Efficiency gain from elastic optical networks
Invited paper

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ABSTRACT

We compare the cost-efficiency of optical networks based on mixed datarates (10, 40, 100Gb/s) and datarate-elastic technologies. A European backbone network is examined under various traffic assumptions (volume of transported data per demand and total number of demands) to better understand the impact of traffic characteristics on cost-efficiency. Network dimensioning is performed for static and restorable networks (resilient to one-link failure). In this paper we will investigate the trade-offs between price of interfaces, reach and reconfigurability, showing that elastic solutions can be more cost-efficient than mixed-rate solutions because of the better compatibility between different datarates, increased reach of channels and simplified wavelength allocation.

Keywords: Coherent communications, communication system nonlinearities, communication system planning, wave-length-division multiplexed (WDM).

1. INTRODUCTION

Due to the increase of traffic and the limited number of wavelengths per fiber, transmission technologies with ever higher spectral-efficiencies are required. A first step towards enhancing the spectral efficiency of a network is to increase the datarate per wavelength, for instance through multi-level modulation formats, as for the introduction of 40Gb/s channels and now 100Gb/s optoelectronic interfaces [1]. The presence of these high-datarate interfaces means that near future optical transport networks will carry channels having different rates: 10, 40 and 100Gb/s, or higher (400 Gb/s to 1 Tb/s [2] have actively researched based on higher-level, M-ary, modulation formats).

While the signal is transmitted with higher spectral efficiency, its transparent distance (i.e., the maximal distance that the signal covers ensuring a bit error rate – BER – lower than a defined threshold) tends to sharply decrease because it becomes more sensitive to physical impairments occurring during its transmission.

Mixed-rate networks relying on different technologies for each datarate have been extensively studied [3], often referred to as mixed line rates (MLR) networks. These studies show that data-rate diversity is required to optimize the cost (and energy consumption) of translucent optical network in order to address the heterogeneity of traffic demand in terms of sizes and distances to be covered. Low datarates remain interesting because of the price erosion of mature technologies while higher rates are introduced to reduce the spectral occupancy of high capacity requests. However, MLR leave very little place for reconfiguration [4] and conflicting requirements between different generations of technologies make it hard to use all datarates at their full potential jointly [5].

At the same time, another network model, referred to as “elastic optical networks”, proposes to use a single type of optoelectronic (OE) interface to handle all connection rates. These rate-tunable interfaces will simplify the design of network and allow optimal sharing of resources in dynamic networking scenarios, though at the cost of a high price per piece of equipment [6], [8].

So far, the benefits of elastic technologies have been studied with a number of metrics such as number of interfaces or occupied bandwidth [6], [7]. In this article, we present an analysis of the network efficiency of dynamic optical networks in terms of required OE interfaces and cost by comparing them to the MLR networks for static and restorable networks.

2. CONCEPTS OF FORMAT-VERSATILE TRANSCEIVERS BASED ON 100Gb/S PDM-xPSK TRANSMISSION SYSTEM

Various schemes have been proposed in the literature enabling “elastic” (or “adaptive” or “software-defined”) transmission systems. Most have focused on orthogonal frequency division multiplexing (OFDM) modulation formats for that purpose [9]-[11]. While OFDM indeed provides almost unlimited control on the achievable data rate and spectral efficiency of each optical channel, it is still a long-term prospect for industrial purposes, in particular due to the need for high-speed electronics and digital signal processing both at the transmitter and receiver ends. In this following we present an elastic network solution based on 100Gb/s Polarization-Division-Multiplexed Quaternary Phase Shift Keying (PDM-QPSK) transceivers adapted for modulation-format versatility. This solution is based on currently available on the market 100Gb/s devices [1] and thus amenable to short term applications.

The basic architecture of such 100Gb/s PDM-QPSK transponders is briefly summarized in **Figure 1**. Such modulation format allows data to be encoded on four phase states for each of two orthogonal polarizations of the light, giving a good balance between: a spectrum width compatible with current high-speed electronics; reasonable transceiver complexity; and tolerance to physical impairments.

