Metro-PON Convergence: 400 Gbps Full Coherent Transmission using Pre-Commercial transceivers

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Metro-Passive Optical Network Convergence: 400 Gbps Fully Coherent Transmission Using Pre-Commercial Transceivers

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Abstract: The capacity of passive optical networks (PONs) is continuously increasing, and it has been standardized up to 50 Gbit/s. The two main standardization organizations, IEEE and ITU-T, are actively working on the next-generation PON, which appears to be a 100G-PON still based on intensity modulation. Even though direct detection would be preferred for its cost and simplicity, the choice of coherent detection seems inevitable when the bit rate reaches 200–400 Gbit/s, specifically to guarantee the optical power budget requirement of an access network. The introduction of coherent systems in the PON scenario, allowing high-power-budget performances, should encouragetelecom operators to merge the metro and access networks into a single domain. This paper analyzes the mentioned metro + PON convergence scenario with experimental results focusing on a 400 Gbit/s fully coherent transmission (50 GBaud PM-16QAM). We characterize three different transceivers, two of which are pre-commercials. We perform experimental demonstrations, with real urban fiber and laboratory set ups, of the metro–access convergence network in terms of the minimum OSNR value of the metro path, producing an acceptable optical power budget within the access network. Our work demonstrates feasibility of merging the metro–access network by using currently coherent optical transceivers for PON applications.

Keywords: access network; high-capacity passive optical network; metro–access convergence; coherent transmission

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1. Introduction

An access network is the final part of a telecommunication network, delivering data to end users. For the past 15 years, access networks have been based on the passive optical network (PON) infrastructure, which consists of point-to-multipoint bidirectional single-fiber links between a central office and the end users. The PON architecture has achieved significant success due to its simplicity and relatively low cost compared to other network schemes. Each PON tree consists of the following main elements: one Optical Line Terminal (OLT) located inside the central office at the boundary between the metro and the access network, one or more cascade passive splitters and a pool of Optical Network Units (ONUs), one for each end user.

Over the years, the capacity of PON systems has increased to meet the end users' requirements [1], according to specifications published by the two main standardization organizations, the IEEE and the ITU-T. In September 2021, the ITU-T released the 50G-PON standard [2], setting a downstream capacity of 50 Gbit/s. Despite remaining based on direct detection and intensity modulation, the capacity of PON structures has increased from a few Gbit/s (first G-PON standard) to several tens of Gbit/s (actually 50 Gbit/s), thanks to various strategies [2]. One key strategy has been the implementation of Low-Density Parity-Check (LDPC) codes. LPDC codes, performing error corrections until a 10^{-2} Bit Error Rate (BER) [2], enhance optical receiver sensitivity, thereby increasing the overall optical power budget performance. Furthermore, advancements in photodetector technology have led to the availability of high-bandwidth Avalanche Photodiodes (APDs) capable of detecting high capacities in current PON structures. Finally, starting from the 50G-PON standard, the ITU-T introduced a digital signal equalization process at the receiver side to compensate for the bandwidth limitations of the optoelectronic components.

The standardization bodies are currently actively discussing the next-generation PON. The most probable scenario will be based on a 100G-PON with a downstream transmission rate of 100 Gbit/s [3]. This architecture still uses direct detection at the receiver side, but the capacity increase is achieved through a change in modulation format from PAM-2 to PAM-4 and the introduction of semiconductor optical amplifiers [4]. Despite the associated little increases in complexity and cost, these seem tolerable for telecom operators.

