Value Proposition of High Capacity and Flexible Line Interfaces in Next-Generation Transport Networks

João Pedro[1,2], João Santos[1], Nelson Costa[1]
[1] Infinera Unipessoal Lda, Rua da Garagem 1, 2790-078 Carnaxide, Portugal
[2] Instituto de Telecomunicações, Instituto Superior Técnico, Avenida Rovisco Pais 1, 1049-001 Lisboa, Portugal
{JPedro, JoaSantos, NCosta}@Infinera.com

Abstract—**This paper provides a comprehensive comparative analysis of the impact of deploying state-of-the-art high capacity and flexible line interfaces instead of lower cost optical interfaces, which natively target data center interconnection (DCI), in metro and regional networks. With that aim, the media channel (MCh) formats supported in both cases are introduced and a set of MCh provisioning algorithms to mimic network operation over multiple periods is described. Simulation results obtained in two reference networks highlight the hardware savings and extended amount of carried traffic enabled by the former type of interfaces. Moreover, it provides insight on the (i) relevance of selecting the most suitable MCh provisioning algorithm depending on network topology and traffic pattern and on the (ii) impact of implementing lower cost interfaces having different performance and cost trade-offs.**

Keywords—coherent interfaces, network design, optical network

I. Introduction

Steady traffic growth trends keep network operators under pressure to reduce the cost per bit transported. Attaining this goal requires adopting several strategies, such as increasing the capacity per optical interface [1] and adopting disaggregated and open line systems [2] to reduce capital expenditures (CAPEX), as well as relying on progress in software and automation to reduce operational expenditures (OPEX) [3]. The higher growth in DCI applications is setting the stage for investigating low cost and interoperable short-reach coherent interfaces, such as the ones addressed in the 400ZR project [4]. Eventually, the same technology can be exploited for longer reach applications, albeit at the expense of lower per channel capacity [5]. This means that these ZR-based interfaces would compete with traditional high capacity state-of-the-art coherent interfaces in metro or even regional network deployments. Importantly, significant progress is being reported with the latter optical interfaces. Particularly, higher symbol rates and more sophisticated modulation formats, such as time domain hybrid quadrature amplitude modulation (TDHQAM) and probabilistic amplitude shaping (PAS), hold the promise of higher capacity per interface, media channels (MCh) formats with higher spectral efficiency (SE), and the flexibility to adapt the MCh format to the path characteristics.

This work describes a comprehensive framework to gain insight on how both types of coherent interface are expected to perform in metro and regional networks. Firstly, the network scenario considered is described, which includes a simplified modelling of both types of interfaces, detailing the MCh formats supported. Secondly, a network design framework is introduced, comprising a model to estimate the performance of the MChs and a set of MCh provisioning algorithms that are used to set up new MChs to route client traffic demands. Using one metro and one regional reference networks, a multi-period planning of these networks supporting 100 and 400GbE client signals is simulated with the aim to assess the (i) hardware count, in terms of line interfaces, line cards and tributary cards, as well as the (ii) traffic load that can be successfully routed over the original fiber infrastructure. Note that the latter impacts the need to lease/roll-out additional fibers. The simulation results clearly show that high capacity and flexible interfaces, despite their higher unit cost, can provide significant hardware savings, while also enabling to postpone investments in augmenting network capacity. The extent of these benefits is scenario-dependent, with hardware savings being more expressive in the metro network and additional carried traffic load more pronounced in the regional one. In addition, it is shown that the best-performing MCh provisioning algorithm is also scenario-dependent. Finally, the results also include a sensitivity analysis of different implementations of the lower cost coherent optical interfaces.

II. Network Scenario

A. Open Line System and SDN Control

The emergence of standard small form-factor pluggable transceivers (such as 400ZR) can be viewed as another advance towards disaggregated optical networks. For instance, the Open ROADM multi-service agreement [6] promotes a disaggregated data plane architecture including ROADMs, transponders and pluggables. In a compliant deployment, the network operator can mix and match systems from different vendors with full interoperability. Such flexible ecosystem can foster competition, speed-up innovation and improve operational efficiency. Since Open ROADM and similar efforts are work in progress and generalized adoption has not been yet achieved, intermediate solutions, such as open line system (OLS), are being introduced. In an OLS, disaggregation takes place not within but between the line system and the transponders. Therefore, ROADMs can be from a single vendor while preserving the ability to add/drop/switch optical signals using transponders from distinct vendors. However, due to proprietary digital signal processing (DSP) implementations, transponder interworking is restricted to the same vendor. Nevertheless, with standardized pluggable coherent interfaces such limitation is also obviated.

