

Resource Requirements in Mixed-Line Rate and Elastic Dynamic Optical Networks

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Abstract: We estimate through a probabilistic model and simulations the sharing potential of rate-adaptive transponders in dynamic optical networks and draw comparisons with mixed-line-rate networks, showing up to 40% saving potential for adaptive solutions.

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1. Introduction

Traffic demands in core networks are characterized by their strong heterogeneity on at least two counts: firstly, they may vary in capacity requirements (typically from tenths to tens of Gigabits per second); secondly, the distances over which such capacities need to be transported may also vary by an order of magnitude or more (e.g. from a few hundred kilometers to several thousands in an American backbone). Mixed-line rate (MLR) networks have been shown to be a cost-efficient solution to address this heterogeneity of the traffic matrix [1]. MLR networks indeed use different types of transponders to serve different demands balancing the capacity and distance requirements of the demand with the optical reach and cost of the different types of transponders. MLR networks however require one to commit a precise number of transponders for each line-rate in each node of the network depending on the specifics of the traffic matrix and may therefore struggle with changes in the distribution of traffic (e.g. because of the emergence of new applications) or in the network topology (e.g. fiber cut requiring optical restoration of a large number of demands).

An almost exactly opposite approach is that proposed by elastic optical networks (EON), whereby a single type of rate-adaptive transponder is used to serve all demands. While rate-adaptive transponders may be individually more expensive than MLR transponders, their increased potential for sharing and re-use may drive the overall cost of the network below what is possible with MLR architectures[2][3].

The aim of this article is therefore to quantify the resource requirements in both MLR and EON in dynamic optical networks and to assess the merits of each solution in terms of resilience to changes in the traffic matrix. For that purpose, in section 2 we propose a probabilistic model estimating the number of transponders of each type to be deployed in each node for the simplified case of completely transparent networks. In section 3, we turn to network simulations to assess the validity of the aforementioned model and measure the impact of complex but crucial issues in practical networks, such as the need for regeneration and wavelength conversion.

2. Transparent networks

We consider an N -node network in which n random demands need to be routed. Each demand may be assigned to any node pair with equal probability and requires a capacity C_i with probability x_i ($i=1 \dots m$ with m the total number of available line rates). The exact number of transponders at rate C_i that must be installed in each node to guarantee a given blocking probability is a complex function of the network topology, number of wavelengths per fiber and optical reach of wavelength with datarate C_i . We may however estimate it assuming the network to be fully-transparent, namely assuming regeneration is never necessary whether that be for maintaining a high-enough quality of transmission or for wavelength contention issues.

The probability of a random demand to originate in a given node and require a capacity C_i is x_i/N so that the probability $P_{k,i}$ that k demand among n originate in this node, all k requiring a capacity C_i is given by the binomial distribution

$$P_{k,i} = \binom{n}{k} \left(\frac{x_i}{N} \right)^k \left(1 - \frac{x_i}{N} \right)^{n-k}$$

The mean number of demands at rate C_i is then $\bar{n}_i = nx_i/N$ and the variance $\sigma_i^2 = n \cdot (x_i/N) \cdot (1 - x_i/N)$. One may now provision $(\bar{n}_i + q\sigma_i)$ transponders at rate C_i in each node where q measures the acceptance rate of demands. For large n , the binomial distribution is very well approximated by a normal distribution so that $q=1, 2$ and 3 correspond to acceptance rates of 74.1%, 97.8% and 99.8% respectively.

The total number of transponders to be deployed in the network for a MLR network, $N_{TSP,MLR}$, is therefore:

$$N_{TSP,MLR} = 2 \cdot N \sum_{i=1}^m \left(\frac{nx_i}{N} + q \sqrt{\frac{nx_i}{N} \left(1 - \frac{x_i}{N} \right)} \right) = 2n + 2q\sqrt{n} \sum_{i=1}^m \sqrt{x_i \cdot (N - x_i)}$$

where the factor of 2 is due to each demand requiring one transponder at the source and one at destination. In an fully transparent elastic optical network, the distinction between line-rates is irrelevant and the number of required transponders $N_{TSP,EON}$ for the whole network is therefore $N_{TSP,EON} = 2n + 2q\sqrt{n}\sqrt{N-1}$ (i.e. setting $m=1$, $x_i=1$ in the formula for $N_{TSP,MLR}$). The transponder saving brought by rate-adaptive transponders with respect to comparable MLR networks is therefore:

$$S_{TSP} = \frac{N_{TSP,MLR} - N_{TSP,EON}}{N_{TSP,MLR}} = \frac{q \left(\sum_{i=1}^m \sqrt{x_i \cdot (N - x_i)} - \sqrt{N-1} \right)}{\sqrt{n} + q \sum_{i=1}^m \sqrt{x_i \cdot (N - x_i)}} \quad \text{Eq(1)}$$