Subsequently, the standards released with even higher transmission rates (such as 200G-PON and beyond), based on direct detection receivers, become very challenging. Even if there are some studies [5,6] in which high-capacity PON systems are still using the direct detection technique, the trend seems to be moving toward coherent detection [7]. This is primarily due to the limitations of the direct detection technique caused by chromatic dispersion above 50 GBaud/s, bandwidth limitations of optoelectronic components and the very high optical power budget required by PONs, which is currently fixed by [2] at 29–35 dB depending on the class and may increase over the years. Coherent transmission can overcome all these issues with higher levels of modulation (intensity, phase and polarization multiplexing) and better-quality transmission thanks to digital signal processing. The result is an increased transmission rate with a higher power budget, offering greater coverage distance and more reachable end users. For this reason, the coherent technology already used in core and metro networks is under study for the access segment of PONs as well [8]. Unfortunately, this choice also has some drawbacks that need to be addressed. First, implementing coherent technology in PONS can lead to increased costs and complexity, which are currently not acceptable for telecom operators. Additionally, the coherent transceivers used in long-haul networks utilize the same wavelength for downstream and upstream transmission, a characteristic that is not applicable in PONs, which are bidirectional. However, the scientific community has already begun to discuss and try to overcome these critical issues. Indeed, regarding the cost and power consumption, it is expected that they will decrease over time [9], making them more affordable. Regarding bidirectional transmission, the community has already started to discuss whether, for future coherent PONs, transmission with multi-sub-carrier single-center wavelength (choosing, for instance, even sub-carriers for the downstream and odd for the upstream) [10] is better or a double-wavelength solution (one for each direction) is preferable, trying to find the best solution in terms of cost and complexity. The high complexity introduced by coherent transmission may be tolerated thanks to the huge increase in its performances. Additionally, it seems that coherent transmission may find application primarily in front-haul use cases rather than residential cases, reducing the number of implementations. This targeted deployment could help mitigate some of the challenges associated with cost and complexity while still leveraging the benefits of coherent transmission where it is most needed. The purpose of this paper (a follow-up to our conference papers [11,12]) is to suggest the introduction of coherent transmission in a PON access network, show the performance of this choice and also to study the possibility of merging a metro network and an access network together by providing a joint design between its segments. Metro–access network merging could be achieved by introducing Reconfigurable Optical Add-Drop Multiplexers (ROADMs) between the two networks boundaries; in this paper, we demonstrate its feasibility and the performance results obtained. Figure 1 shows these concepts graphically, visualizing the current division between networks and the proposed network aggregation. The core network is depicted in yellow, the metro network in green and the access network in blue. The central office (CO), situated between the metro and access networks (at the top of the figure), illustrates the current division between networks, where coherent transmission is used inside the metro network, and intensity modulation with direct detection is used inside the access network. At the center of the figure, the sector represented by a teal dotted line, which includes the metro network, the access network and the ROADM between them, shows the proposed network configuration resulting from the merger of metro and access network domains.

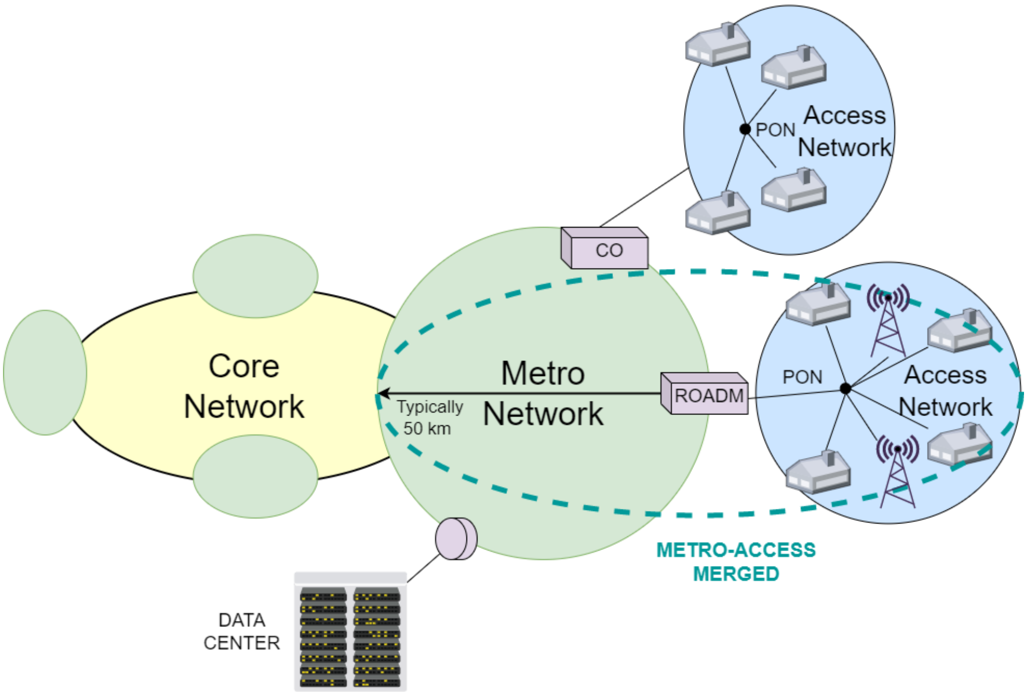

Figure 1. Comparison of telecommunication networks: current networks (yellow, green and blue) and the future merged network (teal dotted).

In our work, we extend previous studies [11,12], considering different transceivers, also including some pre-commercials ones. In particular, we experimentally analyze the merger between metro and access networks, by means of a fully coherent 400 Gbit/s downstream transmission system (50 GBaud PM-16QAM, where the PM acronym stands for polarization multiplexing) in the C-band. We demonstrate the metro–access convergence by experimental characterizations in the following two different scenarios:

- A real installed urban test-bed with a fully coherent transceiver and offline processing.
- A laboratory test-bed using pre-commercial fully coherent transceivers.

