Next Generation Coherent PONs: Technical Challenges and Outlook

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ABSTRACT

After the standardization of 50 Gbit/s PONs (ITU-T recommendation G.9804.3), the next generation of passive optical networks (PONs) is expected to achieve a data rate of 100 Gbit/s per λ and above, with a preference towards 200 Gbit/s per λ to maintain the usual x4 bit rate increase from one generation to the next. To support such high data rates, there is ongoing discussion about introducing coherent technologies into PONs for the first time. This decision poses several technical challenges that must be addressed. For instance, will future coherent PONs be based on single-carrier solutions (i.e., pure time division multiplexing) or multi-carrier solutions (wavelength division multiplexing, frequency division multiplexing)? And how will the burst-mode coherent DSP needed for the upstream channel be implemented?

1. INTRODUCTION

It is estimated [1] that over 1.5 billion fixed broadband subscriptions are active worldwide today. Most of these end users are connected through a Fiber-To-The-X (FTTX) architecture on a passive optical network in the access segment of the network. ITU-T standardization efforts for PONs have defined an already commercially available solution in the O-band (G.987 XG-PON [2]) at 10 Gbps based on intensity modulation and direct detection (IMDD) with on-off keying (OOK) modulation and PIN photodetectors. Moreover, ITU-T released the standard for 50G-PON (G.9804 [3]) in 2021, also in the O-band with OOK but using avalanche photodetectors (APDs), feed forward equalization (FFE) and strong forward error correction (FEC) algorithms.

Discussion on the next generation PON has already started within the ITU-T G.suppl.VHSP work program, focusing on two main potential solutions at the physical layer: i) the introduction of suitable digital signal processing (DSP) for signal equalization at the receiver, enabling the use of higher order modulation formats such as PAM-4, while still relying on the IMDD approach, but in combination with optical amplification, likely at both the transmitter and the receiver sides; ii) a paradigm shift that would officially introduce coherent detection in the short-reach access segment for the first time, leveraging the maturity that this technology has achieved in longer-reach communication systems and the economies of scale that would result from its adoption by a large number of users. Whether the target bit rate of the next implementation of PON will be 100 Gbps per λ or 200 Gbps per λ remains to be decided, although previous trends show about a four-fold line-rate increase with each new PON generation [4]. If that continues to be the case, research and industrial efforts will focus on achieving 200G PON on a single wavelength, a goal that is challenging to attain with IMDD-based systems, unless a strong DSP contribution is introduced, with a consequent increase in cost and complexity of the direct detection approach. In fact, transmission speeds obtainable through the traditional IMDD solutions are limited by a number of factors such as: i) the chromatic dispersion (CD) effect [5] that relegates the transmission wavelength to the O-band, where several legacy standards (e.g. G-PON, XG-PON, 50G-PON) have to coexist, thus restricting the available low-CD lambdas around the zero-dispersion wavelength of the standard single mode fiber (SMF); ii) the bandwidth limitation of the commercially available opto-electronic components that forced ITU-T to release the 50G-PON standards based on 25G-class devices [6]; iii) the direct detection receiver sensitivity and the fiber nonlinear effects that limit the lowest admissible received and the highest possible transmitted optical power, respectively, thus setting a stringent cap to the maximum achievable optical power budget (OPB).

In [7], [8] we demonstrated the performance of coherent detection in short-reach downstream communications, through numerical simulations, analytical models and experimental measurements. Unlike long-haul transmission affected by amplified spontaneous emission (ASE) noise, this scenario is influenced by noise sources at the receiver, especially in low received power conditions typical of PONs. Additionally, in [9], [10] we addressed the very interesting case of coherent detection employed in a metro+PON converged scenario, where the system is impacted by a combination of optical and electrical noise. Additionally, in [11], [12] we compared coherent detection with the IMDD approach, highlighting its potential to achieve high optical power budget levels at very high bit rates, up to 400 Gbps per wavelength. This capability opens the door to ultra-high-speed long-reach PON solutions in the C-band.

