Impact of Filterless and Small ROADM Architectures in the Scalability of Metro-Aggregation Networks Leveraging Coherent Pluggable Optics

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***Abstract*—Metro-aggregation networks are undergoing a major transformation to accommodate the exponential growth in data traffic, requiring scalable and cost-effective solutions. On the transceiver side, coherent pluggable optics are set to be the dominant transmission solution, in view of the cost, footprint, power consumption, and interoperability benefits. On the line system side, filterless optical networks (FONs) offer architectural simplicity and potential CAPEX savings, despite introducing challenges such as spectrum waste, channel power imbalance, and increased impact of out-of-band noise. Conversely, reconfigurable optical add-drop multiplexer (ROADM) architectures based on wavelength blocker (WB) using wavelength selective switch (WSS) mitigate these limitations, albeit at the expense of higher insertion loss (IL) and complexity. A comprehensive comparative analysis of FON and WB-based ROADM architectures considering a horseshoe topology in metro-aggregation network scenarios is presented. Customized algorithms to optimize optical amplifier (OA) settings are proposed for each architecture. The resulting network design framework is used to characterize the scalability of metro-aggregation networks based on each architecture when considering different network sizes and offered capacity per node. Results highlight that adopting higher-performance multi-source agreement (MSA) transceivers and implementing tailored OA settings optimization mitigates the limitations of FON architectures. Moreover, the study demonstrates that the most suitable solution, in terms of transceiver type and line system architecture combination, depends on the network size and target capacity.**

***Index Terms*—filterless network, optical amplification, pluggable transceiver, network optimization**

I. Introduction

The emergence of applications based on artificial inteligence and the fact that approximately three-quarters of the population use Internet [1] are boosting the requirements of optical networks [2]. In particular, the global traffic is projected to grow 3-7 times through 2034 [3]. Metro-aggregation networks have a leading role in this transformation [4]. Hence, selecting the best network architecture is pivotal for delivering the most effective solution in terms of capacity, scalability, flexibility, and cost-effectiveness [5].

Filterless optical networks (FON) combined with coherent-detection based transceivers have the potential to contribute to the abovementioned objective [6], [7]. FONs are also key enablers of point-to-multipoint (P2MP) transmission via digital subcarrier multiplexing (DSCM), to realize further capital expenditure (CAPEX) savings [8]. They rely on passive components, such as power splitters and couplers, to create a drop-and-waste architecture, i.e. channels are not filtered out in optical add-drop multiplexers (OADMs). Due to their simpler nature, FONs have limited optical power equalization capability. Moreover, FONs lead to spectrum waste due to the abovementioned drop-and-waste nature (i.e., channels are not filtered out) and increased impact of out-of-band (OB) noise. Combined, these factors contribute also to more easily reaching the saturation power of optical amplifiers (OA). Fortunately, the hub-and-spoke traffic pattern typical of metro-aggregation networks is more amenable to spectrum waste, whereas the specifications of high-capacity, cost-effective and interoperable coherent pluggable transceivers (e.g., Open ZR+ [9], Open ROADM [10], and Open XR [11]) play an important role in how robust the overall transmission solution is to the sources of performance degradation present in FONs. Nevertheless, as the network scales—for instance, by increasing the number of nodes while maintaining a high number of connected client devices—the said limitations of FONs may render infeasible designs. Therefore, assessing the prospects of FONs in realistic network deployments requires a comprehensive system and network-wide analysis that factors in all the effects discussed above.

By deploying wavelength selective switches (WSSs) and consequently enabling wavelength routing and filtering, a traditional filtered network allows for efficient spectrum re-use, leverages power equalization, and minimizes the impact of OB transmitter noise. Still, this is achieved at the expense of higher node complexity and cost. Moreover, it may also result in higher insertion loss (IL) experienced by expressed or added/dropped channels, which may need to be compensated via higher OA gain, generating more amplified spontaneous emission (ASE)