In both cases, we perform experimental characterizations in terms of BER curves for different OSNR and received optical powers. The collected data have been analyzed in post processing by fixing the BER target to 10^{-2}, thus investigating the metro–access convergence optical power budget.

The paper is organized as follows: In Section 2, we present the two test-beds used in our study, the real in-field set-up within Turin city, performing offline processing at the optical receiver side, and the laboratory set-up using the pre-commercial transceivers. Next, in Section 3.1 we present the transceivers' experimental characterization results for both test-beds. Then, in Section 3.2, we show the metro–access convergence, analyzing the metro segment and the access segment performances and discussing the obtained results. Finally, in Section 4, we conclude our work, summarizing the findings and implications.

This structured approach allows us to clearly demonstrate the feasibility of merging metro and access networks and the conditions to make a joint design of both networks.

2. Test-Bed

We experimentally test a 400 Gbit/s fully coherent downstream transmission in a convergence between metro and access networks. We first test it in a real installed fiber-urban test-bed using transceivers with offline processing, and then, we repeat the measurements with two pre-commercial transceivers using a laboratory test-bed (the overall system in the same structure). Let us begin by describing the first set-up. The upper part of Figure 2 depicts the utilized set-up, while the bottom part illustrates the corresponding path of 16.5 km urban span (each direction) in the city of Turin, thus, overall, representing a 33 km link of a real installed optical fiber (Single Mode Fiber following the standard ITU-T G.652) operated by a TIM telecom operator.

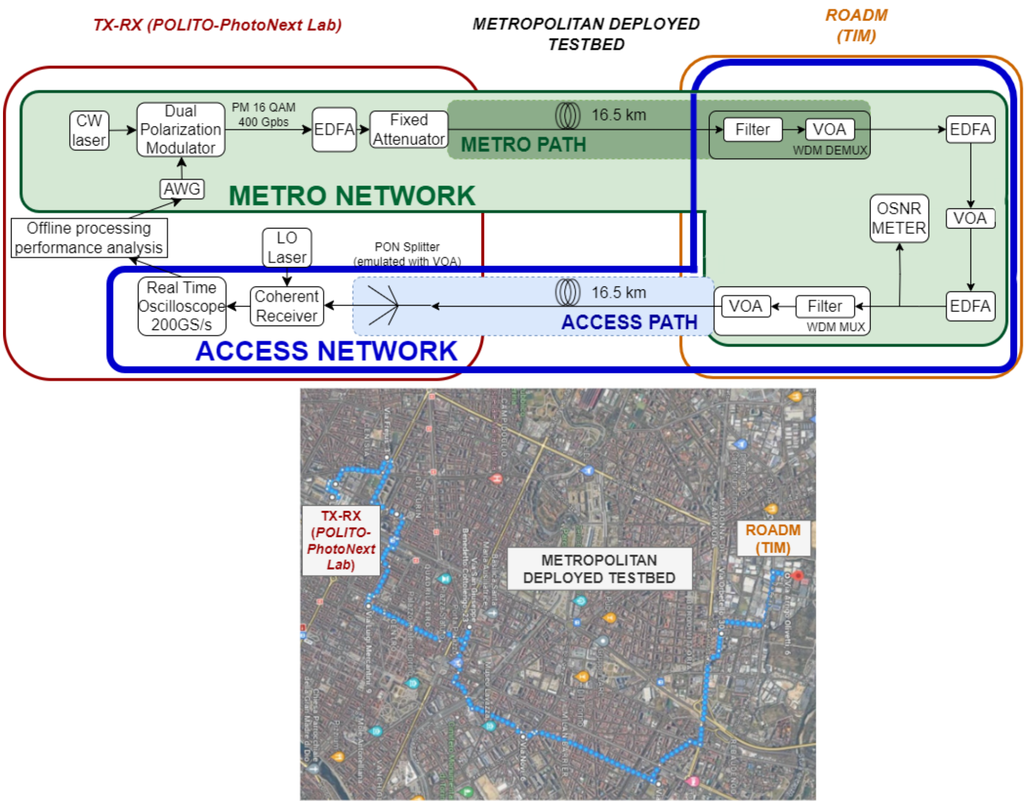

Figure 2. Above: Set-up used for demonstrating the convergence between the metro and access network with 400 Gb/s fully coherent transmission and a ROADM between the boundary of the networks. Bottom: Fiber urban path inside the city of Turin used to perform the experiment.