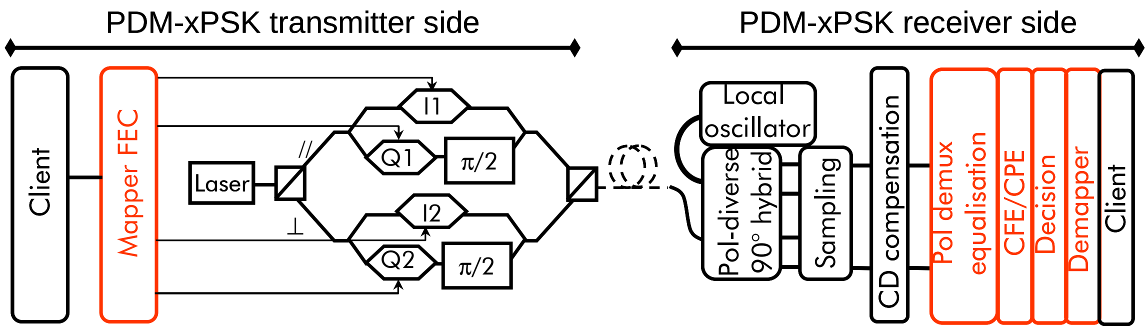

Figure 1: Example of a versatile PDM-xPSK transponder architecture. Left-hand side: transmitter, right-hand side: receiver. The red boxes indicate the parts of the transmitter and receiver sides that require a redesign compared to the legacy 100 Gb/s PDM-QPSK transponder architecture.

2.1 PDM-xPSK transmitter

The modulator used to generate PDM-QPSK consists of nested Mach-Zender interferometers (MZI), phase-shifter and polarization beam-splitters (PBS). Figure 1 shows the corresponding set-up consisting of a continuously operating laser source, a PBS to split the light along two orthogonal polarization states (indicated by ⊥ and // in Figure 1), a conventional splitter to further divide light into two paths of equal intensity, two MZIs operating as phase modulators, an optical phase shifter in one of the path, a combiner and a polarization beam-combiner (PBC) to produce a single-output signal. The four inner MZI are driven with four independent 28Gb/s electrical signals I1, Q1, I2, Q2 modulating the in-phase and quadrature components of the X and Y polarizations of the light allowing communication at 100Gb/s , accounting for 12% overhead for error correction and framing.

By changing the modulation signals of the MZI, one can generate various datarates (25, 50, 75 and 100Gb/s which we refer to collectively as PDM-xPSK) with variable spectral efficiency. Simple logic operations between I1, Q1, I2 and Q2 allow one to modify the PDM-QPSK emission scheme to encode either 1, 2, 3 or 4 bits per symbol. This allows communication at 1R, 2R, 3R or 4R where R is the symbol rate, provided the DSP on the receiver end is able to adapt to different modulation formats. The parts of the transponder that require a redesign compared to the 100 Git/s architecture of **Figure 1** are shown in red.

Using identical driving signals for in-phase and quadrature modulation in a polarization (I1=Q1 or I2=Q2) makes it only possible to encode the 00 and 11 words on this polarization [6]. This is strictly equivalent to a Binary Phase Shift Keying (BPSK) signal, but for an irrelevant $\pi/4$ rotation. Forcing I1=Q1 and I2=Q2 thus generates a 50Gb/s PDM-BPSK signal. Similarly, forcing the modulation to be identical on both polarizations (I1=I2, Q1=Q2) turns a PDM signal into a Single Polarization (SP) signal modulated along the X+Y polarization. Using identical driving signals in all the inner MZI (I1=Q1=I2=Q2) thus straightforwardly generates a 25Gb/s SP-BPSK signal [6]. Little different is the realization of the 75Gb/s rate, which is realized using polarization-switched (PS) QPSK [12] modulation format. The PS-QPSK is obtaining driving independent binary sequences for the three modulators I1,Q1, I2, while for the remaining Q2 the sequence is obtained operating two XOR on the previous sequences, i.e. Q2= I1 XOR Q1 XOR I2.