This work was supported by the H2020 Metro-Haul project (761727), by FCT/MCTES through national funds and when applicable co-funded EU funds under the project UIDB/EEA/50008/2020.
978-3-903176-21-8

Apart from the data plane, OLS and disaggregated networks also require a different approach for the control plane. In both network scenarios, the ROADMs and transponders must be reachable via standard northbound APIs (e.g., NETCONF) and use open YANG data models, as defined in OIF, ONF, Open ROADM and OpenConfig. The management of these elements is the responsibility of an orchestrator that can be assisted by layer-specific controllers (e.g., packet controller for L3 devices). With an orchestrator supervising and controlling all network elements, advanced network usage strategies can be seamlessly implemented, such as multi-layer resiliency [3] and restoration based on real-time optical performance monitoring [7].

B. Client and Line Interface Technology

Ethernet client signals are increasingly dominant in transport networks. Currently, 100 GbE client interface deployments are well-matured and growing rapidly, with 400 GbE forecasted to be the next main step in Ethernet client interfaces [8]. Hence, in the medium-term, it is likely that optical transport networks will support a mix of 100 and 400 GbE signals [1].

There are two major streams of development in coherent optical interface technology. In the first one, traditional high capacity interfaces continue to push the boundaries of capacity and spectral efficiency with respect to state-of-the-art. Basically, the support of advanced modulation formats (e.g. 64QAM, TDHQAM, PAS) and the availability of higher symbol rates (in excess of 90 Gbaud) set the stage for the next-generation of high performance optical interfaces [9]. These interfaces will be highly flexible, being capable of varying the modulation format, symbol rate, and FEC such that the MCh format deployed is the one that best fits a given application [1]. In the following, these interfaces are designated as high capacity and flexible (HCF).

The second stream of coherent optical interface technology development targets lower cost power-efficient solutions. Most notably, the OIF's 400ZR project is defining an implementation agreement for single-carrier 400G short-reach DCI [4]. In parallel, ongoing initiatives, such as OpenZR+, intend to relax the strict 400ZR specifications – e.g. 400G, 16QAM, cFEC and under 15 W power consumption – as to leverage the underlying technology to fulfil the requirements of a wider set of applications [5]. Support of lower order modulation formats, adopting other FECs and using improved DSP are among the options. In the remaining of this work, these interfaces are simply denominated as ZR+.

For modelling HCF and ZR+ interfaces, given that both are still under development, a set of assumptions is made. Firstly, the optical transport network is assumed to have ROADM nodes with state-of-the-art flexible-grid wavelength selective switches (WSSs). Optical channels are deployed over frequency slot widths (Δ_f) of 100 or 50 GHz for HCF and of 75 or 150 GHz when using ZR+ interfaces. The symbol rate is upper bounded such that optical filtering penalties are negligible. Expression (1) of [1] estimates the symbol rate f_S for a given target data rate R, number of bits/symbol transmitted log_2m (e.g. for mQAM), number of optical carriers N_C, FEC overhead OH_{FEC} and other overheads (e.g. framing) OH_{nonFEC}. Expression (2) of [1] sets the Δ_f required based also on roll-off factor α and additional guard band B. The latter expression is reworked to determine the maximum symbol rate as a function of Δ_f, B, N_C and α:

$$f_S \leq \frac{\Delta_f - B}{N_C \cdot (1+\alpha)}. \quad (1)$$

Based on this figure and reworking expression (1) of [1], the required number of bits/symbol with a minimum granularity of M_{min} is estimated as:

$$log_2 m \geq \left\lceil \frac{R \cdot (1+OH_{FEC}) \cdot (1+OH_{nonFEC})}{2 \cdot N_C \cdot f_S \cdot M_{min}} \right\rceil \cdot M_{min}, \quad (2)$$

where $\lceil x \rceil$ denotes the ceiling function.

In the scope of this work, the following values are assumed as common to HCF and ZR+: N_C = 1, B = 2 GHz, α = 15%, OH_{nonFEC} = 9%. For ZR+, f_S is fixed to 63 Gbaud, OH_{FEC} = 15% and in addition to the baseline 16QAM [4], 8QAM and QPSK are supported for extended reach. Table I shows the set of ZR+ media channel (MCh) formats supported. In order to transport 400 GbE signals over longer links, configurations based on two carriers using lower order modulation formats are also possible.

For HCF two different maximum values are assumed for f_S: 84 and 39 Gbaud for Δ_f = 100 and 50 GHz, respectively. For simplicity, only OH_{FEC} = 15% is considered. The number of bits/symbol using TDHQAM formats are obtained from (1) with M_{min} = 0.25 bits/symbol. Table II shows the set of MCh formats available with HCF interfaces, in the scope of this work.

