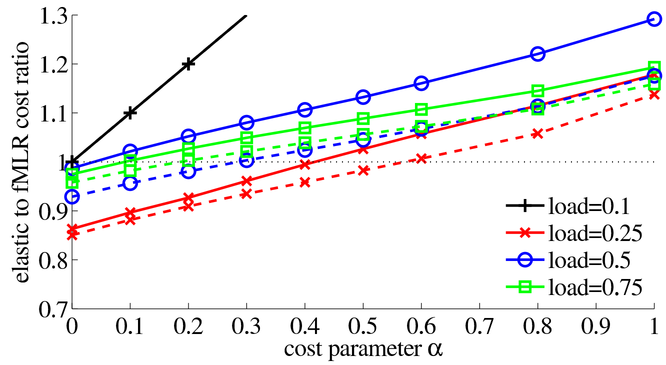

Fig. 6. Cost of elastic vs. fMLR networks for N=10 nodes, D=100 km, 3 rates ($\mathcal{R} = \mathcal{R}_3$). Plain lines: uniform traffic, dashed lines: gravity traffic.

are available. Finally, Figs. 3, 4 and 6 indicate that the gains of elasticity are generally higher with gravity traffic than with uniform traffic as the elastic TRX are more suitable to support the high traffic between closer nodes experienced in a gravity traffic pattern.

V. Conclusions

The paper proposed optimal dimensioning techniques for elastic and fMLR optical slot switching networks and showed that fMLR networks are typically more cost-efficient than elastic networks, although gains of up to 20% are possible in certain conditions in elastic networks. Whether elastic networks are more cost-effective than fMLR networks strongly depends on the number of rates, TRX cost structure, network load and size. In particular, increasing the number of available rates in an elastic network does not necessarily result in higher cost savings, as the additional complexity (and hence cost) for a larger number of available rates may be exploited only by few routes to be worth deploying. The optimization problem can be extended to include the issue of slot scheduling stability as proposed in [9].

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