In figure 1(a) we illustrate the evolution of S_{TSP} when scaling the total number of demands n from 50 to 500 in a 31-node network assuming 3 datarates (e.g. 10Gb/s On-Off Keying, 40Gb/s partial Differential Phase Shift Keying and 100Gb/s Polarization-Division-Multiplexed Quaternary Phase Shift Keying). We consider either a uniform distribution of demands among all three rates (triangles) or a more realistic tilt towards low datarates with 10, 40 and 100G demands in a 50:35:15 ratio (circles). We also consider two acceptance rates for connection, namely $q=2$ (dashed lines) and $q=3$ (solid lines).

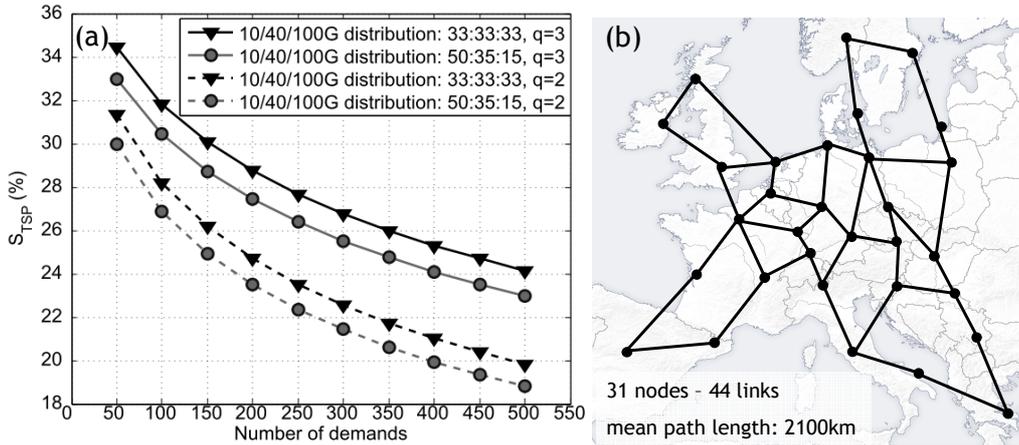


Figure 1: (a) Transponder savings of 10/40/100G EON w.r.t 10/40/100G MLR fully transparent network for two distributions of datarates (triangle and circle markers) and two acceptance rates (dashed and solid lines). (b) Topology and main characteristics of the network used for simulation

Three points are worth noticing. Firstly, the savings brought by elasticity are sizeable across the whole range of network load considered, typically above 20% and reaching 30% at low loads. Secondly, the more one wants the network to be resilient to variations of the traffic matrix (i.e. the higher the value of q), the higher the benefits of EON are. Finally, the savings due to the sharing capability of rate-adaptive interfaces are all the more important that demands are distributed evenly across the range of available datarates.

3. Partially transparent networks

While the model of the previous section allows one to identify important trends in the comparison of EON and MLR networks, it cannot easily be extended to take into account important features such as the exact topology of the network, the different reaches of different datarates and issues such as wavelength contention. In order to probe these aspects, we have run dynamic network simulations for a 31-node European network (ref?). Demands arrive to the path computation engine (PCE) following a Poisson distribution with mean arrival rate λ . They are allocated a random lifetime drawn from an exponential distribution with mean μ and a datarate $C_i \in \{10,40,100\}$ Gb/s with probability x_i . The product $\lambda \cdot \mu$ is adjusted so as to reach a target value for the mean number of connections in the network. The PCE allocates a path using a Dijkstra algorithm, reserving add/drop resources at either end of the path and resources along the path whenever the signal needs to be regenerated or converted to a new wavelength. In order to compare the sole effect of transponder sharing, we choose the reach of 10, 40 and 100G to be identical in MLR and EON and equal to 3000, 1600 and 800km respectively [3].

For each value of the product $\lambda\mu$ (ranging from 50 to 500 demands in the network on average), we simulate the evolution of the network over the set-up and tear-down of 10000 demands, keeping track of the number of transponders that need to be provisioned in each node so that all demands are served. The simulation is repeated 15 times for each value of $\lambda\mu$.