TABLE I. MCh FORMATS SUPPORTED WITH ZR+ INTERFACES

Data Rate [Gb/s]	Δ_f [GHz]	Bits/symbol	Modulation Format	SE [b/s/Hz]
400	75	4.00	16QAM	5.33
300	75	3.00	8QAM	4.00
200	75	2.00	QPSK	2.67
600[a]	150	3.00	8QAM	4.00
400[a]	150	2.00	QPSK	2.67

a. Two optical carriers to support 400 GbE signals over longer links.

TABLE II. MCh FORMATS SUPPORTED WITH HCF INTERFACES

Data Rate [Gb/s]	Δ_f [GHz]	Bits/symbol	Modulation Format	SE [b/s/Hz]
800	100	6.00	64QAM	8.00
700	100	5.25	32/64QAM	7.00
600	100	4.50	16/32 QAM	6.00
500	100	3.75	8/16QAM	5.00
400	100	3.00	8QAM	4.00
300	100	2.25	QPSK/8QAM	3.00
300	50	4.75	16/32QAM	6.00
200	50	3.25	8/16QAM	4.00
100	50	2.00	QSPK	2.00

An optical simulator developed in-house is used to estimate the optical performance of the MCh formats shown in Tables I and II. Optical interfaces are modelled using typical parameters. Close to ideal optical performance is obtained in back-to-back (B2B) operation when using lower order modulation formats and lower baud rates. However, non-negligible implementation penalties are obtained for high baud rate and higher order modulation formats. Such penalties arise from the bandwidth limitation of both optical and electrical components, as well as from implementation imperfections both in the transmitter and in the receiver.

Given the power, space and cost constraints that ZR+ implementations may be subject to, there is a higher degree of uncertainty of the required optical signal-to-noise (ROSNR) figures. With the aim of providing a comprehensive analysis, this work assumes four different classes of ZR+ performance, each applying an additional ROSNR penalty with respect to the values computed: Platinum (0.5 dB), Gold (1.5 dB), Silver (2.5 dB), Bronze (3.5 dB). As a guideline, ZR+ Bronze for 16QAM has a ROSNR of 26 dB, which is aligned with the target in [10].

III. Network Design Framework

A. Optical Performance Model

The Gaussian noise approach is used to estimate the impact of non-linear interference (NLI) originated in the optical fiber transmission [11]. Taking into account that the main objective of this work is to compare the potential of different optical line interface technologies and not to do an actual optical network deployment, a rough estimate of the optical system performance is sufficient. Hence, the quality of each MCh is evaluated by calculating the residual margin (*RM*) defined as the difference between the total available *SNR* ($SNR_{eq,tot}$) and the *ROSNR* for a given signal quality in B2B. Incoherent noise accumulation along the link is assumed, which has the advantage of allowing the evaluation of the NLI contribution of each fiber span independently of the remaining spans. Additionally, a local optimization for a global optimization (LOGO) approach can be used in this case for launch power optimization [12]. The total available SNR of each optical channel is given by:

$$\frac{1}{SNR_{eq,tot}} = \frac{1}{OSNR_{add}} + \sum_{k=1}^{S} \frac{1}{SNR_{eq,k}} + \frac{L-1}{OSNR_{exp}} + \frac{1}{OSNR_{drop}}, \quad (3)$$

where $OSNR_{add}$, $OSNR_{exp}$ and $OSNR_{drop}$ are the OSNR at the add, express and drop ROADMs, respectively, in linear units, *S* (*L*) is the number of fiber spans (links) traversed. $SNR_{eq,k}$ is the equivalent SNR after transmission along fiber span *k* [11]:

$$SNR_{eq,k} = \frac{P_{Rx}}{P_{ASE}+P_{NLI}}, \quad (4)$$

where P_{Rx} and P_{ASE} are the average optical signal and amplified spontaneous emission (ASE) noise power levels, respectively, and P_{NLI} is the NLI contribution to noise.

In order to cope with other transmission effects, an additional system margin is also considered. Therefore, the final *RM* of a given MCh is given by:

$$RM = SNR_{eq,tot} - ROSNR - SM \text{ [dB]}. \quad (5)$$

In this work, the system margin (*SM*) has two contributions: a 1 dB margin, set to guarantee that the system still operates correctly after aging and to accommodate the power ripple along the transmission bandwidth and polarization dependent losses, and an additional fixed system margin of 0.05 dB every time a ROADM or amplifier are traversed. Two fiber types are used. SSMF (LEAF) is characterized by a dispersion parameter of 17 (3.8) ps/nm/km, an attenuation of 0.21 (0.22) dB/km and a non-linear coefficient of 1.3 (1.5) W^{-1}/km. A power level per channel of 1 dBm is set at each ROADM input by a pre-amplifier. The optical signal is attenuated by 15 dB in add and drop ROADMs and by 18 dB in pass-through ROADMs. The noise figure of optical amplifiers is set to 5 dB.