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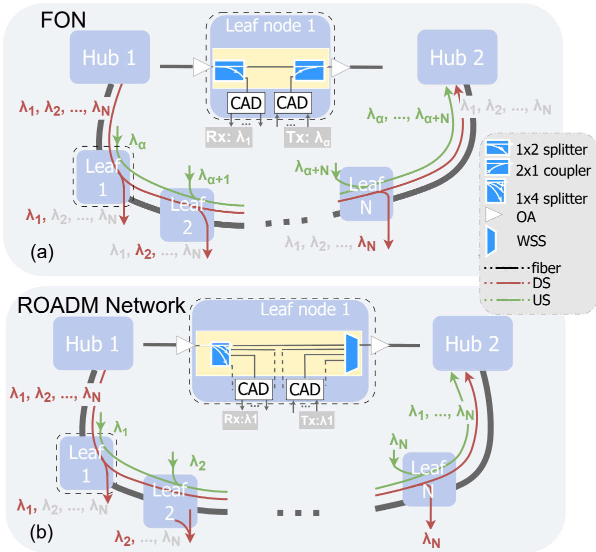


Fig. 1: Horseshoe network with (a) filterless and (b) ROADM based leaf nodes.

noise and ultimately degrading the quality of transmission (QoT). Among the available ROADM architectures, the broadcast-and-select (B&S) architecture is typically used in cost-sensitive deployments. It comprises an optical splitter at the input (demultiplexing) stage and a WSS at the output (multiplexing) stage. A wavelength blocker (WB) based device can be used to realize low-port count WSSs, further reducing cost.

In summary, the decision on the node architecture to adopt is non-trivial, given that each has its own benefits and shortcomings and that the specifications of the transceivers to be deployed will also impact the viability of the overall solution. Hence, this paper reports a comprehensive analysis of the performance and capacity of horseshoe metro-aggregation networks based on different combinations of filterless and WB-based B&S ROADM nodes with coherent pluggable transceivers compliant with diverse multi-source agreements (MSAs). As far as we know, this is the first time the trade-off between reducing the OB noise contribution from transceivers (using WB-based ROADM) at the cost of increased ASE noise contribution from amplifiers is analyzed in detail for the considered network scenarios. For that purpose, Section II describes the proposed node architectures, characterizes the line system and transceiver sub-systems used, and details the optimization algorithms developed to optimize the amplifier settings in each case, bearing in mind the specifics of downstream (DS) and upstream (US) transmission directions in horseshoe networks with dual-hub communication. The performance model and the key results of the analysis are presented in Section III, considering multiple network instances (in number of nodes and number of channels supported) and allowing to grasp how each solution effectively scales. Finally, Section IV presents the conclusions of this work.

II. Node Architecture and Design Methodology

A. Network scenario and node architectures

Figure 1 illustrates the metro-aggregation networks considered in this work, featuring a horseshoe topology implemented with either filterless (Figure 1(a)) or B&S ROADM nodes (Figure 1(b)). Protection against single link or single hub failure is guaranteed by generating and receiving traffic in both hub nodes; e.g., if a link within the horseshoe structure fails, each leaf node can still communicate with one hub node, ensuring service continuity. Note that this redundancy requires doubling the number of transceivers (i.e., each wavelength service demands two transceivers at the leaf node and one transceiver at each hub node). For simplicity, the initial analysis considers propagation from Hub 1 to Hub 2 only, where the fiber carries DS traffic from Hub 1 to leaf nodes and aggregates UP traffic from each leaf node to Hub 2. Network capacity is then calculated assuming that the worst-performing transmission direction dictates the capacity between a particular leaf node and both hub nodes.

In the FON architecture, signal splitting and merging at each leaf node are performed using a 1×2 50/50 splitter/coupler. In the ROADM architecture, the signal is broadcasted by a 1×4 splitter, as per a commercially available configuration adopted in this study. The WSS component is constituted by four WBs followed by a 4×1 coupler. Each WB can attenuate or block one or more selected channels of the incoming signal. They have a minimum settable channel bandwidth of 25 GHz. Local channel add/drop is implemented using optical couplers and splitters forming colorless add/drop (CAD) modules. CAD modules with 8, 10 or 16 ports (CAD8, CAD10 or CAD16) are deployed at hub nodes, while splitters/couplers or CAD modules with 4 ports (CAD4) are used at leaf nodes. The type of modules deployed depend on the number of added/dropped channels in each case. OAs are placed at the input and output of each node, i.e., as pre-amplifier and booster amplifier, respectively. Table I presents the IL of CADs, connectors, WSS and fibers and key characteristics of the QSFP28 pluggable OA [12] used as booster and pre-amplifier in this work.

