Scaling Regional Optical Transport Networks with Pluggable and Integrated High-Capacity Line Interfaces

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Abstract: This paper provides insight on the role of next-generation coherent interfaces and use of an extended C-band to cost-effectively scale regional transport networks. © 2020 The Author(s)

1. Introduction

The first three generations of coherent technology were developed consecutively and introduced key features such as higher order modulation formats and higher baud rates [1] to allow up to 600 Gb/s per interface and fine-grained capacity and reach trade-off. Nowadays, two different generations of coherent technology are reaching commercial maturity. On one hand, driven by growth in DCI applications, low-cost, interoperable and short-reach pluggable coherent interfaces, such as OIF's 400ZR [2] are becoming available, and serving as basis for improved versions, relying on better FEC and modulation format and symbol rate adaptation to enable longer reaches. These interfaces are labeled as OpenZR+ and OpenROADM [3] and target metro network deployments. On the other hand, high-end coherent (HEC) interfaces are pushing technology boundaries with symbol rates up to 100 Gbaud, probabilistic shaping (PS) and digital subcarrier multiplexing (DSCM) [4], enabling up to 800 Gb/s per interface, high spectral efficiency and fine-grained capacity and reach trade-off. These features make them ideal for long-haul and subsea applications as well as for demanding shorter reach deployments. Despite being complementary in terms of target applications, both interface generations may contend in regional networks deployments. Cost-effectively scaling these networks will be paramount for service providers in the medium-term [5]. This can be attained with one or more of the following strategies: (i) using more spectral efficient channel formats; (ii) exploiting spectrum bands beyond the C-band; and (iii) lighting more fibers. Adding fibers can be expensive [5], particularly if no dark fibers are available. Exploiting the C+L-band has been shown to be a viable option [6], albeit it requires additional filters and amplifiers, and transmission impairments can increase the complexity of planning and operation. Alternatively, a simpler upgrade is to expand the usage of the C-band and use the 6 THz of the SuperC or C++ band [7].

This paper provides a comparative analysis of scaling a regional transport network using either OpenZR+ or HEC interfaces and in combination with exploiting the SuperC-band or selectively deploying additional fibers. The results highlight the effectiveness of using HEC interfaces and SuperC-band to postpone costly fiber roll outs, while providing insight on the relative cost of both interface types that determines which one will be more cost-effective.

2. High-Capacity Coherent Interfaces

The OpenZR+ interfaces can support 400G, 300G, 200G (60 Gbaud) and 100G (30 Gbaud), whereas HEC interfaces can support a multitude of different channel formats. For simplicity, in this work it is assumed that the latter support 800G (96 Gbaud), 700G (91 Gbaud), 600G (96, 84 Gbaud), 500G (91, 84 Gbaud) and 400G (84, 63 Gbaud). In both cases it is assumed that a line card can host two interfaces, enabling to set up a media channel (MCh) with one or two carriers (supporting inverse multiplexing of a 400 GbE signal via two 200G channels). Table 1 highlights some of the key differences between both interface technologies. For each optical channel format considered, the required optical signal-to-noise ratio (ROSNR) for error free transmission and other relevant parameters such as, maximum tolerable accumulated chromatic dispersion, penalty from polarization dependent losses and transmitter output and receiver input power ranges were obtained based on data collected from different suppliers and experimental results.

Table 1. Qualitative comparison of OZR+ and HEC interfaces.