2.2 Coherent Receiver

Thanks to coherent detection [13] it is possible to linearly sample in-phase and quadrature components of the received optical signal. Again, in Figure 1 we have marked in red the parts of the legacy 100Gb/s PDM-QPSK receiver requiring a redesign. It is expected that the whole format-versatile PDM-xPSK transponder will have a cost very similar to that of the 100Gb/s receiver it is derived from.

3. NETWORK MODEL AND SIMULATION HYPOTHESES

3.1 Network model

To perform the comparison between the two network solutions (elastic and MLR) we consider a European-like backbone network. This network comprises 31 nodes and 44 bidirectional links. A summary of the network characteristics is given in Table 1.

Characteristics of the European backbone network		
Node connection	Mean	2.9
	Max	4
Link length	Mean	575 (km)
	Max	800 (km)
	Min	218 (km)
Shortest path length	Mean	1700 (km)
	Max	5000 (km)
	Min	218 (km)

Table 1: Description of the European network used for simulation results.

Each link is assumed to be made of SMF spans carrying up to 80 wavelengths spaced fixed on a 50GHz grid in the C-band and a single fiber per direction is deployed. The carried traffic will vary from 1 to 25Tb/s, demands are drawn between nodes following random and distance-correlated distributions; the capacity of demands is normally distributed with mean varying from 10 to 80Gb/s.

We assume that the cost of a network design is largely dominated by the price of the optoelectronic interfaces (emitters, receivers and regenerators) it requires. Moreover, as we suppose to have only one fiber per link, other network elements, such as optical amplifiers or optical cross-connects, are expected to be very similar in numbers and cost for both network solutions.

3.2 Cost and physical assumption

For the MLR network we suppose the two transmission scenarios: the first is based on 10Gb/s On-Off Keying (OOK) with quadratic detection, 40Gb/s partial Differential PSK (pDPSK) with differential detection and 100Gb/s PDM-QPSK with coherent detection. About the first MLR scenario, the price of OE interfaces is assumed to be 1, 3 and 6 respectively, which is balanced between mature and bleeding-edge cost models [4]. The transparent reach available is assumed to be 3000, 1600 and 800km for 10, 40 and 100Gb/s respectively. To mitigate the deleterious effect of OOK channels on phase modulated 100Gb/s channels [5] we divide the optical comb into different bands where each different datarates are routed; 40G pDPSK channels act as buffer between 10 and 100G wavelengths.

The second transmission technology scenario considers only coherent PDM formats and the 40Gb/s transmission is now based on PDM Binary Phase Shift Keying (PMD-BPSK). In this second MLR scenario, where 10Gb/s interfaces are not present, the 40Gb/s interface cost is modified because of the more complex modulation format and required receiver, reaching 5 a.u. In this scenario, 100Gb/s reach is now 1200km. The 400km increased reach of 100Gb/s in this scenario is due to the combined effects of (i) the absence of OOK channels in the fiber [5], (ii) the absence of dispersion management, lowering slightly the noise figure of optical amplifiers and improving the resistance to non-linearities [14]. In the same settings, 40Gb/s channels transparently reach 2500km. Moreover, because all channels are phase modulated, no band partition is performed in the following.

Concerning the elastic network scenario, we consider OE interfaces generating PDM-xPSK described in Section 2. The price of such interfaces is expected to be very similar to the price of 100Gb/s interfaces and for this reason is set to 6. The transparent distance available at 25, 50, 75 and 100Gb/s is assumed to be 3000, 2400, 1600 and 1200km [7].

Cost and transparent reaches for MLR with two and three possible datarates are summed up in Table 2, while data about elastic networks are summarized in Table 3.

Mixed-rate network (3 rates)		
Datarate (Gb/s)	**Price (a.u)**	**Reach (km)**
10	1	3000
40	3	1600
100	6	800

Mixed-rate network (2 rates)		
Datarate (Gb/s)	**Price (a.u)**	**Reach (km)**
40	5	2500
100	6	1200

Table 2: Cost and reach estimation model for optoelectronic interfaces in mixed-rate networks working at three (left hand side) and two (right hand side) datarates.