B. Provisioning Algorithms

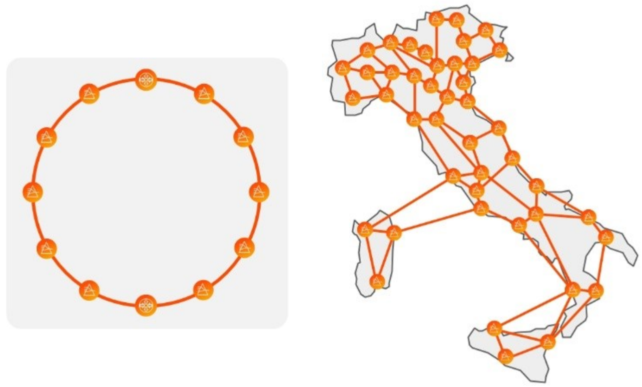
In transport networks, client traffic demands are set up along several periods and, in each period, a routing, grooming and spectrum assignment (RGSA) algorithm is used to determine the resources required to accommodate each demand. A key part of the decision process is the MCh format do deploy, balancing factors such as reach, capacity and spectral occupation. In the scope of this work, it is assumed that the SDN controller sorts all demands to be routed on a given period (e.g. longest distance first) and runs a specific RSGA algorithm. Given the scenario described, demands are aggregated and routed end-to-end (i.e. no intermediate grooming). Moreover, the RSGA algorithm can enforce one of three different options that can impact the MCh format selected in each execution, particularly with respect to capacity, spectral efficiency and spectral occupation.

Input:	Demand, *d*; candidate routing paths, Π; MCh format list, Φ; existing MChs over path $\pi \in \Pi$, $M(\pi)$.
1.	If MCh $m \in M(\pi)$ has idle capacity to support *d*, route *d* over *m*. **End**.
2.	For each MCh format $\phi \in \Phi$ and path $\pi \in \Pi$, create auxiliary graph *G'* with nodes representing physical nodes and links representing feasible MChs (in terms of performance, spectrum continuity and add/drop port availability). Set link cost according to the number of idle interfaces and cards at the edge nodes of the link. Compute lowest cost solutions over the graph (i.e. with minimum number of new line interfaces).
3.	Let $R(\phi)$ and $\Delta f(\phi)$ denote the data rate and frequency slot width of MCh format ϕ. Shortlist MCh formats/paths that minimize the number of new line interfaces/cards and select the optimum solution according to one of the following strategies:
3.1.	**MSE-MaxC** (Most Spectral Efficient – Maximum Capacity)
	Select the MCh format/path with highest SE, i.e., $\max\{R(\phi) / \Delta f(\phi)\}$, and break ties with the one with maximum capacity, i.e. $\max\{R(\phi)\}$.
3.2.	**MSE-MinS** (Most Spectral Efficient – Minimum Spectrum)
	Select the MCh format/path with highest SE, i.e., $\max\{R(\phi) / \Delta f(\phi)\}$, and break ties with the one with minimum spectrum usage, i.e. $\min\{\Delta f(\phi)\}$.
3.3.	**JEC** (Just Enough Capacity)
	Let $r(d)$ denote the data rate of *d* and $\overline{r}(d)$ denote the cumulative data rate of all traffic demands between this node pair. Select the MCh format/path with best capacity fit, i.e. $\min\{R(\phi){:}R(\phi) \geq r(d) + \overline{r}(d)\}$ and break ties with the one with minimum spectrum usage, i.e. $\min\{\Delta f(\phi)\}$.
Output:	Routing path π^*; existing MCh m^* or new MCh with format ϕ^*.

IV. Results and Discussion

A. Simulation Setup

Two network topologies, representative of a metro and of a regional/long-haul network and depicted in Fig. 1, are used: a 12-node ring and the reference Italian backbone network (IBN) of [13]. The ring topology comprises 12 ROADM nodes and 12 bidirectional SSMF links with 80 km each. The longest shortest path between any node pair is 360 km. The IBN has 44 ROADM nodes and 71 bidirectional links, consisting of 200 SSMF and LEAF fiber spans. All ROADMs have a broadcast-and-select express layer and a colorless, directionless add/drop layer with 24-port tributary cards [1]. Only the C-band (4.8 THz) is used.



(a) 12-node ring network (b) Italian backbone network (IBN)

Fig. 1 Reference network topologies.

