Experimental Demonstration of In-Field 400G Coherent Metro-Access Convergence

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Abstract: We present an experimental demonstration and analytical scaling of optically amplified metro combined with PON access transmission over installed fibers, using coherent 50GBaud PM-16QAM and discuss the technical feasibility of future 400G metro-access convergence.

1. Introduction

The two biggest revolutions in optical networking in the last 15 years are undoubtedly optically amplified DSP-based coherent transmission, that lead to an enormous increase in performance in long haul and (more recently) metro networks, and the widespread deployment of Fiber-to-the-Home worlwide, where more than 800 million fibre broadband subscribers are estimated today, almost all on the Passive Optical Network (PON) architecture [1]. For techno-economic reasons, PON transmission is based on intensity modulation and direct detection (IM-DD), like all the other shorter reach fiber applications. The PON IM-DD-based IEEE and ITU-T standards are anyway approaching today fundamental physical layer limitations in terms of increasing transmission speed (see the recent 50G-PON ITU-T standard [1]), but also in reach and/or optical power budget [2]. These shortcomings are today being addressed in an ITU-T discussion on future 100 or 200 Gbps/λ PON by considering new solutions, such as 4-PAM as opposed to traditional binary OOK, even more powerful FEC and strong of pre- or post-equalization through DSP [2, 3]. While this brainstorming is not closed yet, it seems that for 100G-PON, IM-DD will again be used. Thus, many research groups are today studying which solutions may in the future enable even higher speeds, if and when PON targets will try to go beyond 100 Gbps/λ. This is also the topic of the current paper, where we will present some of the implications of using coherent transmission also for PON.

The cost of coherent transceivers is currently prohibitive for PON applications. However, it is evident that real commercial demand for such high speeds in PON will happen in several years from now (e.g. in conjunction and support of future 6G wireless front-hauling or mid-hauling) and in such a relatively long time frame, one can envision a significant cost reduction of coherent technologies (see for instance the progress in this direction in the current ZR-Optic initiative). Moreover, coherent in PON would also undoubtedly provide unprecedented transmission performance [4] thanks to the improved sensitivity and DSP-enabled flexibility, so that at least three major upgrades in PON can be envisioned:

- moving PON wavelength out of the O-band (which was a must for the recently released 50G-PON standardd, to combat IM-DD chromatic dispersion CD limitations), enabling again the use of the C-band (and even, if needed, the adjacent L and S bands)
- extending reach towards longer reach PON, targeting significantly more than the current 20-40 km
- linked to the previous point, a significant network-level re-organization would also be possible since, as we consider in this paper, it would become technically feasible to send the same transmitted optical wavelength transparently along different sections of the network, in particular allowing an all-optical convergence between the metro and the access-PON segments without employing different transmission/detection/switching technologies in the two segments, thus effectively establishing convergence of the whole optical network to a full-coherent ultra-high-speed system.

In this paper, we address one of the key points to be studied before a decision toward such a significant technological revolution is taken, and in particular we investigate the physical layer scalability of a possible all-optical metro-access transmission. Given the 3-page constraint of this Conference, we focus on downstream (DS) transmission only, and briefly discuss upstream in the Conclusion Section.

A metro+PON transmission has to meet the requirements imposed by the two segments, handling the constraints associated to the required optical signal to noise ratio (OSNR), to the filtering effects inside reconfigurable optical add-drop multiplexers (ROADMs) while still ensuring optical power budget (OPB) levels above 29 dB for the PON optical distribution network (ODN) loss. To this end, in this paper we improve and extend the work presented in [5], demonstrating 400 Gbps (50 GBaud PM-16QAM) full-coherent downstream along two sections of an installed fiber link, separated by a commercial ROADM. Then, using these experimental results, we fit the free parameters required by a larger theoretical scalability investigation. We focus on finding the resulting joint limitations in terms of available OSNR at the output of the metro section and target OPB in the PON segment.

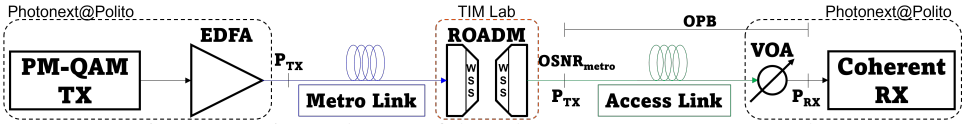

Fig. 1: Experimental setup of the coherent metro-access network.

2. Experimental Setup and Results

A simplified block diagram of the experimental setup is shown in Fig. 1. Transmitter and receiver are located in the PhotoNext laboratory at Politecnico di Torino, whereas the ROADM is hosted at the TIM laboratory. The two sites are connected through two 16.5 km fiber links deployed over a legacy infrastructure underground in the city of Turin, Italy. At the transmitter, a 50 GBaud PM-16QAM signal at 1550 nm is generated through a 92 GS/s arbitrary waveform generator driving a nested Mach-Zender modulator, then EDFA-amplified before the input of the first fiber link, representing the metro section. At its other edge, a commercial ROADM is used to route and re-amplify the signal towards the PON segment. Three intermediate central offices are passed through along the link, emulating the scenario of network operator sites' consolidation enabled by a long reach metro access solution.