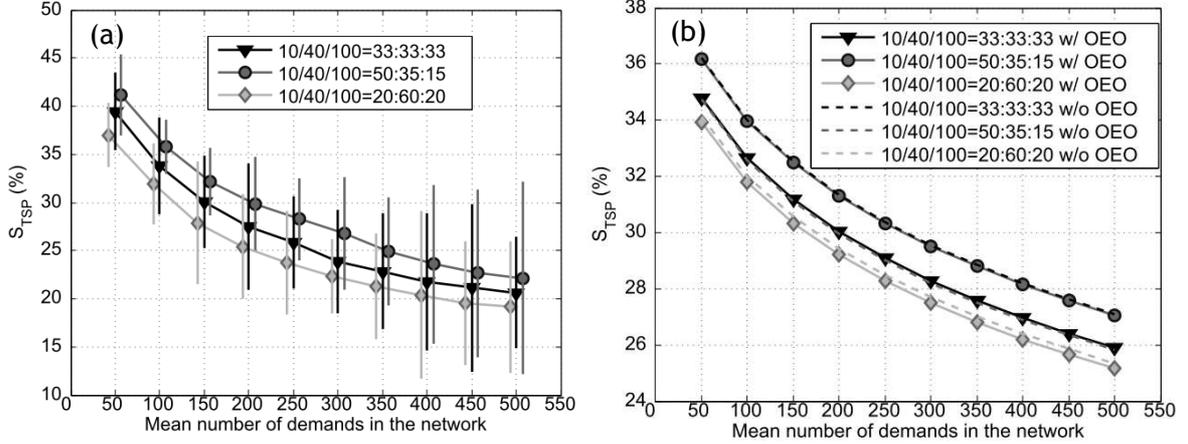


Figure 2: (a) Transponder savings of 10/40/100G EON w.r.t 10/40/100G MLR in partially transparent network for three distributions of demands. Markers are offset for the sake of clarity. (b) Estimation of transponder savings through Eq(1) with and without correction for regeneration requirements (solid and dashed lines respectively)

In figure 2(a) we report the average reduction on the number of transponders S_{TSP} brought by EON over MLR architectures for three distributions of x_i . The evolution of S_{TSP} with the average number of demands in the network $\lambda\mu$ is in line with the findings of section 2 as is the magnitude of S_{TSP} (from approx. 40% at low loads to 20% at high traffic volumes). Simulations were run over 10000 demand arrival and with the provisioning of enough transponders to avoid blocking, i.e. corresponding to $q \sim 4$ or beyond.

The smaller-scale features of figure 2(a) are somewhat in disagreement with the simplified model of section 2 (dashed line in figure 2(b)). We indeed find that S_{TSP} is larger when the traffic is split 50:35:15 amongst 10, 40 and 100G demands (circles) than when all three line-rate are requested with equal probability (triangles). This can be attributed to the very different reaches of 10, 40 and 100Gb/s wavelengths and thus the very different average number of optoelectronic (OEO) regenerations required for demands at different rates. Averaging over all shortest paths in the network, we find the average number of required regeneration per demand $n_{OEO,i}$ to be 0.2, 0.86 and 2.6 respectively for $i=10,40$ and 100G respectively. The proportion of transponders at rate C_i to be deployed is thus no longer determined by the probability x_i but by its value renormalized to the mean number of required transponder per demand $x_i' = x_i(1 + n_{OEO,i}) / \sum_j x_j(1 + n_{OEO,j})$.

Feeding the values of x_i used earlier into this formula, we find $x' = [0.2, 0.3, 0.5]$ when $x = [0.33, 0.33, 0.33]$ and $x' = [0.36, 0.37, 0.27]$ when $x = [0.5, 0.35, 0.15]$. The latter values of x' are much more evenly distributed than the former and thus help explain the difference in behaviour between figure 1(a) and 2(a).

More generally, based on this consideration, one can extend the simple model of Eq(1) to partially transparent networks, provided we substitute x_i' for x_i . The results of this substitution are shown in solid lines in Fig 2(b) and qualitatively reproduce the trends of the simulations presented in Fig 2(a).

4. Conclusion

We have proposed a simple formula to assess the reduction in number of transponders allowed by dynamic elastic optical networks with rate-adaptive interfaces with respect to mixed-line rate networks relying on the same set of datarates. Checking it against detailed network simulation, we find that elastic network may provide up to 40% transponder savings in networks resilient to variations of the traffic matrix.

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