The transmission begins at the Polito-PhotoNext lab (left in red in Figure 2), where the signal is generated. It then travels, by using the installed urban fiber, to the TIM laboratories (right in yellow/orange in Figure 2), located 16.5 km away, where it passes through a ROADM. Afterward, the signal returns through another 16.5 km of urban installed fiber links to reach the Polito-PhotoNext lab, where the receiver side is located. This set-up allows the transmission to be tested over a significant distance and its performance to be evaluated under real-installed urban conditions.

The signal is generated using a Continuous Wave (CW) laser operating in the C-band and is then modulated to produce a 50 Gbaud PM-16QAM fully coherent optical transmission, resulting in a bit rate of 400 Gbps. Following modulation, the signal is amplified and then attenuated to achieve power level of 11 dBm. After this signal generation at the Polito-PhotoNext lab, the data stream travels along the "metro path" (green in Figure 2) which covers a distance of 16.5 km of fiber length and concludes at the ROADM, placed at the TIM laboratory premises. By setting different values of the Variable Optical Attenuator (VOA) placed inside the ROADM, signals with different Optical Signal-to-Noise Ratio (OSNR) values can be achieved, ranging from 21 to 36 dB. Referring to Figure 2, the described VOA is inside the block labeled "WDM DEMUX", which represents the first of the five ROADM components. This first block consists of an optical tunable filter set to 100 GHz bandwidth and the aforementioned VOA. After that, the signal crosses the ROADM second block, an Erbium-Doped Fiber Amplifier (EDFA), operating with fixed optical gain. Next, there is the third block: another VOA, set to 0 dB of attenuation. Then, the signal is amplified once again by the ROADM fourth block, this time operating at a fixed output power. Finally, the signal arrives at the fifth and final ROADM block, the "WDM MUX", where the signal is filtered again with an optical bandwidth of 100 GHz and then set to transmit 11 dBm of optical power on the access path of Figure 2, i.e., the same amount of optical power transmitted on the metro path. Overall, the ROADM is installed with the goal of filtering the signal, producing a different OSNR, and amplifying the signal. At this point, similarly to the "metro path", the "access path" (blue in Figure 2) also spans 16.5 km of fiber length, joining a VOA at the Polito-PhotoNext Lab. This VOA emulates a PON splitter, allowing for the generation of different-distance ranges and optical received power levels by varying its attenuation. In the end, the signal reaches the coherent receiver, where offline processing is conducted to perform the experimental analysis.

After the metro–access convergence characterization in the urban test-bed, we address an experimental verification using two pre-commercial transceivers with the same modulation format used before. The purpose remains the same: to conduct acquisitions while varying the OSNR and the received optical power. To achieve this, we implement the set-up illustrated in Figure 3.

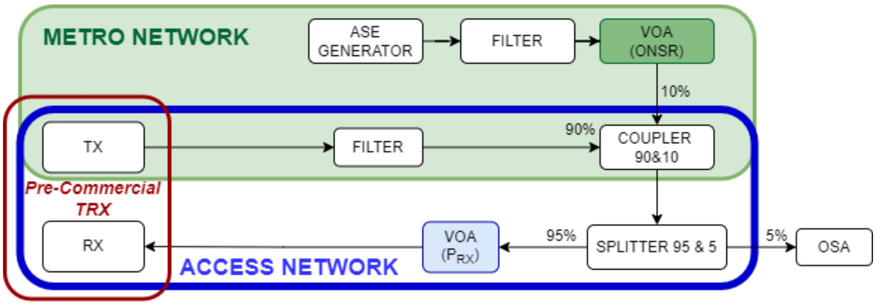

Figure 3. Test-bed used for experimental convergence demonstration using pre-commercial transceivers, analyzing performance versus the metro signal OSNR and the access optical received power.

This time, the experiment is conducted within a laboratory environment. The pre-commercial transceivers transmit 4 dBm optical power. Then, an optical filter shapes the signal emulating distortions at the transmitter side, through a three-order super-Gaussian filter and 95 GHz optical bandwidth (comparable to the previous 100 GHz case). At this point, variable optical noise is added to the signal. The noise is generated using an Amplified Spontaneous Emission (ASE) generator and then filtered with a 500 GHz flat bandwidth optical filter. This noise is then attenuated (green VOA in Figure 3) to set different OSNR values and finally added to the optical signal by a 90:10 optical coupler, generating the optical signal for the metro network (green in Figure 3).