Elastic network		
Datarate (Gb/s)	Price (a.u.)	Reach (km)
25	6	3000
50		2400
75		1600
100		1200

Table 3: Cost and reach estimation model for optoelectronic interfaces in elastic networks.

3.3 Restoration assumption

The benefits of using elastic devices are linked to their ability to adapt their datarate to meet planned (e.g. upgrades) or unexpected (e.g. failures) evolution of the network conditions. Indeed, if a new connection has to be established, any available elastic OE interface can be used and it is not necessary to check beforehand if an available interface is able to support the required datarate. Today, dynamics in the optical layer stands mainly for the capability of the network to reconfigure itself after a failure arises. For this reason hereafter we dimension the OE devices required by both the networks so as they are resilient to all possible single-link failures.

4. RESULTS

The planning algorithm for dimension the network for static situations (no failure events) is detailed in [15], while the procedure for computing the number of spare resources is explained in [16].

4.a 10-40-100Gb/s MLR vs elastic networks

The first comparison between the MLR and elastic scenarios present the global cost of the network for a static dimensioning as a function of the traffic load. In this section the average demand capacity is 60Gb/s. The presented results show the number of required resources and their relative cost for the MLR and elastic network scenarios. The elastic network here has only three possible datarates (i.e. 25/50/100Gb/s).

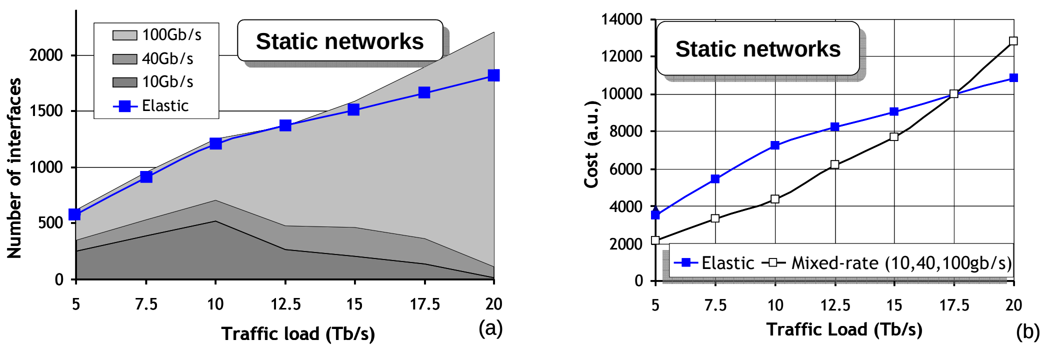

Figure 2: Number of interfaces required for the mixed–rate and elastic networks (a) and whole cost of the two network scenarios (b) as a function of the transported traffic load, static dimensioning is performed.

Figure 2(a) shows the total number of interfaces required for the MLR and elastic networks. The number of interfaces required for elastic networks is always lower than that required for the MLR scenario. In figure 2(a) we have also depicted the allocation of 10, 40 and 100Gb/s resources for the MLR scenario. We notice that for low traffic loads many low-cost 10Gb/s interfaces are used, while with the increase of traffic load more and more 100Gb/s interfaces have to be used so as to reduce demand blocking. The use of 10Gb/s interfaces will provide blocking because of the large use of spectral resources and the necessity to route different datarates in separate bands of the spectrum, producing spectrum waste. The high number of 100Gb/s interfaces in MLR scenario is mainly due to the datarate band separation in MLR scenario: to avoid demand blocking a larger bandwidth for 100Gb/s has to be reserved, forcing the use of 100Gb/s interfaces for low datarate demands. Furthermore in MLR scenario suffer from short reaches for 100Gb/s so that a higher number of regenerators is required. This explains the 22% further interfaces required for 20Tb/s compared to elastic networks, where it is much easier to adapt the datarate of the used interfaces to the demand capacity and the distance that has to be reached. If now we weight the number of used interfaces by their relative cost (Figure 2(b)), we notice that at low network loads we find as expected that MLR solutions are very cost-efficient: they require marginally more interfaces than elastic networks but a large part of these interfaces are very low-cost 10Gb/s cards. When the traffic load increases, the cost benefit of mixed-rate solutions slowly vanishes, because of the high requirement of 100Gb/s interfaces that have the same price as elastic ones.