Although the coherent solution offers many advantages, it is still unclear at this stage how the main challenges associated to its possible adoption in the access segment will be addressed. For instance, the cost and complexity

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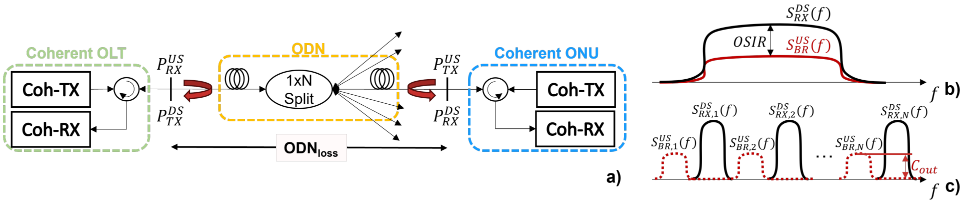

Figure 1: *a) Block diagram of the coherent PON. Qualitative signal and backreflections spectra in the b) single-carrier and c) multi-carrier case.*

of the coherent technology are still considered incompatible with a network segment where the cost per bit is largely borne by the end user. However, even if the economical barrier is overcome, for instance by deploying a coherent-lite version, by taking advantage of economies of scale through massive adoption, or by removing other costs (e.g. those related to the central offices in a metro-access converged scenario, or to the laser itself using semiconductor DFB lasers [13]), technical issues still need to be addressed. Since current coherent transceivers use a single laser (and thus a single λ) for both transmission and detection, an important consideration arises regarding how to deal with optical backreflections in a single-fiber point-to-multipoint scenario for coherent-PON in a bidirectional transmission. To this end, a transmission configuration based on digital multi-subcarriers has been proposed [14], [15]. Additionally, PONs operate according to a time division multiple access (TDMA) scheme common to all the optical network units (ONUs), an approach fundamentally different from the traditional wavelength division multiplexing (WDM) used for coherent communications. As a result, DSP algorithms must be properly designed for use in the new coherent-PON system, where burst-mode transmission has to be accounted for in the upstream direction from the ONU to the optical line terminal (OLT).

In this paper we analyze the latest proposed solutions for coherent-PON focusing on the two main aforementioned challenges regarding bidirectional transmission and burst-mode coherent detection.

2. Bidirectional Transmission

Coherent communications typically use two separate fibers for transmission in downstream (DS) and upstream (US) directions. Conversely, PON have been so far designed and deployed using a single SMF, where different lambdas are allocated for US (in O-band) and DS (in C-band) transmission. This wavelength arrangement ensures that back-reflected signals from one direction due to Rayleigh or Fresnel effects do not interfere with useful data-carrying signals in the opposite direction. However, standard coherent transceivers operate on a single wavelength, using the same laser for both data transmission and as a local oscillator (LO) at the receiver. As a result, a coherent-PON setup would look like the system in Fig. 1a, where both the OLT and the ONU are equipped with a circulator to separate the DS and US signals propagating along the same fiber. At the receiver side, both at the ONU and at the OLT, the useful received signal, attenuated due to propagation and splitting, overlaps in frequency with the backreflected portion of the transmitted signal in the opposite direction. Fig. 1b shows a qualitative example of the power spectral densities at the ONU coherent receiver for the DS received signal and for the backreflection due to the signal propagating US, respectively $S_{RX}^{DS}(f)$ and $S_{BR}^{US}(f)$.