TABLE I: Component characteristics.

Optical fiber	Length = 25 km
	Attenuation = 0.25 dB/km
Coupler/Splitter	IL: 50/50 = 3.4/3.4 dB
CADs	IL: CAD4 = 6.8 dB; CAD8 = 10.2 dB
	IL: CAD10 = 11.6 dB; CAD16 = 13.6 dB
Connectors	IL: 0.25 dB
WB WSS	IL_{demux} = 7.55 dB
	IL_{mux} = 12.25 dB
Optical amplifier	Gain = 9–24 dB
	Noise Figure = 6.5 dB
	Saturation power = 17 dBm

TABLE II: Transceivers characterization.

MSA Standard	IB OSNR [dB]	OB OSNR [dB]	Tx pwr. [dBm]	Mode	ROSNR [dB]	Target Rx pwr. [dBm]
Open ZR+ [9]	36	43	0	400G	24	-12
				300G	21	-15
				200G	16	-18
Open ROADM [10]	37	36	0	400G	24	-14
				300G	21	-16
				200G	16	-18
Open XR [11]	42	42	-1	400G	24	-12
				300G	20	-16
				200G	15	-17
eOpen XR	42	42	0	400G	23	-12
				300G	19.5	-15
				200G	15	-17

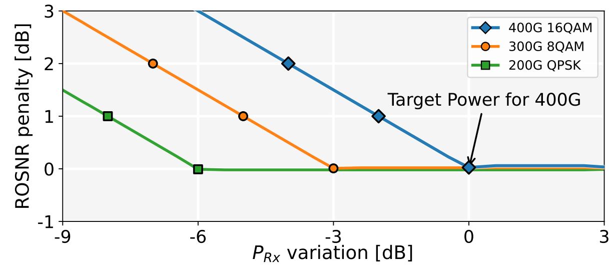


Fig. 2: ROSNR penalty as a function of Rx power.

B. Coherent pluggable transceivers

Table II summarizes the key specifications of the different coherent pluggable transceiver MSAs – Open ZR+ [9], Open ROADM [10] and Open XR [11] – that support modes at 400 Gbps, 300 Gbps, and 200 Gbps. These modes correspond to signals at approximately 60 Gbaud employing 16- and 8-level quadrature amplitude modulation (16-QAM and 8-QAM) and quadrature phase-shift keying (QPSK), respectively. The parameters showed include in-band (IB) and OB transmitter optical signal-to-noise ratio (OSNR), transmitter (Tx) output power, target receiver (Rx) power and required OSNR (ROSNR) (at the target Rx power). To compare a strictly standards-compliant implementation with the vendor-specific interface, an enhanced Open XR (eOpen XR) transceiver is also evaluated, featuring higher output power and slightly better ROSNR. The Open ZR+ MSA specifies two transceiver variants: colored (HA) and colorless (HB). Among these, the HB has been identified as the only feasible option for FONs and, therefore, is the one considered in the remaining of this work.

Importantly, due to the high IL of employed components and the absence of dedicated add/drop OAs, receiver power (P_{Rx}) may be lower than the target value. This can lead to a degradation of QoT, which is taken into account as a ROSNR penalty. Open ROADM [10] provides a characterization of this penalty, which has been applied to each considered MSA. Figure 2 illustrates the ROSNR penalty as a function of P_{Rx} variation, referenced to the 400 Gbps target power. Higher bit rates increase the achievable data throughput but impose stricter requirements in terms of ROSNR and target receiver power. In this study, the initial configuration starts at the highest rate (400 Gbps); if the channel is not feasible (due to too low QoT), the rate is reduced, first to 300 Gbps and then to 200 Gbps, if still needed, until a feasible operating point is achieved, ensuring that both DS and US directions operate at the same rate in both fibers.