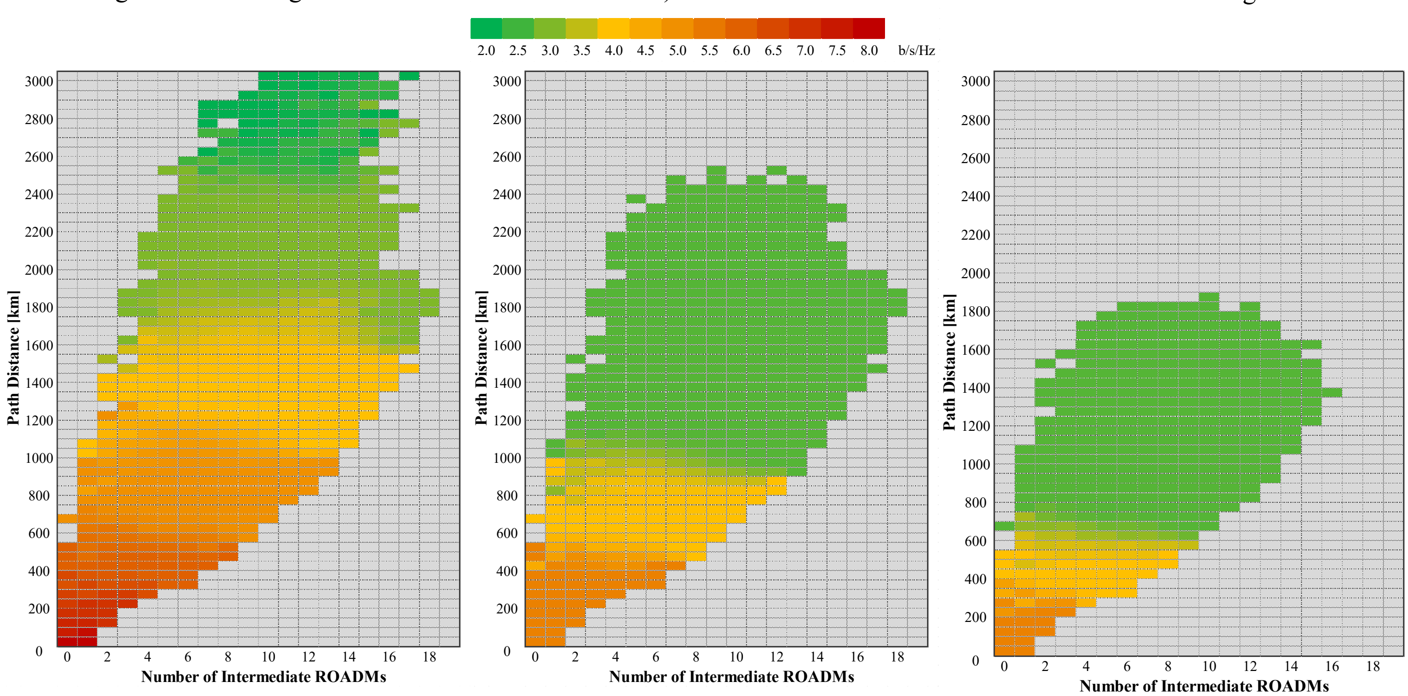
Client traffic is an even mix of 100 and 400 GbE. The traffic load is varied as to consider both lightly and heavily loaded cases. For each load figure, 50 independent traffic traces are generated and the simulation results presented are the average value of all 50 simulations. In the ring network, all nodes can exchange traffic. Node pairs including one of the two hub nodes have in average 3 times more offered traffic. In IBN, the spatial traffic pattern given in [13] is used to generate the traffic traces. It assumes that 590 node pairs (out of 946) exchange traffic with varying probabilities between different node pairs. Multiple period planning is assumed: (1) 20 periods without traffic churn; (2) 50 periods with 30% traffic churn per period.

Shortest path routing is used in the 12-node ring, whereas the 5 shortest (distance) paths are considered when routing over the IBN. First-fit spectrum assignment is enforced. Simulation results are obtained with the MCh format selection algorithms described in Section III.B when using HCF interfaces (no impact when using the different algorithms for the set of ZR+ formats).

B. *Simulation Results*

The first set of results intends to give insight on the expected impact from the differences of performance and SE of HCF and ZR+ interfaces. For that purpose, for every node pair the 100 shortest paths are computed in the IBN and the most spectral efficient format is identified. All paths are then grouped in bins according to their length (in 50 km steps) and hop count and the average SE of the paths in each bin is computed. Figure 2 depicts the resulting SE heatmap for HCF, ZR+ Gold and ZR+ Bronze interfaces. Two main observations are due. Firstly, it clearly highlights the reach differences between the three cases: HCF interfaces enable to transparently bridge considerably longer paths than ZR+ interfaces, with ZR+ Gold outperforming ZR+ Bronze. Secondly, it also highlights that for many sets of paths having the same length and hop count characteristics, HCF interfaces allow to use MChs with higher SE. This is particularly visible, for example, for shorter paths. However, the heatmap does not reflect the frequency with which each path will actually be used, since this depends on several other factors, such as the traffic pattern and the provisioning algorithm.