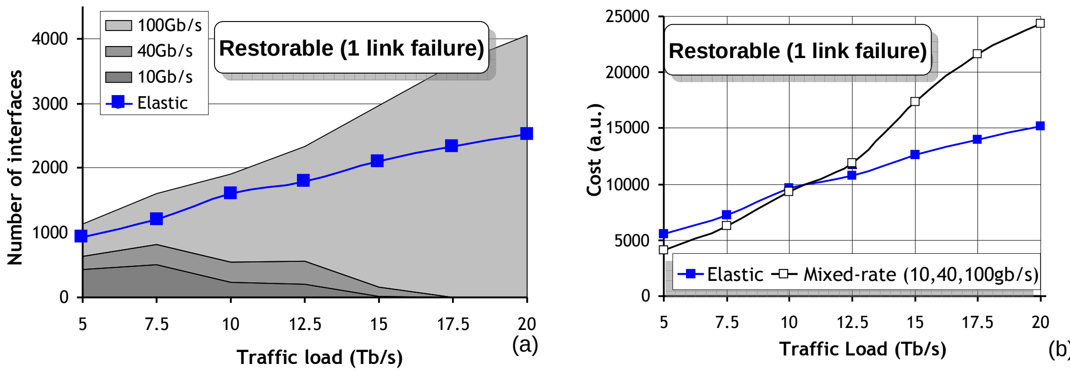

Figure 3: Number of interfaces required for the mixed–rate and elastic networks (a) and whole cost of the two network scenarios (b) as a function of the transported traffic load, the dimensioning is performed such as the network is resilient for one link failure.

In restorable networks due to reconfiguration requirements, the benefits of elasticity become more visible. The number of resources required for the restorable network is computed considering the amount of resources required to set-up the nominal path and then all the spare resources (wavelengths and types of optoelectronic devices) required for the rerouting of the failed paths. In elastic networks the same spare interfaces can be used for restoration, independently of the datarate of failed paths; while for MLR scenarios, different spare interfaces must be provisioned as a function of the datarates of the failed path, thus limiting the sharing capability and requiring a higher number of spare resources [15].

In figure 3(a) we notice that even for low datarates a large amount of 100Gb/s interfaces are required for MLR. This is above all due to the need of free wavelengths in each of the datarate band for allowing restoration; this forces the RWA process to preferentially target high-datarates to free up part of the spectrum, which means an increased need for regeneration, in particular in MLR scenarios.

The requirement of dedicated spare resources per each datarate present in the MLR and because of the large amount of regenerators used when 100Gb/s interfaces are used, MLR scenario uses more interfaces than elastic one (from 15% to 45% for low and high traffic loads, respectively). If now the number of interfaces is weighted by the interface cost unit, as shown in figure 3(b), we observe that for low traffic load the MLR is more efficient only of 20% (compared to 85% of static networks) and with the increase of the network load elastic networks become more 40% efficient than MLR networks (compared to 12% in static scenario), the tipping point between the two solution being at approximately 10Tb/s.

4.b 40-100Gb/s MLR vs elastic networks

In this section we want to estimate the interest of a higher-performance MLR scenario, by using PDM transmission and coherent reception for both 40 and 100Gb/s transmission reaching longer distances, as indicated in Table 2. At the same time we want to investigate the interest of having finer granularities for the elastic scenario passing from three and four datarate tunability : 25/50/100Gb/s and 25/50/75/100Gb/s, respectively. The cost comparisons between MLR and elastic networks are based on cost values presented in Table 2 and are shown in Figure 4(a) for static scenarios and 4(b) for restorable scenarios.