C. Filterless optical network design

In FONs, DS channels and OB noise are not filtered. Consequently, there is an additional risk that the OA saturation power (P_{sat}) is reached at a certain span, potentially hampering optical performance. Moreover, it implies that added signals in the US transmission direction are impacted by the OB noise of all DS signals, as well as of all other US signals added at the previous and local leaf nodes. In the absence of WSS elements, which provide selective attenuation capabilities per channel or spectrum slice, balancing the optical power of expressed and added signals is only possible, in a very coarse way, by carefully setting the gains of the pre-amplifier and booster amplifier. Albeit being a limited capability, it can prove to be critical, because power imbalance exacerbates the impact of accumulated OB noise. Particularly, when merging express and add signals, the ones with lower signal power levels will be impacted by the relatively higher OB noise present in the set of signals with higher power levels.

D. ROADM optical network design

The WSS elements enable to remove DS channels at their destination nodes, ensuring they are not present in the remaining fiber spans and mitigating the risk of OAs reaching P_{sat}. Importantly, WSSs also filter OB noise when merging different optical signals, for example, when multiplexing the sets of express and add signals at each leaf node. Still, whenever multiple signals are colorless aggregated (e.g., via a CAD), both during traffic aggregation at Hub 1 and at the add stage in leaf nodes, the OB noise from each added signal degrades the QoT of the other jointly added signals. The IL of ROADM nodes, particularly the ones based on WBs, is high. Hence, OAs may need to be set to higher gains, introducing more ASE noise. Note that, although OB noise is filtered by the WSS, balancing the power level of express and add signals is still desirable. Moreover, whenever the pre-amplifier gain can be kept in a region of interest of the OA operation and there is enough input power at the local receivers, it is preferably to achieve power equalization by setting the gain of this amplifier. Otherwise, equalization is achieved by attenuating the add signals in the WSS (ATT_{WSS}) deployed at the ROADM.

E. Optimization Algorithm

In view of the described differences in the predominant effects impacting signal degradation in FON- and ROADM-based networks, it is paramount to customize the settings of the OAs as to improve optical performance and maximize system capacity. Algorithm 1 has been devised to estimate the OAs output power: booster amplifiers are designed to inject the maximum per-channel power into the optical fiber, which is bounded by the Kerr effect, while pre-amplifiers aim to equalize the add and express signal powers at the booster input — unless a deliberate power imbalance (P_{imb}) is applied. In this work, P_{imb} is set to 0 dB (perfect power balance) for the reasons described in paragraphs II-C and II-D. When the required OA gain G falls below the minimum specified value G_{spec}^{min}, a variable optical attenuator (VOA) is added to the link; conversely, if the estimated output power surpasses the saturation threshold (P_{sat}), the gain is clipped to prevent overload (see Algorithm 2). At the receiver hub node, the pre-amplifier is used to set the target receiver power, which may not be attainable if the OA saturation power is reached, leading to a ROSNR penalty. The main input parameters and decision variables of the algorithm are listed as follows.

Input Parameters

- P_{Tx}: transceiver output power.
- $IL_{\text{CAD,hub}}$, $IL_{\text{CAD,leaf}}$: IL of CAD employed at hub/leaf nodes.
- IL_{express}: IL experienced by expressed signal in OADM node.
- P_{imb}: power imbalance between expressed and added signals.
- $Link_{loss}(i)$: total link loss in node i.
- $N_{ch,DS}(i)$, $N_{ch,US}(i)$: number of DS/US channels at i node.
- $P_{OB}(i)$: out-of-band noise power.
- P_{lim}^{max}: quasi-linear optical fiber transmission regime power level.
- $P_{Rx,target}$: target Rx power.
- L: number of leaf nodes.
- δ_{ARC}: architecture selection setting, set to 1 in the ROADM and to 0 in the FON cases, respectively.

Output Parameters

- $P_{out}^{pre}(i)$, $P_{out}^{boost}(i)$: pre/booster OA output power.

The OA optimization Algorithm 1 applies to both FON and ROADM architectures, with the variable δ_{ARC} being used to differentiate the two cases. To simplify the algorithm description, the impact of connectors insertion loss is omitted (but account for) as well as the steps required to calculate the total OB noise.