The second set of results comprises the detailed network simulations. Only results for the case with 20 planning periods are shown, since very similar trends were observed for the case with 50 planning periods and 30% traffic churn. Figure 3 plots average results as a function of the offered traffic load for both networks. The average number of line interfaces and line cards deployed in the 12-node ring, assuming each line card can host two line interfaces, is shown in Fig. 3(a). As expected, as more traffic is offered the number of line cards and line interfaces increases. The increase rate is smaller at higher traffic load, since an increasingly larger fraction of the offered traffic is blocked due to the lack of resources (e.g. free spectrum). Comparing ZR+ and HCF interfaces, the utilization of the former requires more cards and interfaces. This difference is higher when the



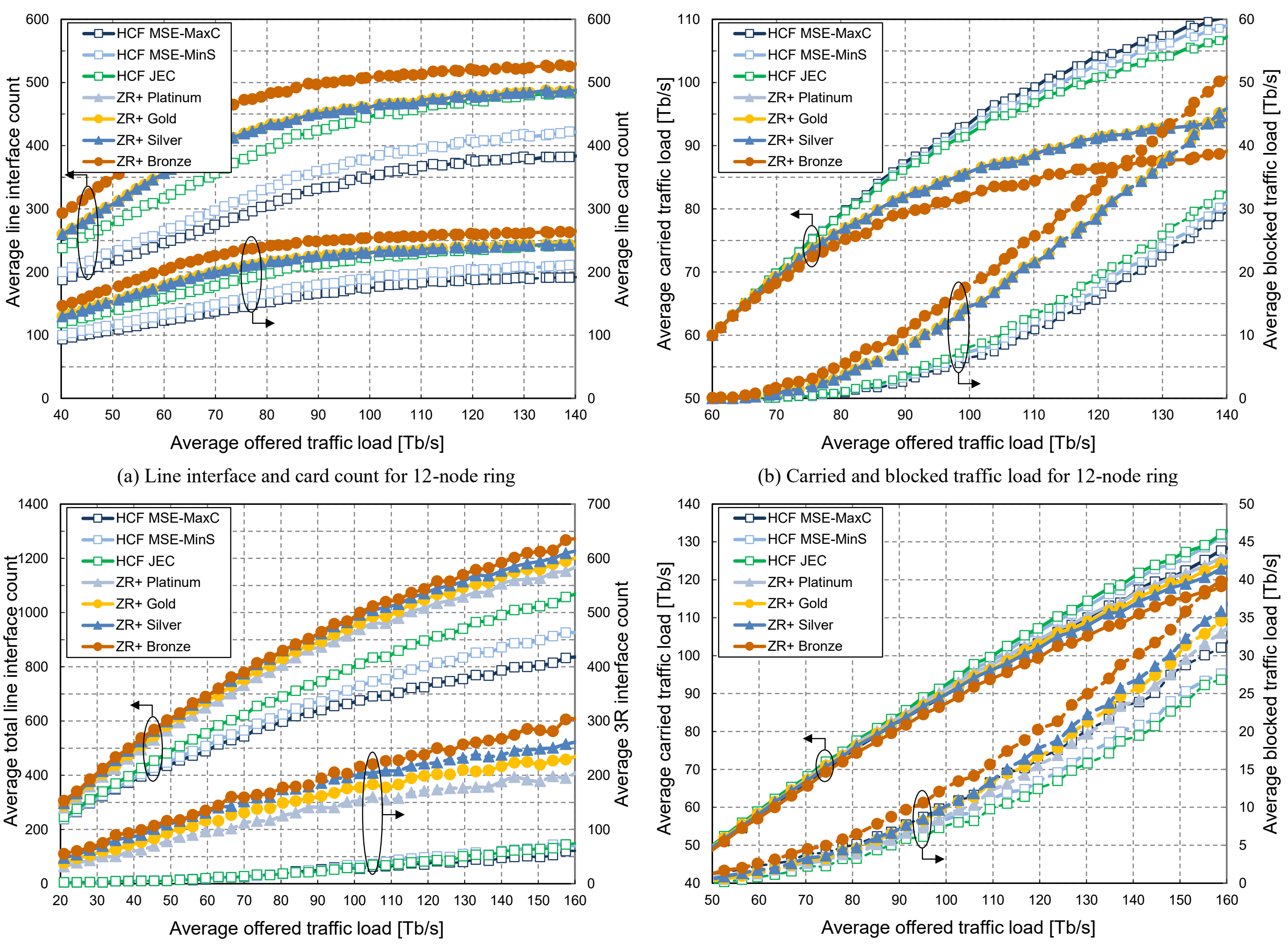
(a) HCF interfaces (b) ZR+ Gold interfaces (c) ZR+ Bronze interfaces