ITU-T specifies an overall minimum optical return loss R_{ODN} in the optical distribution network (ODN) of 32 dB when all fiber terminations in the ODN are connected. In the presence of an open connector, this requirement lowers to 20 dB [16]. Assuming a transmitted DS signal with power P_{TX}^{DS}, at the ONU receiver we have a received power $P_{RX}^{DS} = P_{TX}^{DS} - ODN_{loss}$ in dB, where ODN_{loss} is the total loss (in dB) introduced in the ODN. Indicating the average power of the US signal as P_{TX}^{US}, at the ONU receiver, we also have its backreflected portion P_{BR}^{US}, calculated as $P_{TX}^{US} - R_{ODN}$ in dB. Thus, we can define an optical signal-to-interference-ratio (OSIR) at the ONU as the difference in dB between the useful signal power and the backreflected interference power: $OSIR = P_{TX}^{US} - P_{BR}^{US} = P_{TX}^{DS} - ODN_{loss} - P_{TX}^{US} + R_{ODN} = R_{ODN} - ODN_{loss}$. This very simple analysis of the involved power levels highlights that, even in the best case scenario when R_{ODN} =32 dB, assuming the typical power budget for a PON around 30 dB, the resulting OSIR in a bidirectional single-wavelength single-carrier coherent PON would be only about 2 dB. Such a low value demonstrates how critical it would be to employ the coherent technology as is in a PON scenario.

The two main alternatives to the traditional coherent architecture are the use of the single-carrier approach on two spectrally separated wavelengths for US and DS (solution implemented in all current PON standards), and the use of the multi-carrier approach on the same central wavelength, with interleaved subcarriers in the two directions for spectral separation [15], [17]. As the former option requires a significant re-design of the coherent transceiver with two different lasers for transmission and LO and a modified DSP for laser locking, many academic and industrial efforts are now targeting the use of digital subcarriers for crosstalk-free bidirectional coherent transmission. As depicted in Fig. 1c, in this case the backreflected signals from the subcarriers allocated for the US do not intentionally overlap in frequency with the DS subcarriers, thus improving the system robustness against coherent crosstalk. Fig. 2 shows, as an example, the achievable ODN loss at $BER = 10^{-2}$

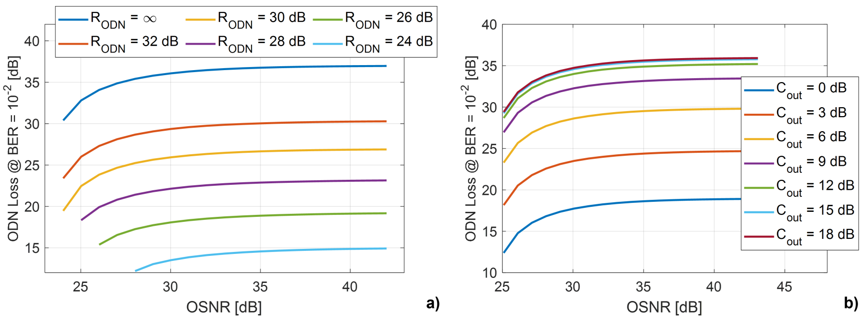

Figure 2: ODN Loss at $BER = 10^{-2}$ for a) single-carrier same wavelength and b) multi-subcarrier 50 GBaud PM-16QAM transmission vs. $OSNR$ for several values of the backreflections level. In b) the backreflected signal is 32 dB below the transmitted one.

for a 50 GBaud PM-16QAM metro-access converged system [10] as a function of the OSNR at the output of the metro segment, obtained through the analytical model presented in [18]. Fig. 2a shows that $R_{ODN} = 32$ dB is enough to decrease the single-carrier same-wavelength coherent PON performance by about 7 dB. Moreover, a very high OSNR above 30 dB is required in this case to enable the lower N1 PON class with 29 dB ODN loss. On the other hand, Fig. 2b shows that in the multi-carrier, subcarrier-interleaved system, with 16 PM-16QAM 4 GBaud subcarriers, significantly higher ODN loss values can be tolerated when the out-of-band subcarrier spectral rejection (C_{out}) is sufficiently high. Obviously, due to the specific spectral allocation of the multi-carrier solution, the advantage in terms of resilience to backreflections is offset by a twofold reduction in the maximum achievable data rate for a given analog-to-digital and digital-to-analog converters sample rate.