Subsequently, the signal is split by a 95:5 optical splitter to monitor the OSNR by an Optical Spectrum Analyzer (OSA). The following VOA is used to emulate the access network optical loss due to PON optical splitters and fiber link loss (blue in Figure 3); its characterization versus OSNR defines the metro network characteristics' impact on the access network power budget performances.

The VOA settings, indeed, change the optical received powers, exactly as in the previous urban-fiber set-up. Finally, the signal is sent to the optical receiver of the pre-commercial transceiver for data acquisitions. The purpose of both configurations is to produce different OSNR signal levels (affected by the metro network) and detect them at different optical received powers (access network optical receiver side).

3. Results and Discussion

In this section, we present and discuss the three transceivers' experimental characterizations and the resulting metro–access convergence performances, fundamental for the design of joint metro and access network segments.

3.1. Transceivers Experimental Characterization Results

Following both set-ups outlined in the previous section, we can collect and present the transceivers' experimental characterizations in terms of Bit Error Rate (BER) versus the received optical powers for several OSNR values. Figure 4 depicts the results that refer to the first urban-fiber test-bed, using a transceiver with offline processing, while Figure 5 depicts the results that refer to the two pre-commercial transceivers. For all graphs, we change the OSNR with a step of about 1.5 dB and the received optical power with a step of about 1 dB.

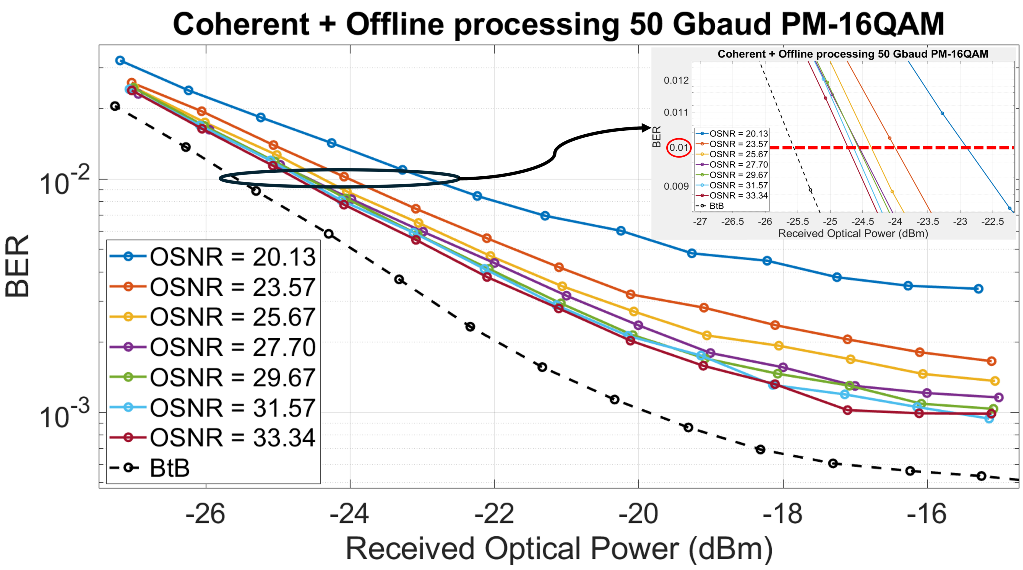

Figure 4. BER curves versus received optical power with OSNR varying from 20 to 33 dB for a transceiver with offline processing, in the case of the urban-fiber test-bed shown in Figure 2, with transmitted optical power of 11 dBm.

Referring to Figure 4, the graph shows sensitivity at a BER target of 10^{-2} ranging from −24.7 dBm to −22.7 dBm, depending on the OSNR. In addition to these OSNR curves from 20.1 to 33.3 dB, there is a case represented by a black dashed line called "*BtB*", which refers to the BER values obtained without the ROADM, meaning only the fiber is present in the "TIM laboratories". In this case, the OSNR is very high (more than 35 dB) and it is missing the ROADM polarization-dependent loss (PDL) contribution of about 0.8 dB, thus explaining the sensitivity gap between the "*BtB*" black curve without the ROADM and the other ones when using it (see Figure 4). Since the black curve represents the best case, it can serve as a reference when the ROADM is inserted for this test-bed.

The results obtained for the two pre-commercial transceivers, plotted in Figure 5, have the following sensitivity performances (referring to BER = 10^{-2}): TRX #1 shows sensitivity from −24.95 dBm for high OSNR to −24.1 dBm for low OSNR; TRX #2 sensitivity between −25.85 dBm (high OSNR) and −25.2 dBm (low OSNR).

We observe that the second pre-commercial transceiver (bottom of Figure 5) has a better performance, with approximately 1 dB improvement in sensitivity compared to the first one (top of Figure 5). In conclusion, both pre-commercial transceivers' performances are very close each other.