Fig. 2 Spectral efficiency heatmap in the Italian backbone network.

provisioning strategy used with HCF gives preference to higher capacity and spectral efficient formats (MSE-MaxC) and ZR+ relies on the least performant Bronze implementation. The results also highlight that in this metro-sized transport network there is virtually no difference among the other three ZR+ implementations, which supports that there is no tangible gain of better, potentially more expensive, implementations in this case. The average carried and blocked traffic load are plotted in Fig. 3(b). From this plot, it is clear that the network can carry considerably more traffic load (i.e. block fewer demands) when HCF interfaces are used to transport client traffic over the same fiber infrastructure. It also shows that the best results with respect to carried/blocked traffic load are obtained with the MSE-MaxC algorithm.

The average total number of line interfaces and the average number of these interfaces used for 3R regeneration in the IBN are shown in Fig. 3(c), whereas the average carried and blocked traffic load are depicted in Fig. 3(d). The results obtained in this larger and more meshed network exhibit some different trends from the ones observed in the smaller metro ring network. For instance, it is visible the impact of the different performance of the four ZR+ implementations. This is because of the longer and more diverse paths, when compared to those in the regular ring network, enabling to have cases where a given modulation format is only feasible with a sub-set of the implementations. In general, it is also clear that HCF interfaces outperform ZR+ interfaces in this network. As highlighted in Fig. 3(c), the use of HCF interfaces enables to significantly reduce the number of 3Rs, contributing to the savings observed in total line interface count. Although the MSE-MaxC algorithm grants the lowest number of required line interfaces, its usages does not lead to the highest carried traffic load. Instead, the more conservative JEC strategy provides the best results for this performance metric. This is explained by the fact that, due to its large size and meshed traffic pattern, different node pairs contend for capacity in the same links and, as a result, it is more effective to adopt a MCh provisioning algorithm that is more conservative in terms of allocated spectrum. In this case, the MSE-MinS strategy allows for a more balanced solution in terms of hardware requirements and blocked traffic load.

Tables III and IV give further insight on these observations. The former shows the maximum offered traffic load for a target blocking probability (BP) of 0.1, 1 and 10%. For instance, it can be seen that for a blocking probability of 1%, HCF interfaces



(a) Line interface and card count for 12-node ring

(b) Carried and blocked traffic load for 12-node ring

(c) Total and 3R line interface count for IBN

(d) Carried and blocked traffic load for IBN

Fig. 3 Simulation results for 12-node ring and Italian backbone networks.

enable to increase traffic load by up to 22% and 34% in the ring network and the IBN, respectively. It also shows that in the IBN, the Gold implementation of ZR+ allows to increase traffic load by up to 18% when compared to the Bronze implementation.

Table IV shows the hardware (HW) requirements – number of line interfaces (LI), line cards (LC) and tributary cards (TC) – when using HCF and ZR+ interfaces for a given offered traffic load. In order to ensure a fair comparison the load value must be such that there is only negligible blocking (i.e. approximately the same traffic load is successfully routed) in all scenarios under comparison. Hence, the average offered traffic load value considered is such that blocking probability is below 1%, regardless of the scenario. The figures show that up to 40 and 27% line interfaces/line cards can be saved when using HFC instead of ZR+ Bronze interfaces in the ring and the IBN, respectively. This is complemented with savings of up to 4 and 16% in tributary cards. Moreover, using a more spectrally aggressive MCh provisioning with HFC interfaces reduces interface/card count by 23% (8%) in the 12-node ring (IBN), when compared to a conservative strategy. Adopting a Gold implementation, instead of Bronze, grants ZR+ interface savings in the order of 12% (4%) in the ring network (IBN).

A final observation relates to the fill ratio of MChs being set up, which is defined as the ratio between used capacity and total MCh capacity, averaged over all MChs. In average, the MCh fill ratio is around 75% (50%) and 88% (70%) for HCF and ZR+, respectively, in the ring network (IBN). Therefore, this evidence hints at the possibility that HCF interfaces may enable to carry even more traffic load in these networks by exploiting, for example, intermediate grooming or flexible client rates [14].