Algorithm 1 OA Optimization Process

Input: P_{Tx}, $IL_{\text{CAD, hub}}$, $IL_{\text{CAD, leaf}}$, IL_{express}, P_{imb}, $Link_{\text{loss}}(i)$, $N_{\text{ch, DS}}(i)$, $N_{\text{ch, US}}(i)$, $P_{OB}(i)$, $P_{\text{lim}}^{\text{max}}$, $P_{\text{Rx, target}}$, L

$P_{\text{target}}(0) \leftarrow P_{\text{lim}}^{\text{max}}$
$N_{\text{ch}}(0) \leftarrow (\sum N_{\text{ch, DS}}(i))_{\text{dB}}$
$P_{\text{in}}^{\text{boost}} \leftarrow P_{\text{Tx}} - IL_{\text{CAD, hub}}$
$P_{\text{out}}^{\text{boost}}(0) \leftarrow \text{P\_SET}(P_{\text{in}}^{\text{boost}},\ N_{\text{ch}}(0),\ P_{OB}(0),\ P_{\text{target}}(0))$
for $i = 1$ **to** L **do**
  $P_{\text{target}}^{pre}(i) \leftarrow P_{\text{Tx}} - IL_{\text{CAD, leaf}} + IL_{\text{express}} - P_{\text{imb}}$
  $P_{\text{in}}^{pre}(i) \leftarrow P_{\text{out}}^{\text{boost}}(i-1) - Link_{\text{loss}}(i)$
  $P_{\text{out}}^{pre}(i) \leftarrow \text{P\_SET}(P_{\text{in}}^{pre}(i),\ N_{\text{ch}}(i-1),\ P_{OB,pre}(i),\ P_{\text{target}}^{pre}(i))$
  if $P_{\text{out}}^{pre}(i) < P_{\text{target}}^{pre}(i)$ **then**
    $ATT_{ADD}(i) \leftarrow \delta_{ARC}(P_{\text{target}}^{pre}(i) - P_{\text{out}}^{pre}(i))$
  $P_{\text{target}}^{boost}(i) \leftarrow P_{\text{lim}}^{\text{max}}$
  $P_{\text{in}}^{\text{boost}}(i) \leftarrow P_{\text{out}}^{pre}(i) - IL_{\text{express}}$
  $N_{\text{ch}}(i) \leftarrow \left(N_{\text{ch}}(i) + N_{\text{ch, US}}(i) - \delta_{ARC}\ N_{\text{ch, DS}}(i)\right)_{\text{dB}}$
  $P_{\text{out}}^{\text{boost}}(i) \leftarrow \text{P\_SET}(P_{\text{in}}^{\text{boost}}(i),\ N_{\text{ch}}(i),\ P_{OB,boost}(i),\ P_{\text{target}}^{boost}(i))$
$P_{\text{in}}^{pre}(L+1) \leftarrow P_{\text{out}}^{\text{boost}}(L) - Link_{\text{loss}}(L)$
$P_{\text{target}}^{pre}(L+1) \leftarrow P_{\text{Rx, target}} - IL_{\text{CAD, hub}}$
$P_{\text{out}}^{\text{pre}}(L+1) \leftarrow \text{P\_SET}(P_{\text{in}}^{\text{pre}}(L+1),\ N_{\text{ch}}(L),\ P_{OB,pre}(L+1),\ P_{\text{target}}^{\text{pre}}(L+1))$

Output: $P_{\text{out}}^{\text{boost}}(i)$, $P_{\text{out}}^{\text{pre}}(i)$ per $i = 0, \ldots, L+1$

Algorithm 2 OA Output Power Setting

function $\text{P\_SET}(P_{\text{ch}},\ N_{\text{ch}},\ P_{OB},\ P_{\text{target\_ch}})$
  $G \leftarrow P_{\text{target\_ch}} - P_{\text{ch}} + N_{\text{ch}} + P_{OB}$
  if $G < G_{\text{spec}}^{\text{min}}$ **then**
    $VOA \leftarrow G_{\text{spec}}^{\text{min}} - G$
    $G \leftarrow G_{\text{spec}}^{\text{min}}$
    $P_{\text{ch}} \leftarrow P_{\text{ch}} - VOA$
  $G \leftarrow \min\left(G,\ G_{\text{spec}}^{\text{max}}\right)$
  if $G \cdot \left(P_{\text{ch}} + N_{\text{ch}} + P_{OB}\right) > P_{\text{sat}}$ **then**
    $G \leftarrow P_{\text{sat}} - \left(P_{\text{ch}} + N_{\text{ch}} + P_{OB}\right)$
  $P_{\text{out\_ch}} \leftarrow P_{\text{ch}} \cdot G$
  return $P_{\text{out\_ch}}$