Even though we use a single span and a single ROADM in the metro segment, we wanted to parametrize results vs. the $OSNR_{metro}$ available at the metro segment output. To this end, we intentionally use the ROADM internal variable optical attenuators (VOA) to emulate different span loss and adjust the resulting OSNR. The resulting signal is set to achieve $P_{TX} = 11dBm$ and sent again on another deployed fiber, then to a VOA that emulates the PON splitter loss (in the following graphs, the access section OPB is defined as the sum of the access fiber loss plus the additional VOA attenuation). Finally, the signal is coherently detected using commercial components and then acquired by 200 GS/s real-time oscilloscope and off-line processed using standard DSP techiques to evaluate the resulting bit error rate (BER). We show in Fig. 2a BER vs. received optical power P_{RX} for different $OSNR_{metro}$ (defined on a bandwidth equal to the symbol rate, i.e. on 50 GHz in our experiments), for a case in which the passband of the wavelength-selective switch (WSS) inside the ROADM is set to 300 GHz (i.e. a situation where there is no optical filtering penalty). This is an important type of measurement to characterize a coherent transceiver, since it allows to obtain performance metrics that are very relevant for a metro+PON transmission. For instance, it allows to obtain the results shown in Fig. 2b and c, that are the countour plots at $BER = 10^{-2}$ and $2 \cdot 10^{-2}$ (typical for hard and soft decision FEC respectively) vs. $OSNR_{metro}$ and the OPB (in dB) in the PON segment, a type of representation that is very relevant to discuss the transmission ultimate scalability, as further discussed in the next Section. For instance, the curves show that at $BER = 10^{-2}$ the 29-33 dB OPB required by PON OPB loss classes can be easily achieved for all measured $OSNR_{metro}$ values, while only for the (highest) 35 dB OPB class the $OSNR_{metro}$ should stay above 23 dB.

In Fig. 2b and c, we report the results for different types of filtering in the ROADM (different WSS BW and different misalignment Δf_c between the central frequency of the WSS and that of the signal, ranging from 12.5 GHz to 25 GHz), showing that the transmission is quite robust versus imperfect filtering, apart from the somehow extreme situation of a WSS bandwidth equal to 75GHz and for Δf_c=25 GHz. The three Figures also include curves obtained in back-to-back (BtB) without propagation on the fiber link, and with the total 33 km fiber link but without ROADM (fiber loopback). A slight performance reduction of about 0.7 dB at $BER = 10^{-2}$ with respect to the BtB, even for very high OSNR, is attributable to the PDL introduced by the ROADM (1.1 dB from datasheet).

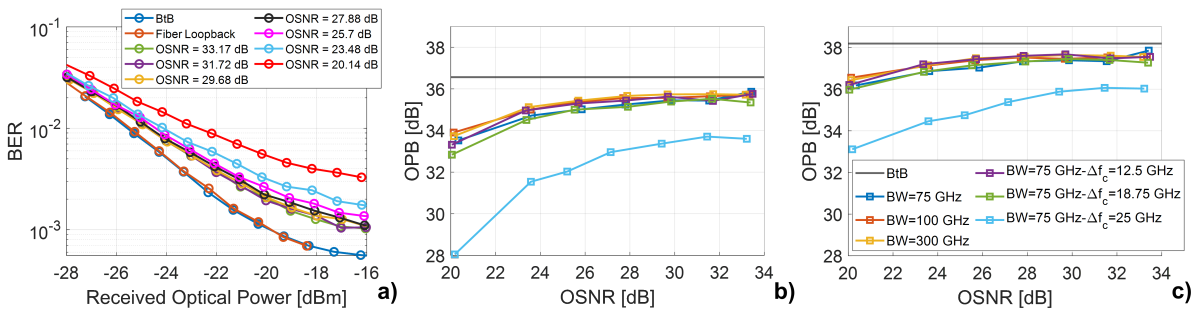

Fig. 2: a) Measured BER vs. P_{RX} in BtB, with the fiber link and for different $OSNR_{metro}$. b) OPB at $BER = 10^{-2}$ vs OSNR for different WSS BW and Δf_c values. c) OPB at $BER = 2 \cdot 10^{-2}$ vs. $OSNR_{metro}$ for different WSS BW and Δf_c values. Legend in c) applies to b) as well.