3. Burst-Mode Detection

Whether in single-carrier or multi-carrier configuration, coherent PON will likely require time division multiple access (TDMA) in the upstream direction to avoid collision of signals sent by multiple ONUs at the optical combiner/splitter, and to take advantage of statistical multiplexing, making full use of the PON channel capacity. Thus, traditional DSP algorithms need to be replaced or properly modified with suitable fast-converging algorithms, to meet the constrained imposed, as a reference, by the 50G-PON standard, that defines a 100 ns convergence timescale for the DSP in IMDD PON. Many recent works have addressed this subject, experimentally demonstrating that coherent burst-mode detection can be achieved through efficient digital techniques in both single-carrier and multi-carrier PON, often enabling high flexible rates in a mixed scenario with both time and frequency division multiple access (TFDMA).

In [19] the authors propose a novel 416-symbol-long training sequence at the beginning of the burst before the payload, and the use of data-aided DSP enabling frequency offset estimation, timing recovery, frame synchronization, and equalizer training with pilot-based carrier phase recovery with 52 ns convergence time. The system is based on 8 digital subcarriers modulated with 8 GBaud PM-16QAM for a total 400 Gbps net bit rate, and provides more than 35 dB optical power budget. The convergence time is increased to 102.4 ns in [20] with a proposed 2560-symbol preamble in a single-carrier system at 25 GBaud with QPSK modulation. The same sequence can be used with different payload associated with various modulation formats including PM-16QAM and PM-64QAM to ensure net transmission rates up to 300 Gbps and a rate-flexible approach in the coherent PON scenario. Flexibility in US direction is ensured by a frame detection algorithm based on power detection, able to determine, entirely in the time domain, the duration of the burst and therefore the modulation format used inside a specific payload, taking advantage of the power drop during the guard band between consecutive bursts. This approach requires that the entire burst be stored before DSP can be applied, potentially leading to drawbacks related to latency and memory occupancy. Two physical layer architectures are analyzed showing good performance, one based on two-fiber configuration for US and DS signal separation and one with wavelength division multiplexing (WDM) in DS and TDM in US. However, the measured achievable optical power budget in the 25 GBaud PM-64QAM case does not reach the minimum 29 dB required by PON standards. Finally, the flexible TWDM coherent PON demonstrated in [21] supports symbol rates up to 200 Gbps in DS with four 50G subcarriers and 100 Gbps in US with eight 12.5 Gbps subcarriers. The system employs a full coherent transceiver at the OLT and a simplified coherent transceiver at the ONUs equipped with one DAC and ADC, one Mach Zender modulator, an optical coupler, a single balanced photodetector and two DFB lasers. Simplification and cost-effectiveness of the coherent approach are achieved by employing single-polarization heterodyne detection and Alamouti coding in DS and mono-dimensional signal generation with real-valued carrier-less amplitude phase signals at the ONU. While the achieved bit rates may not match those of full-coherent systems, this simplified coherent PON solution can still offer significantly high power budgets exceeding 32 dB.

4. CONCLUSION

We have presented and discussed the main technical challenges and recently proposed solutions for the possible future adoption of coherent detection technology in the context of point-to-multipoint links in a PON environment. We have focused on two key requirements that the coherent approach must meet if applied to the access segment: robust bidirectional communication on a single fiber with reduced backreflection-related impairments and burst upstream detection with fast-convergent DSP solutions. While many obstacles remain, we have shown that research and industrial efforts are intensifying with the goal of bringing this technology to a maturity level that will allow unprecedented performance in the PON access network in terms of speed, flexibility, number of users, reliability and cost-efficiency.

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REFERENCES

[1] Regional global Key ICT indicator aggregates, ITU, November 30, 2023. [Online]. Available: https://www.itu.int/en/ITU-D/Statistics/Documents/facts/ITU_regional_global_Key_ICT_indicator_aggregates_Nov_2023.xlsx

[2] "10-Gigabit-capable passive optical networks (XG-PON): Physical media dependent (PMD) layer specification," ITU-T G.987.2.

[3] "50-Gigabit-capable passive optical networks (50G-PON): Physical media dependent (PMD) layer specification," ITU-T G.9804.3.

[4] V. Houtsma and D. van Veen, "Higher-speed PONs based on data center technology and optics [Invited]," *Journal of Optical Communications and Networking*, vol. 16, no. 2, pp. A98-A104, February 2024.