III. Results and Discussion

The analysis conducted in this work utilizes as QoT estimator the residual margin (RM) at the receiver, which is defined for a given path as:

$$RM = OSNR - ROSNR(P_{Rx}) - M. \qquad (1)$$

OSNR denotes the available OSNR at the receiver input, tracking from Tx to Rx both signal and noise and considering OB, IB and ASE noise sources. M is a system margin (used to accommodate for other performance impacting factors, such as fiber and component aging). In this work, M is set to 1 dB. The ROSNR for a given receiver input power P_{Rx} is defined by the selected MSA and the channel mode (see Table II and Fig. 2).

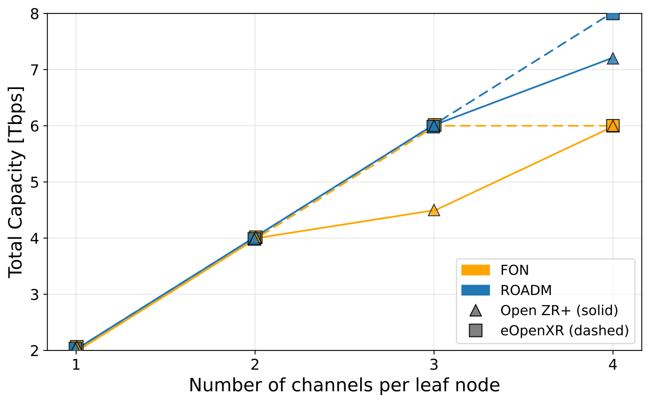
A comprehensive scalability analysis using the described architectures and MSA-compliant transceivers is conducted by: (i) increasing the number of leaf nodes (and consequently the number of transceivers and channels) across the network; and (ii) augmenting the number of transceivers per leaf node. Both in the FON and ROADM cases, to maintain a quasi-linear transmission regime, the maximum launch power into the optical fiber is limited to 3 dBm per channel ($P_{\text{lim}}^{\text{max}}$). The more relaxed OB Tx OSNR value allowed in Open ROADM makes this standard unfeasible for FON, preventing a meaningful comparison between the two architectures. Hence, results related to Open ROADM were omitted to improve readability. Open ZR+ has been selected as the baseline MSA because it features the lowest optical performance among the evaluated feasible options.

Table III summarizes the total achievable capacity, with a breakdown of the per channel capacity of leaf nodes, for three different numbers of leaf nodes ($L_{\text{leaf nodes}}$) and four different number of channels to be added/dropped at each node. Fiber spans are assumed to have a 25 km length. To

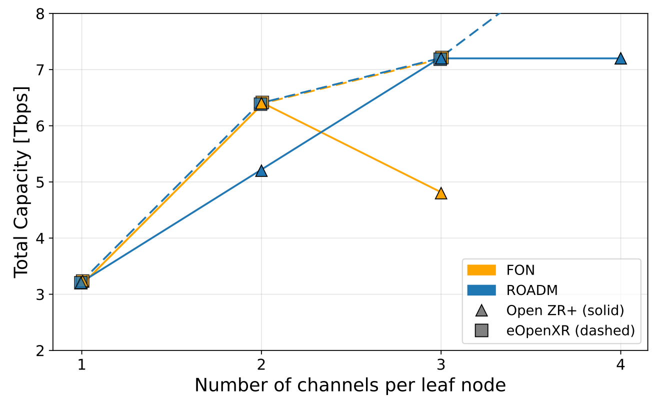
TABLE III: Capacity per architecture and number of channels, Open ZR+ MSA.