3. Analytical Performance Formulae for Scalability Discussion

In [4, 6], we developed an analytical model to predict the performance (in terms of SNR and BER) of a coherent receiver in optically amplified, unamplified or mixed transmission scenarios. The model is based on the fitting of four parameters representing the transimpedence amplifier (TIA) noise current (i_{TIA}), the common mode rejection ratio ($CMRR$) of the receiver, the photodiode responsivity (R) and the SNR_Q parameter to account for additional implementation penalties such as quantization noise, phase noise and imperfect constellation generation, plus

the avaliable OSNR and the shot noise in the coherent detection process. We apply this analytical tool to the experimental measurements reported in previous Section to be then able to obtain some more general scalability graphs at different modulation formats and baud rate. The fitting procedure was performed at 25 GBaud and on the experiments at the highest OSNR only (returning the values $i_{TIA} = 20.73 \cdot 10^{-12}[A/\sqrt{Hz}]$, $CMRR = -18.35$ dB, $R = 0.067$ A/W and $SNR_Q = 17.7$ dB) but it obtained an excellent match, particularly around the target BER of modern FEC systems, on all the cases reported in Fig. 3a i.e. two baud rates and over a wide range of different P_{RX} and $OSNR_{metro}$ values.

The analytical formula and the fitted parameters were then used to obtain results shown in Fig. 3b, which are reported as an example of a scalability analysis in terms again of achievable maximum $OSNR_{metro}$ and OPB_{PON} at the two different target BERs. Just as an example, Fig. 3b shows potentially extremely high OPB_{PON} levels for 200G PM-QPSK, allowing in this case to envision extra-high splitting factors in the PON, if needed in some future network configurations related to central offices' consolidation, without particularly demanding $OSNR_{metro}$ values.

4. Final comments

Some ongoing research projects are starting today to study a future all-optical convergence between the metro and PON segments enabled by coherent transmission. This completely novel scenario, when and if it happens, will require a complete rethinking of the transmission and networking paradigms used so far in the two segments, and a lot of work is still needed. In this paper, we started to show that, focusing only on downstream transmission, the physical layer scalability using commercial coherent transceiver is extremely promising (very high achievable PON ODN loss with modest requirements on $OSNR_{metro}$ and good resilience to optical filtering mismatch) at 200G and even 400G bit rates. Another relevant message given by our paper is that the coherent transceiver should be characterized not only in terms of BER vs. $OSNR_{metro}$ but also jointly in terms of P_{RX}, since the received power will be much lower than the typical values seen in long-haul coherent systems. Besides techno-economics, other physical layer issues are still open and requires further research work. In particular, coherent metro-access would require a solution for handling also the upstream transmission (US) on the PON single fiber, a point that opens two somehow joint issues: how to obtain multiple access among all the involved ONUs (unless the target is a pure point-to-point link on a metro+PON tree, a case that may be of interest in some specific situations) and how to avoid coherent crosstalk between the two PON transmission directions. Given the PON target OPB, it is easy to show that DS and US transmission should use disjoint optical spectra, otherwise Rayleigh Back Scattering and/or optoelectronic component reflections would kill transmission performance. Thus, two different wavelengths should be used for US and DS for single-carrier coherent transceivers (which is NOT the common configuration of today commercial coherent transceivers), or different (i.e. spectrally disjoint) optical subcarriers in a multi-carrier coherent system.

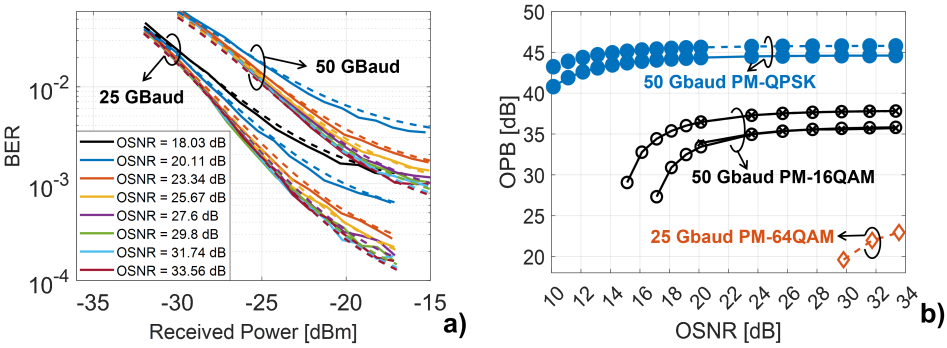

Fig. 3: a) Experimental (solid) and analytical (dashed) BER vs P_{RX} at different $OSNR_{metro}$ for 25 and 50 GBaud PM-16QAM. b) OPB vs. $OSNR_{metro}$ at $BER = 10^{-2}$ (solid) and $2 \cdot 10^{-2}$ (dashed) for analytical 50 GBaud PM-QPSK (blue, dots), analytical (circles) and experimental (crosses) 50 GBaud PM-16QAM (black) and analytical 25 GBaud PM-64QAM (orange, diamonds).

Acknowledgments This work was carried out in the PhotoNext Center facilities at Politecnico di Torino (www.photonext.polito.it) and it has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101092766 (ALLEGRO Project). Mrs. Casasco's PhD is sponsored by TIM.

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