[5] P. Torres-Ferrera et al., "Experimental Demonstration of 100 Gbps/λ C-Band Direct-Detection Downstream PON Using Non-Linear and CD Compensation with 29 dB+ OPL Over 0 Km–100 Km," *Journal of Lightwave Technology*, vol. 40, no. 2, pp. 547-556, 2022.

[6] R. Bonk et al., "50G-PON: The First ITU-T Higher-Speed PON System," *IEEE Communications Magazine*, vol. 60, no. 3, pp. 48-54, March 2022.

[7] G. Rizzelli et al., "Scaling Laws for Unamplified Coherent Transmission in Next-Generation Short-Reach and Access Networks," *Journal of Lightwave Technology*, vol. 39, no. 18, pp. 5805-5814, Sept.15, 2021.

[8] G. Rizzelli and R. Gaudino, "Sensitivity and Scaling Laws of Unamplified Coherent Architectures for Intra-Data Center Links Beyond 100 Gb/s," in *Prof. of 2019 21st International Conference on Transparent Optical Networks (ICTON)*, Angers, France, 2019, pp. 1-4.

[9] M. Casasco et al., "Experimental Demonstration of a 400 Gb/s Full Coherent Transmission in an in-field Metro-Access scenario," in *Proc. of 2023 23rd International Conference on Transparent Optical Networks (ICTON)*, Bucharest, Romania, 2023, pp. 1-4.

[10] G. Rizzelli et al., "Experimental Demonstration of In-Field 400G Coherent Metro-Access Convergence," in *Proc. of Optical Fiber Communications Conference and Exhibition (OFC)*, 2024, paper W1J.1.

[11] G. Rizzelli et al., "An Analytical Model for Performance Estimation in Modern High-Capacity IMDD Systems," *Journal of Lightwave Technology*, vol. 42, no. 5, pp. 1443-1452, March 1, 2024

[12] G. Rizzelli and R. Gaudino, "Planning Tools for Next Generation DSP-based Passive Optical Networks above 50G," *Journal of Optical Communications and Networking*, Vol. 16, Issue 7, pp. C88-C96 (2024)

[13] R. Gaudino et al., "On the use of DFB Lasers for Coherent PON," in *Proc. of Optical Fiber Communication Conference (OFC)*, 2012, paper OTh4G.1.

[14] J. Zhou et al., "Flexible Coherent Optical Access: Architectures, Algorithms, and Demonstrations," *Journal of Lightwave Technology*, vol. 42, no. 4, pp. 1193-1202, 15 Feb.15, 2024.

[15] C. Castro et al., "Scalable filterless coherent point-to-multipoint metro network architecture," *Journal of Optical Communications and Networking*, vol. 15, no. 5, pp. B53-B66, May 2023.

[16] "Broadband optical access systems based on Passive Optical Networks (PON)," ITU-T G.983.1.

[17] P. Torres et al., "Single-Fiber Bidirectional Transmission using 400G Coherent Digital Subcarrier Transceivers," in *Proc. of Optical Fiber Communications Conference and Exhibition (OFC)* (2024), Tu3E.5.

[18] G. Rizzelli et al., "An Analytical Model for Coherent Transmission Performance Estimation after Generic Jones Matrices," *Journal of Lightwave Technology*, vol. 41, no. 14, pp. 4582-4589, 2023.

[19] H. Wang et al., "Fast-Convergence Digital Signal Processing for Coherent PON Using Digital SCM," *Journal of Lightwave Technology*, vol. 41, no. 14, pp. 4635-4643, July 15, 2023.

[20] H. Zhang et al., "Experimental Demonstration of Rate-Flexible Coherent PON Up to 300 Gb/s," *Journal of Lightwave Technology* (in press), doi: 10.1109/JLT.2024.3366163.

[21] J. Zhou et al., "Flexible Coherent Optical Access: Architectures, Algorithms, and Demonstrations," *Journal of Lightwave Technology*, vol. 42, no. 4, pp. 1193-1202, 2024.