$L_{leaf\ nodes}$	**Arch.**	$N = 1$	$N = 2$	$N = 3$	$N = 4$
4	FON	1.6 Tbps (400G × 4)	3.2 Tbps (400G × 4)	4.8 Tbps (400G × 4)	6.4 Tbps (400G × 4)
	ROADM	1.6 Tbps (400G × 4)	3.2 Tbps (400G × 4)	4.8 Tbps (400G × 4)	6.4 Tbps (400G × 4)
5	FON	2.0 Tbps (400G × 5)	4.0 Tbps (400G × 5)	4.5 Tbps (300G × 5)	6.0 Tbps (300G × 5)
	ROADM	2.0 Tbps (400G × 5)	4.0 Tbps (400G × 5)	6.0 Tbps (400G × 5)	7.2 Tbps (300G × 2 + 400G × 3)
8	FON	3.2 Tbps (400G × 8)	6.4 Tbps (400G × 8)	4.8 Tbps (200G × 8)	[a]
	ROADM	3.2 Tbps (400G × 8)	5.2 Tbps (300G × 6 + 400G × 2)	7.2 Tbps (300G × 8)	7.2 Tbps (6 × 200G + 2 × 300G)

[a] Not enough available channels.



(a) 5 leaf nodes



(b) 8 leaf nodes

Fig. 3: Capacity evolution with leaf-node channels per leaf node (N) for FON and ROADM with Open ZR+ and eOpen XR.

add/drop channels, the FON solution employs a CAD4 for $N = 3, 4$, a coupler for $N = 2$, and a direct connection for $N = 1$. Since in ROADM solution the leaf node has a node degree of 2, one port of the WSS is needed for the express connection, leaving 3 port for add/drop. Hence, it uses a coupler for $N = 4$ and a direct connection for lower N cases. A CAD4/CAD8/CAD10/CAD16 is used at the hub nodes when the total number of DS and US channels ($N \times L_{\text{leaf nodes}}$) is less or equal to 4/8/10/16. Two CAD10/CAD16 units and a coupler are deployed when DS and US channels exceed 16/20.

As observed in Table III, both architectures can support the maximum capacity (i.e., all leaf nodes communicate with both hub nodes using the 400 Gbps mode) in a horseshoe network with 4-leaf nodes, even when up to 4 channels per leaf node are set up. Given its inherent simplicity and lower cost, FON is the most cost-effective architecture to be deployed in these conditions. However, for larger horseshoe networks, the limitations of each architecture become more visible as channel count per leaf node is increased. Figure 3 enables to compare how the total capacity achievable in both architectures evolves as a function of the channels supported per leaf node for the cases of L equal to 5 and 8. Moreover, it also highlights the correspondent results when using better performing eOpen XR transceivers.

For $L = 5$, there is a visible impact in total capacity with the FON architecture when the number of channels is higher ($N = 3, 4$). This is mainly due to the augmented OB noise from aggregating more channels. Interestingly, for $N = 3$, it is still possible to achieve the maximum total capacity (i.e., 6 instead of 4.5 Tbps) if a transceiver with better performance (eOpen XR) is used. Nevertheless, for $N = 4$ not even the use of these devices allows to reach the maximum total capacity. With the ROADM architecture, the only case where the maximum total capacity is not achieved is when $N = 4$ and using Open ZR+ transceivers. In this case the coupler used in the add stage increases the IL, leading to a higher OA gain and consequent ASE noise. eOpen XR devices allow to obviate this capacity gap.

For a larger horseshoe network ($L = 8$), only the ROADM architecture can support more than 3 channels per leaf node (e.g., $N = 4$), enabling a total capacity of 12.8 Tbps when eOpen XR transceivers are deployed. Note that this is not a performance limitation of the FON architecture, but rather a consequence since this architecture does not allow to re-use wavelength channels in non-overlapping paths. The impact of OB noise in the FON architecture with $N = 3$ limits the channel data rate to 200 Gbps and 300 Gbps when using Open ZR+ and eOpen XR transceivers, respectively. The ROADM architecture allows to realize the 300 Gbps per channel with either transceiver type. Noteworthy, there is a case where the FON architecture is actually enabling higher total capacity than the ROADM one. That occurs for $N = 2$ and using Open ZR+ transceivers (see also Table III). Figure 4 shows this case and presents detailed results for the case with $L = 8$ and $N = 2$.