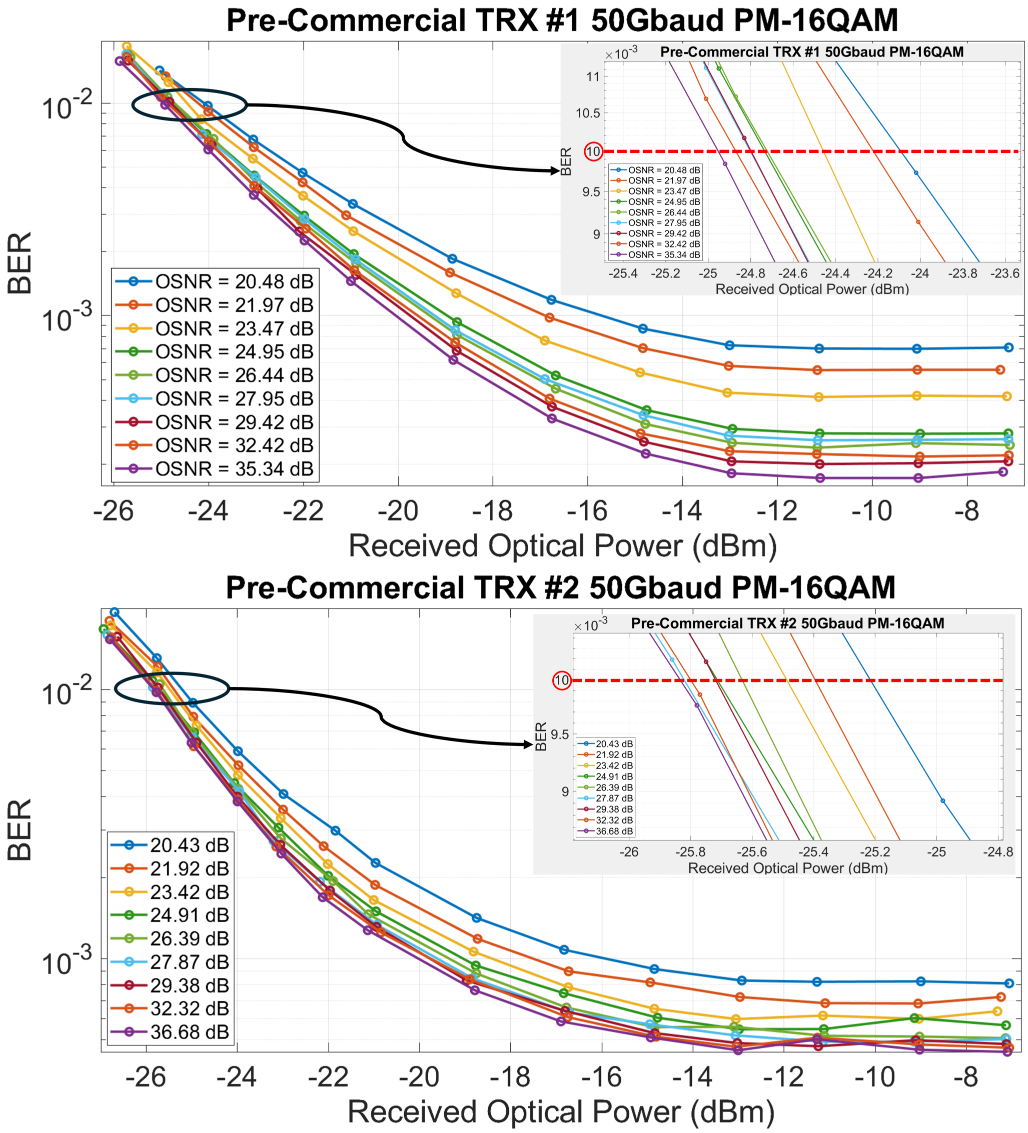

Figure 5. BER curves versus received optical power with OSNR varying from 20.4 to 36.7 dB for the two pre-commercial transceivers, in the case of the laboratory test-bed shown in Figure 3, with a transmitted optical power of 4 dBm.

Even considering a large OSNR range (from 20.4 to 36.7 dB), the comparison of results between both pre-commercial transceivers and the previous one with offline processing used in the urban-fiber test-bed case shows that they are very similar.

3.2. Results on Metro–Access Network Convergence

After characterizing the transceivers, we perform an analysis useful for the merged metro and access network's joint design.