	OZR+	**HEC**
Type	Pluggable (QSFP-DD, CFP2)	Integrated
Maximum capacity	400G	800G
Capacity increments	Coarse-grained 100G	Fine-grained 25G
Symbol rate	Variable up to ~63 Gbaud	Variable up to ~100 Gbaud
FEC	Open FEC	Proprietary FEC
Optical performance	Baseline: limited by form factor, interoperability requirements	Enhanced: e.g., exploiting PS, DSCM, better DSP

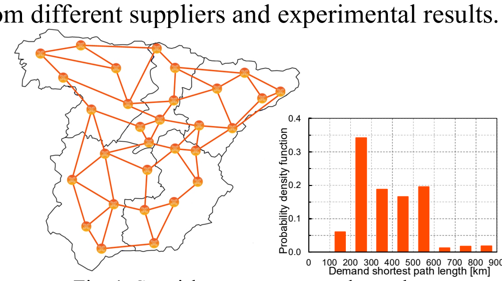

Fig. 1. Spanish transport network topology.

3. Network Scenario and Design Methodology

A reference network topology of regional size is considered. As shown in Fig. 1, it covers Spain and comprises 30 ROADM nodes and 56 bidirectional links. These links have a total of 122 spans of SSMF, which is characterized by an attenuation of 0.21 dB/km, a non-linear coefficient of 1.07 W^{-1}/km, a dispersion parameter of 16.8 ps/nm/km and a Raman gain of 0.43 $(W\cdot km\cdot Hz)^{-1}$. The traffic spatial distribution is as in [8], corresponding to the probability density function in Fig. 1. Client traffic to be supported consists of 100 GbE and 400 GbE (even mix in volume).

The ROADM nodes have a route-and-select express layer using 1x20 WSSs and a colorless add/drop layer based on 1x16 splitter/combiners (includes an EDFA). Key properties such as insertion losses, filter shape and EDFA gain and noise figures are based on commercial devices. In-line EDFAs have a 6 dB noise figure. Frequency slots with 75, 100 and 112.5 GHz are assigned to channels with 60/63, 84 and 91/96 Gbaud, respectively. The 4.8 THz C-band comprises the [191.325, 196.125] THz window, while the 6 THz SuperC-band exploits the [190.725, 196.725] THz window. The possibility to increase capacity by selectively adding new fibers is considered via a simple algorithm: (i) set the target number of additional links; (ii) order existing links by decreasing traffic load based on routing demands using the C-band only; (iii) use a round-robin algorithm to select the next existing link to be duplicated.

A routing, modulation format and spectrum assignment (RMSA) algorithm is used to set up the traffic demands such that minimizing cost (number of line cards/interfaces) is the primary optimization criteria, whereas minimizing spectrum usage is the secondary one. The algorithm routes traffic demands sequentially and for each demand, it checks if there is an established MCh with enough capacity to accommodate the demand. In case there is, the demand is routed over it. Otherwise, a new MCh must be set up. It considers a set of K shortest paths and each candidate path/MCh format is evaluated with the format selection algorithm below to select the best one. Spectrum is assigned to new MChs according to the first-fit algorithm. In case no solution is found the demand is blocked.

The quality of transmission of each MCh to be set up is assessed using the incoherent Gaussian noise model for estimating the impact of nonlinear fiber interference (NLI). To (i) account for the impact of inter-channel stimulated Raman scattering (SRS), which is higher when using a wider spectrum of the optical fiber, while (ii) maintaining a reasonable computational complexity, the closed-form approximation in [9] was implemented. The total available signal-to-noise ratio (SNR) of an optical channel is given by (1), where $OSNR_{add}$, $OSNR_{exp}$ and $OSNR_{drop}$ are the OSNR at the add, express and drop ROADMs, respectively, whereas S and L are the number of fiber spans and links traversed, respectively. The equivalent SNR after transmission along fiber span k is estimated with (2), where P_{Rx} and P_{ASE} are the average optical signal and amplified spontaneous emission (ASE) noise power levels, respectively. The NLI contribution to noise, P_{NLI}, is obtained using equations (10) and (11) of [9] to compute the contributions from self-phase modulation and cross-phase modulation, respectively. The launch power is optimized per span [10]. Using this approach, Fig. 2 plots the NLI coefficient for a 74.3 km span of the network assuming full channel load and 3.6 dBm launch power. Finally, the residual margin is obtained from (3) by subtracting from the total available SNR the required OSNR of the MCh format, the penalty due to cascaded WSS filtering [11], the penalty from accumulated polarization dependent losses and a system margin to account for other effects. A 1 dB system margin is assumed. Noteworthy, the worst performing channel is considered as reference when optimizing the launch power and MChs are only usable by the RMSA algorithm if they are feasible in the entire spectrum.