The increase of high datarate reaches for the MLR design and the lack of 10Gb/s have reduced the cost gap between MLR and elastic networks for low traffic: MLR is only 15% more cost-efficient independently on the number of datarate granularities for elastic networks. With the increase of the traffic load, the advantages of elastic networks reached 15% and 20% as a function of the elastic interface granularity possibility, three and four respectively. The cost efficiency of elastic networks is due to their capability to better adapt the datarate of interfaces to the distance that has to be covered. This capability is better observed when the transponder tunability ranges over four possible rates.

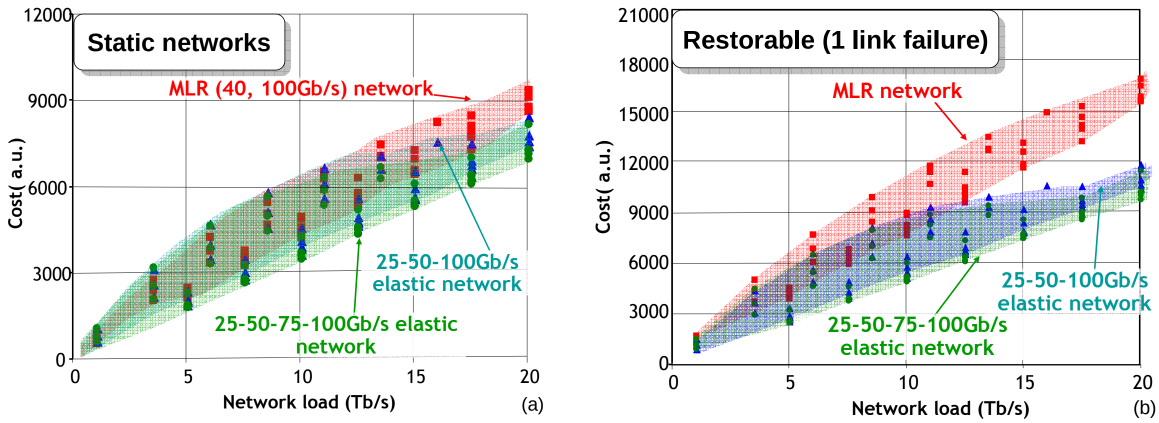

Figure 4: Cost comparison between fixed and elastic datarate networks for static (a) and restorable (b) network dimensioning.

Again, the benefits of elasticity are more significant for reconfigurable networks, as reported in Figure 4(b) where the whole cost of the network is computed for a network resilient to one link failure. The cost benefits of elastic networks increase rapidly as the traffic load goes up, reaching 28% and 35% at 20Tb/s for 3 and 4 rate-tunable interfaces, respectively.

The lower cost savings of elastic versus MLR networks (three rate granularities) are mainly due to the increase of unregenerated reach of high datarate interfaces in the MLR scenario, requiring now fewer regenerators, and also to the reduced number of spare interfaces per datarate that have to be provisioned.

4. Conclusion

In this paper we have estimated the trade-offs between price of interfaces, reach and reconfigurability of mix-line-rate and elastic translucent transport networks. Such comparisons have been performed considering for the mix-line-rate scenario the presence or absence of detrimental 10Gb/s OOK modulated channels, while for the elastic networks we have considered optoelectronic device able to tune among three or four rate granularities (i.e. 25/50/100Gb/s and 25/50/75/100Gb/s).

In all cases elastic networks are more cost-efficient for high traffic load and such advantages are more evident when network reconfiguration (1 link failure resiliency in this study) is required, because of the reduction of spare resources they allow through sharing capability. The benefits of elastic networks are higher when the MLR scenario presents 10Gb/s interfaces (because of the need of spectral separation between datarates and the reduced transmission reach of higher rates): up to 22% and 40% for static and restorable networks. On the other hand, if only 40 and 100Gb/s channels are transported in mix-line-rate networks, the benefits of elastic networks for higher loads reaches 15% and 28% for static and restorable networks when three rate granularities are considered, and increases to 20% and 35% when the elastic interface can tune four rates.

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