As mentioned in the Introduction section, thanks to the LPDC codes used, the current PON specification uses a BER target value of 10^{-2}. Focusing on this BER target performance in the Figure 4 inset, this can be guaranteed only for a subset of receiver optical powers and transmitter OSNR joint values. Referring to Figure 2, we define the "metro path" as the path from transmission to the ROADM first block. Within this path, there is a VOA used to emulate the metro link; its setting produces different signals with different OSNRs. However, this VOA setting also affects the optical signal power loss in the metro path, which we can call the "metro optical power budget" (OPB_{Metro}). Similarly, we define an "access path" from the ROADM output to the VOA used to emulate the PON splitter (placed just before the coherent receiver) and the fiber link loss. This VOA setting changes the received optical power in the access segment but also affects the optical power loss within the "access path", which we can call the "optical power budget" of the access segment (OPB_{Access}). Considering these parameters, we can estimate the received optical power and OSNR satisfying the 10^{-2} BER target of the Figure 4 inset, this evaluating the OPB_{Metro} and OPB_{Access}, producing the left plot in Figure 6.

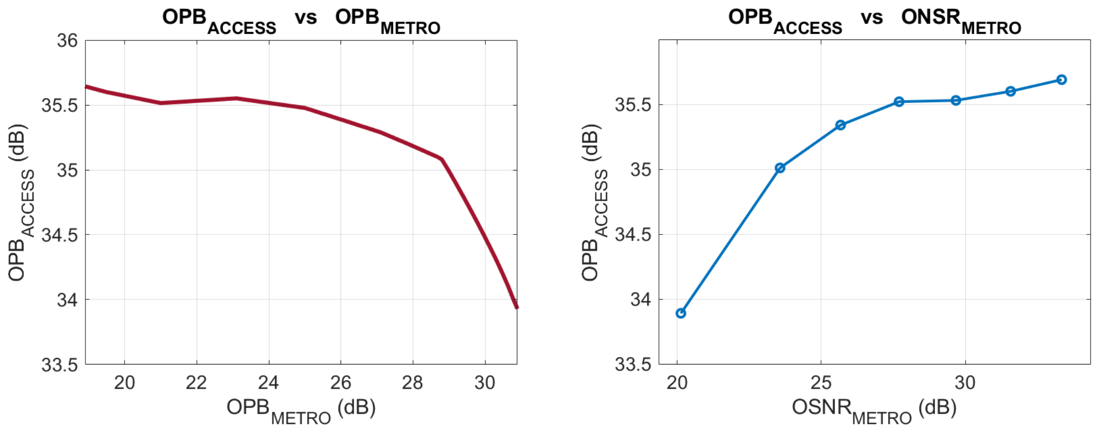

Figure 6. Design of the metro path and access path for $@BER = 10^{-2}$ obtained for coherent transmission and offline processing (using test-bed of Figure 2). (**Left**): Results shown as access optical power budget (OPB_{Access}) vs. metro optical power budget (OPB_{Metro}). (**Right**): Metro–access network convergence performance in terms of access optical power budget (OPB_{Access}) vs. OSNR at the metro segment output ($OSNR_{METRO}$).

The graph on the left in Figure 6 illustrates a joint design between access and metro segments as a function of the two path losses. The results indicate that an optical power budget in the access network can exceed the current class N1 requirement of 29 dB. In particular, the figure demonstrates that if the power budget requirement for the access network increases in the future, there is sufficient margin to accommodate this change. Specifically, achieving a power budget of 34 dB or higher is possible by reducing the metro loss to 30.8 dB or lower.

The access network optical power budget can also be expressed in terms of OSNR (at the metro segment output) instead of the metro optical power budget (on the right in Figure 6). This graph shows that an access optical power budget in excess of 33.8 dB can be achieved if the OSNR of the metropolitan network is greater than 20 dB.

Similarly, we perform the same analysis for the pre-commercial transceivers, thus focusing on the Figure 5 inset, estimating the subset of receiver optical powers and transmitter OSNR values guaranteeing the BER target, and finally, the OPB_{Access} evaluation inside the access network (defined as the optical power difference from the transmitter to the receiver, blue in Figure 3). We also obtain a similar plot to that on the right in Figure 6 for the pre-commercial transceivers. Overlaying the optical power budget results for the three transceivers in a single graph, we obtain the graph on the left in Figure 7.

The graph on the left in Figure 7 illustrates the optical power budget (OPB) of the access network relative to the OSNR values of the metro network for the three transceivers. As shown, all three transceivers meet the current minimum acceptable optical power budget N1 class requirement of 29 dB when the OSNR of the metro network exceeds 25 dB. Additionally, depending on the transceiver, an higher optical power budget can be achieved. Specifically, the plot indicates that transceiver number 2, depicted by the red curve, has a 1 dB higher optical power budget compared to transceiver number 1 in the green curve. Furthermore, the first transceiver in blue reaches the current highest PON OPB of 35 dB (guaranteeing PON class E2 [2]) if the OSNR increases above 25 dB.