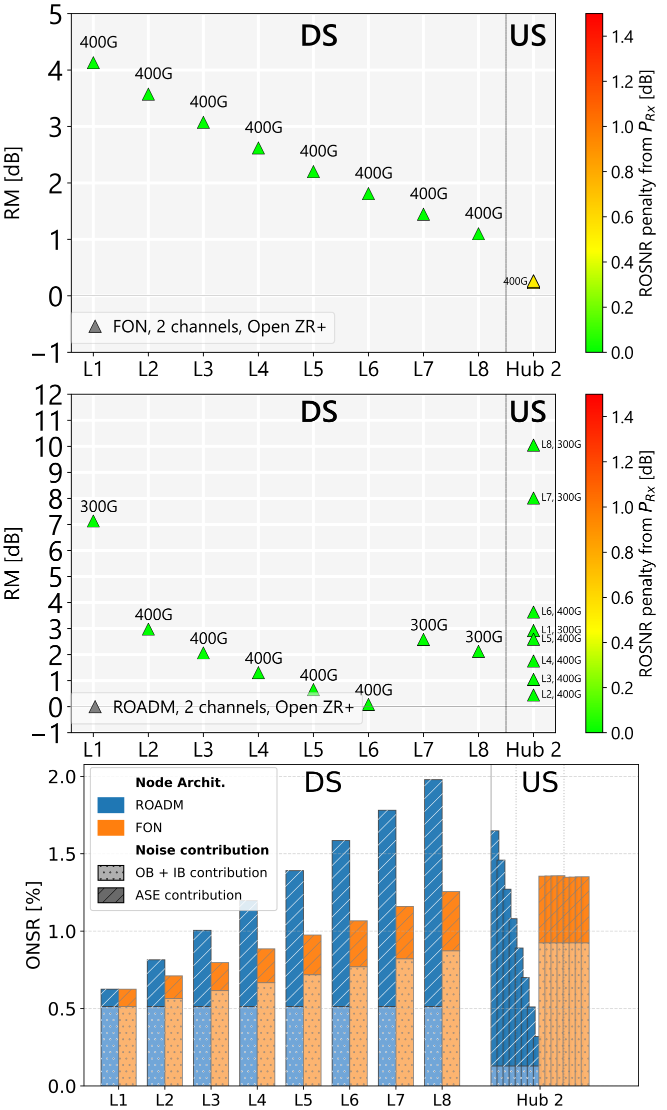


Fig. 4: RM analysis in a 8-leaf-node network with $N = 2$: (a) FON architecture; (b) ROADM architecture; (c) Noise contribution analysis for FON and ROADM cases.

Figure 4(a) and (b) show the RM per leaf node obtained in DS and US transmission directions for FON and ROADM, respectively. As can be seen, the evolution of RM differs in both architectures. Particularly, it can be seen that in the DS transmission direction with ROADM the RM decreases at a higher rate as the optical signals progress towards Hub 2 (see RM evolution from L2 to L6). The reason for this is that the accumulation of ASE noise along the horseshoe (due to the need to compensate for higher IL) grows faster than the accumulation of OB and IB noise, as can be seen in Figure 4(c), which depicts the optical noise-to-signal ratio (ONSR) and the share associated to each noise source. In the US transmission direction, the ROADM ONSR is lower than that of the FON, for every node except the first two leaf nodes. However, since both DS and US transmission directions need to be accounted for and in both fibers to determine the maximum channel capacity per leaf node, the FON actually delivers better performance overall in this particular configuration.

IV. Conclusion

This paper analyzes and compares the potential of a filterless architecture with that of a cost-effective WB-based ROADM architecture. The analysis proposes a customized algorithm to optimize the optical amplifiers' settings according to the node architecture. The results highlight that, in general, the ROADM architecture scales better, accommodating a larger number of leaf nodes and higher channel count (e.g. $N = 3$ and $N = 4$), as well as being more tolerant to the utilization of lower-performing coherent pluggable transceivers. Nevertheless, the FON architecture, when combined with the proposed power setting algorithm, was shown to be a cost-effective option for horseshoe networks with reduced number of leaf nodes or larger ones but with small channel count (e.g. $N = 2$) per leaf node. Although quantitative techno-economic comparison would complement the presented analysis, this aspect is not addressed here. Future work will extend the study in this direction.

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