$$\frac{1}{SNR} = \sum \frac{1}{SNR} + \frac{1}{OSNR} + \frac{L-1}{OSNR} + \frac{1}{OSNR} \quad (1)$$

$$SNR = \frac{P}{P \quad + P} \quad (2) \qquad RM = SNR_{eq,tot} - ROSNR - P_{filt} - P_{PDL} - SM \text{ [dB]} \quad (3)$$

Sequential Best Fitted Capacity (S-BFC) media channel format selection

Input: Unrouted demand set D, demand being routed d, set of K paths Π_d, MCh format list Φ, where $\Delta(\phi)$ is the spectrum usage of $\phi \in \Phi$.

1. Select all unrouted demands between same node pair as d, D'.

2. For each path and MCh format pair (π, ϕ), with $\pi \in \Pi_d$, $\phi \in \Phi$, create an auxiliary graph G' with nodes representing ROADMs over π and links representing feasible MChs (with $RM \geq 0$ and available spectrum). Set link cost according to number of line interfaces required to carry D'.

3. Compute the lowest cost solution (i.e., with minimum interface count Ω).

Output: Routing path π^* and MCh format ϕ^* that minimize interface count Ω^*, breaking ties with the format that minimizes spectrum usage $\Delta(\phi)$.

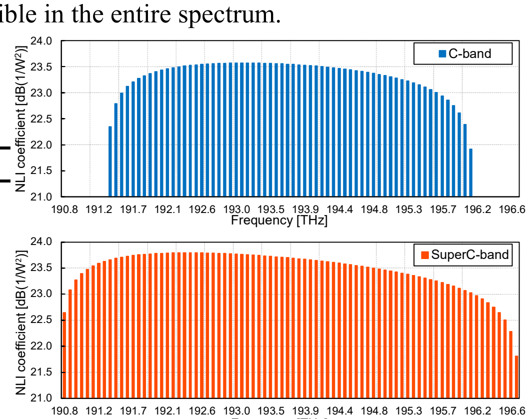

Fig. 2. NLI coefficient for 74.3 km SSMF span with OZR+.

4. Results and Discussion

The described optical performance model and RMSA algorithm were implemented in an event-driven simulator and used to design the referred transport network. Five different configurations were considered: exploiting C- versus SuperC-band over the original fiber infrastructure with both types of interfaces and leasing/rolling-out additional fiber for up to 30% of the most congested links combined with using the C-band and OZR+ interfaces. Figure 3(a) plots the traffic load successfully carried and the blocked one as a function of the total traffic load offered to the network. All results are the average of 50 independent simulation runs. As expected, when the amount of available spectrum increases, either by using the SuperC-band or via additional fibers, the network can carry more traffic load. Table 2 summarizes the traffic load that leads to a bandwidth blocking probability of 1%, highlighting that a 29% and 25% additional traffic load can be supported when exploiting the SuperC-band instead of the C-band and using HEC and OZR+ interfaces, respectively. Moreover, for the same spectrum window, the utilization of HEC instead of OZR+ interfaces allow increasing the traffic load by 24% and 27% when considering the C- and the SuperC-band, respectively. Importantly, as shown in Fig. 3(b), significant savings in the number of line interfaces are possible with HEC interfaces, ranging from 33 to 40% fewer interfaces than when deploying OZR+ in the cases considered. This difference in interface count can be used to have a first estimate of how cost competitive each interface technology must be with respect to the other in a regional transport network deployment. Another interesting result is that by combining the use of the SuperC-band (6 THz) with HEC interfaces, it is possible to support more traffic load than that when duplicating the fiber infrastructure in the 30% most congested fiber links but using only the C-band and OZR+ interfaces (162 vs. 148 Tb/s). A more detailed analysis of the simulation results is presented in Table 3 for an offered traffic load of 146 Tb/s, showing the former configuration requires 40% fewer line cards/interfaces, 23% fewer WSSs, 39% fewer tributary cards and 22% fewer in-line EDFAs, while also avoiding to lease/roll-out 21% extra optical fiber. This provides evidence that the combined use of HEC interfaces and the SuperC-band can enable a service provider of a regional network to maximize the return on investment of the existing fiber infrastructure.