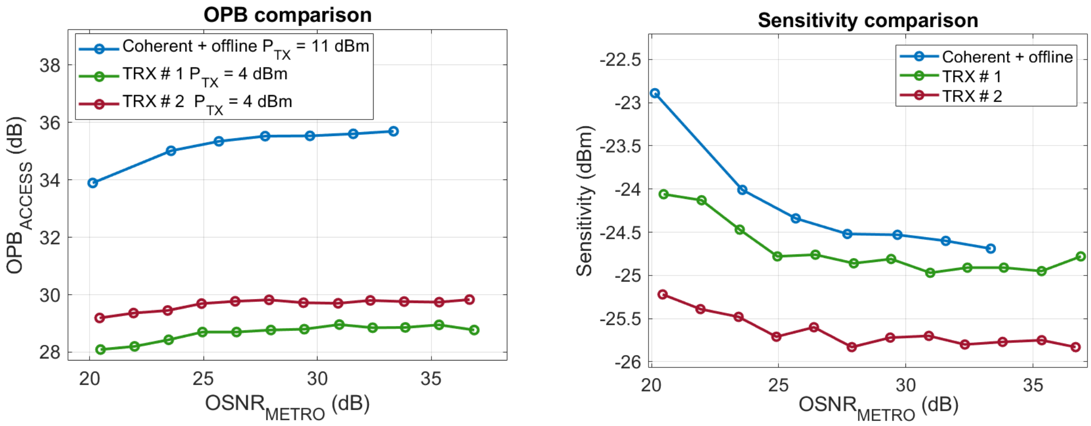

Figure 7. Design of the metro path and access path comparing the performance of the three transceivers at $@BER = 10^{-2}$. (**Left**): Results shown as the optical power budget (OPB) of the access network versus the OSNR of the metro ($OSNR_{METRO}$). (**Right**): Sensitivity at $@BER = 10^{-2}$ of the receivers versus the OSNR of the metro network.

These results seem to suggest that the coherent transmission depicted by the blue curve in Figure 7 and implemented with the set-up shown in Figure 2 outperforms the other two pre-commercial transceivers. However, it is important to note that the transmitted power levels differ, as the blue curve is obtained with a transmitted optical power of 11 dBm, while the red and green curves are achieved with 4 dBm, so the performance comparison is performed in different conditions. Therefore, to have a correct comparison between all transceivers, we present the optical sensitivity power at the BER target of 10^{-2} versus metro OSNR , resulting in the graph shown on the right in Figure 7. From this graph, it is evident that transceiver number 2 exhibits the best sensitivity, being 1 dB higher than transceiver number 1. This latter instead (green curve) has a similar sensitivity to the receiver used in the offline processing (blue curve). Because the sensitivity is almost the same, this explains why the blue curve is approximately 7 dB higher than the green in the left of Figure 7. Indeed, it is due to the difference in the transmitted power from 11 dBm to 4 dBm in the two test-beds. This implies that if a higher power budget is required, it is also achievable with pre-commercial transceivers by simply increasing their transmitted optical power.

4. Conclusions

In our work, we consider the introduction of coherent transmission in a PON infrastructure. Based on recent research, it appears that beyond 200 Gbps, the use of coherent technology for front-haul or industrial applications is a reasonable possibility. In this scenario, it may be cost-effective for telecom operators to merge the metro and access networks into a single domain. We demonstrated the feasibility of converging these segments by designing a joint path for downstream transmission.

To achieve this, we implemented two test-beds and characterized both coherent transmission with offline processing and two pre-commercial transceivers. After presenting the transceivers' characterization results in terms of BER for different OSNR values and received optical power levels, we analyzed the access optical power budget versus the Optical Signal-to-Noise Ratio (OSNR at the metro segment output) versus the optical power budget of the metro path. These results showed that merging the two networks is feasible, and we provided a design for this integration. Specifically, an OSNR in the metro path higher than 25 dB produces an optical power budget of 29 dB in the access network, compliant to the PON N1 class.

This result was achieved with coherent transmission and offline processing, as well as with pre-commercial transceivers that already exhibit a similar optical power budget. Our final comment is that, if an even higher optical power budget is required in the future (i.e., compliant to the PON E2 class), it can likely also be achieved with commercial transceivers by simply increasing their transmitted optical power.

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