TABLE III. OFFERED TRAFFIC LOAD FOR TARGET BP

Network	BP	HCF		ZR+	
		MSE-MaxC	JEC	Gold	Bronze
Ring	0.1%	71 Tb/s	71 Tb/s	65 Tb/s	60 Tb/s
	1.0%	83 Tb/s	82 Tb/s	71 Tb/s	68 Tb/s
	10%	120 Tb/s	117 Tb/s	97 Tb/s	91 Tb/s
IBN	0.1%	36 Tb/s	51 Tb/s	43 Tb/s	36 Tb/s
	1.0%	46 Tb/s	60 Tb/s	53 Tb/s	45 Tb/s
	10%	109 Tb/s	135 Tb/s	108 Tb/s	95 Tb/s

TABLE IV. HARDWARE REQUIREMENTS FOR TARGET OFFERED LOAD

Network / Load	HW	HCF		ZR+	
		MSE-MaxC	JEC	Gold	Bronze
Ring / 67 Tb/s	#LI	266	344	388	440
	#LC	133	172	194	220
	#TC	24	24	25	25
IBN / 46 Tb/s	#LI	416	454	546	568
	#LC	208	227	273	284
	#TC	56	57	64	67

V. CONCLUSIONS

This work targeted to identify and quantify the advantages of high capacity and flexible interfaces over alternative lower cost solutions in future transport network deployments. For that purpose, a simplified yet meaningful modelling of media channel formats, optical performance and provisioning was detailed. Through network simulation, it was shown that in a metro (regional) network these interfaces can reduce hardware count by 40% (27%), while enabling to support 22% (34%) more traffic load over the same fiber infrastructure. In addition to these improvements, the results highlight the importance of selecting the most effective MCh provisioning in each scenario and the impact of different implementations of ZR+. Future work includes assessing the impact of intermediate grooming and Flex Ethernet to extend the benefits of HCF interfaces and a comprehensive cost modelling of the different solutions.

ACKNOWLEDGMENT

The authors acknowledge the insightful comments of Bernd Sommerkorn-Krombholz, Steve Sanders, António Eira, Harald Bock and Antonio Napoli.

REFERENCES

[1] J. Pedro, et al., "Optical transport network design beyond 100 Gbaud [Invited]", IEEE/OSA Journal of Optical Comm. and Netw., vol. 12, pp. A123-A134, Feb. 2020.

[2] J. Santos, et al., "On the impact of deploying optical transport networks using disaggregated line systems", IEEE/OSA Journal of Optical Comm. and Netw., vol. 10, pp. A60-A68, Jan. 2018.

[3] I. Maor, et al., "First demonstration of SDN-controlled multi-layer restoration and its a advantage over optical restoration", in Proc. ECOC, Sep. 2016.

[4] OIF 400ZR project. Available: https://www.oiforum.com/technical-work/hot-topics/400zr-2/

[5] Acacia whitepaper, "OpenZR+ advances coherent interoperability". Available: https://acacia-inc.com/wp-content/uploads/2019/11/OpenZR-Advances-Coherent-Interoperability-WP1119.pdf

[6] Open ROADM whitepaper, "Open ROADM overview", 2016. Available: http://www.openroadm.org/

[7] B. Gangopadhyay, et al., "Exploiting real-time performance awareness for cost-effective restoration in optical transport networks", in Proc. ICTON, paper We.C3.1, July 2019.

[8] Ethernet Alliance, "2019 roadmap", Feb. 2019. Available: https://ethernetalliance.org/technology/2019-roadmap/

[9] Infinera, "Infinite Capacity Engine (ICE)". Available: https://www.infinera.com/innovation/infinite-capacity-engine

[10] I. Lyubomirsky, et al., "Toward baselinefor 400GBASE-ZR optical specs", IEEE P802.3ct Ad-Hoc meeting, Feb. 2019. Available: http://www.ieee802.org/3/ct/public/adhoc/19_0221/lyubomirsky_3ct_01_190221.pdf

[11] P. Poggiolini, et al., "The GN model of fiber non-linear propagation and its applications", IEEE/OSA Journal of Lightw. Techn., vol. 32, pp. 694-721, Feb. 2014.

[12] P. Poggiolini, et al., "The LOGON strategy for low-complexity control plane implementation in new-generation flexible networks", in Proc. OFC, paper OW1H.3, Mar. 2013.

[13] FP7 IDEALIST project, "Elastic optical network architecture: reference scenario, cost and planning". Available: https://cordis.europa.eu/docs/projects/cnect/9/317999/080/deliverables/001-D11ElasticOpticalNetworkArchitecture.doc

[14] OIF, "Flex Ethernet 2.0 implementation agreement", June 2018. Available: https://www.oiforum.com/wp-content/uploads/2019/01/OIF-FLEXE-02.0-1.pdf