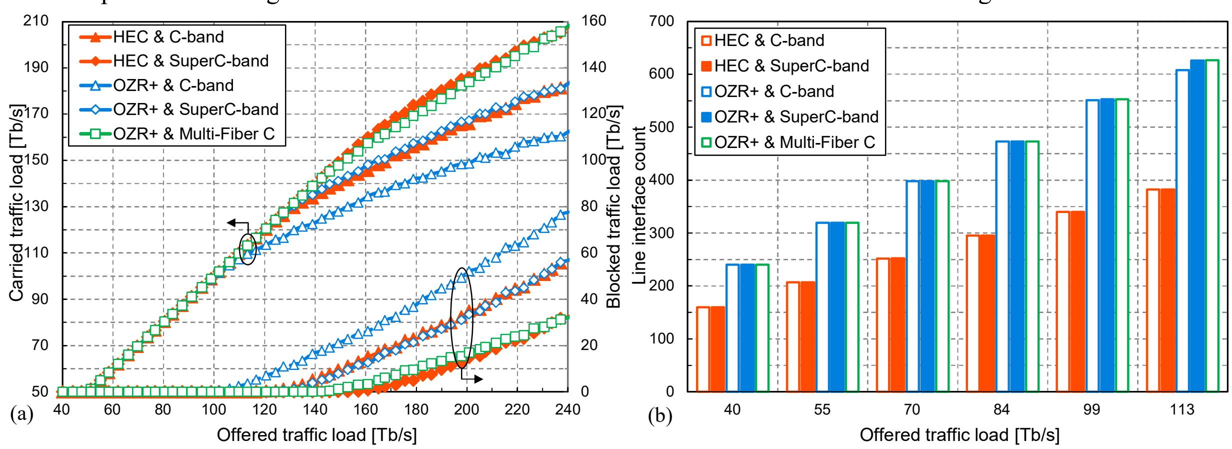

Fig. 3. Network carried and blocked traffic load (a) and number of line interfaces required (b).

Table 2. Network carried traffic load for target bandwidth blocking probability of 1%.

IF Type	Spectrum	Traffic Load
HEC	C-band	126 Tb/s
	SuperC-band	162 Tb/s
OZR+	C-band	102 Tb/s
	SuperC-band	128 Tb/s
	Multi-fiber C	148 Tb/s

Table 3. Hardware and fiber comparison for offered traffic load of 146 Tb/s.

	HEC & SuperC	OZR+ & Multi-Fiber C
Line card count	243	402
Interface count	486	796
R&S card count	112	146
Tributary card count	51	83
In-line EDFA count	66	85
Total fiber amount	8 312 km	10 548 km

5. Conclusions

This paper has provided insight on the importance of using high-end coherent interfaces to extend the lifespan of the deployed fiber infrastructure on a regional transport network. Firstly, they maximize the traffic load carried over line systems exploiting only the C-band. Secondly, when combined with SuperC-band, they enable to scale the network capacity beyond what can be achieved with pluggable interfaces and deploying additional fibers in 30% of the most congested links. Importantly, this is attained with 40% fewer line interfaces, an approximate figure of how cheaper pluggable interfaces must be compared to high-end ones to be cost competitive in this network scenario.

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