Nonlinear Phase Shift Pre-compensation for Improved Power Budget in a 200 Gbps Simplified Coherent PON

Pablo Torres-Ferrera*, Md. Saifuddin Faruk, Istvan Bence Kovacs and Seb J. Savory
Electrical Engineering Division, Department of Engineering, University of Cambridge, Cambridge CB3 0F, UK
*pt449@cam.ac.uk

Abstract: We experimentally investigate a simple fiber nonlinearity pre-compensation technique for 200 Gbps PON downstream using a simplified coherent receiver. A power budget improvement of 1.0 dB is achieved for 50 km reach in C-band.

1. Introduction

Next-generation TDM-PON with 50 Gbps single wavelength (λ) line rate has been recently standardized by ITU-T. For future PON, a four-fold rate of 200 Gbps is considered a rational choice [1]. Since current IM-DD based approach is forecasted to fail to meet the loss budget requirements of such high-capacity TDM-PON [2], coherent technology is considered a solution to achieve this [1-2]. However, the complexity and cost of current coherent technology are the limiting factors for its deployment in the PON scenario. Therefore, low complexity coherent transceiver design for PON is one of the current research interests.

Recently, a simplified heterodyne coherent receiver with a single 3-dB coupler and a balanced photodiode employing transmitter side Alamouti coding based polarization diversity has been demonstrated for 100 Gbps/λ PON using QPSK modulation format [3]. For simplicity we will refer to this approach as "simplified coherent" in the rest of this paper. Using this simplified coherent system, but employing 16-QAM format, 200 Gbps/λ PON experiments have been performed, achieving a power budget of 32.8 dB (with launch power (P_{TX}) of 11.5 dBm and a reach (L) of 25 km) [4] and 29 dB (with P_{TX} = 8 dBm and L = 20 km) [5], respectively. In [4], it is shown that the maximum launch power of 11.5 dBm, and thus the achievable power budget, is constrained by fiber non-linearities.

In this paper, we introduce to the 200 Gbps/λ PON 16-QAM heterodyne simplified coherent system a nonlinearity pre-compensation (NLPC) technique to mitigate the impact of fiber self-phase modulation (SPM). The NLPC is placed at the transmitter side in order to add the extra complexity to the optical line terminal (OLT), which is a shared element, rather than the optical network unit (ONU). We experimentally demonstrate an overall power budget enhancement of 1.0 dB for 50 km reach due to NLPC, thus achieving a power budget of 35 dB in C-band.

2. Experimental setup

The experimental setup to investigate the 200 Gbps/λ PON downstream system is shown in Fig. 1. At the transmitter, a 50 GBaud 16-QAM signal is generated. To make the receiver polarization-insensitive, Alamouti coding in two polarization channels is applied [3]. After Alamouti coding, the signals are shaped with root-raised cosine (RRC) filtering with a roll-off factor, r = 0.1. Following this, a pre-emphasis FIR filter was applied, targeting a flat transmitted spectrum compensating for transmitter impairments. The next step consists of applying a NLPC technique, with reduced complexity (requiring only 28 real multiplications per sample), which jointly processes both polarization components, to introduce a compensation phase modulation calculated as [6]:

$$\phi_{comp}^{x(y)} = -b_1 \gamma L_{eff} \left[P_{x(y)}(n) + b_2 P_{y(x)}(n) \right],$$

where b_1 is a dimensionless scaling factor, γ is the fiber nonlinear coefficient, $P_{x(y)}$ the signal power for the $x(y)$-polarization, b_2 is the cross-polarization coupling factor and L_{eff} is the effective fiber length. The parameters b_1 and b_2 are optimized for each reach and launch power, unless otherwise stated. The pre-compensated signal is then loaded into a 100 GSa/s arbitrary waveform generator (AWG) which performs the digital-to-analog conversion

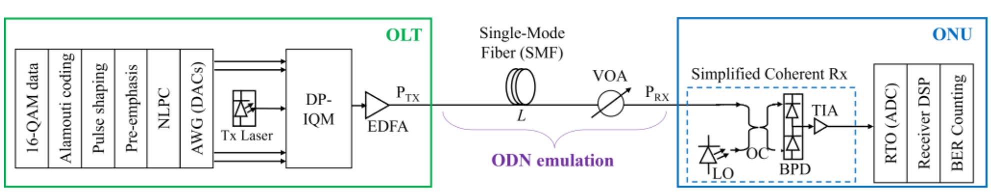

Fig. 1 Experimental setup for downstream operation (P_{TX}: launched power, P_{RX}: received optical power, OC: optical coupler).

(DAC), generating the driving signals of a commercial dual-polarization IQ modulator, operating with central laser frequency of 193.9 THz and having a 6-dB bandwidth of 40 GHz. The modulated optical signal is then amplified (setting the launch power P_{TX}), using an erbium-doped fiber amplifier (EDFA) with a noise figure of 4.5 dB, and launched into a 25 km or 50 km standard single-mode fiber (SMF). After the SMF, a variable optical attenuator (VOA) is placed to set the received optical power (ROP) and thus the Optical Distribution Network (ODN) loss. At the ONU side, the signal is detected with a simplified coherent front-end composed of a 3-dB coupler, a 70 GHz balanced photodiode (BPD), and a local oscillator (LO) laser having 15.5 dBm output power and central frequency of 193.926 THz (*i.e.*, shifted by 26 GHz from the transmitted laser). After photo-detection, the signal is digitized and stored using a real-time oscilloscope (RTO) with a single 10-bit analog-to-digital converter (ADC) operating at a sampling rate of 256 GSa/s and a bandwidth of 70 GHz. Then, off-line digital signal processing (DSP) is applied to recover the transmitted signals. First, the intermediate frequency (IF) is estimated, and the signal is down-converted to the baseband. Then, a frequency domain fixed chromatic dispersion filter is used. After frame synchronization, the signal is resampled at 2 Sa/symbol. Following this, adaptive MIMO equalization and carrier recovery are performed using a least-mean-algorithm (LMS) based method described in [4, 7]. Finally, the symbols are decoded and BER is estimated using direct error counting.

3. Experimental results and discussion

To compute the power enhancement that the NLPC can provide, we evaluate the optimum launch power and the resulting achievable power budget, with and without NLPC, for a 50 km reach. We vary the launch power (P_{TX}) into the fiber and evaluate the corresponding sensitivity at the BER FEC limit of 10^{-2}. The power budget, also referred as the ODN loss, is then computed as the difference between launch power and sensitivity, both expressed in dBm. Our measurement results are shown in Fig. 2(a). An optimum launch power of 11 dBm and 10 dBm, resulting in power budgets of 35 dB and 34 dB, is obtained when using and not using NLPC, respectively. Therefore, an overall 1-dB gain from NLPC is measured for 50 km reach.

To quantify the degree of non-linear mitigation, we proceed evaluating the system back-to-back (BtB) sensitivity without NLPC, considered as the baseline reference for power penalty calculations. In Fig. 2(b), the BtB bit error ratio (BER) as a function of ROP curve is shown in black squares. A BtB sensitivity of -25.9 dBm is measured at a BER FEC limit of 10^{-2}. In Fig. 2(b), we also plot BER versus ROP curves for the cases of 10 dBm and 11 dBm launch powers, using and not using NLPC. Without NLPC, a 1.1 dB degradation is observed when increasing the launch power from 10 to 11 dBm. By applying the NLPC, this 1.1 dB penalty is almost fully recovered. An extra 0.9 dB sensitivity gain is observed due to NLPC for 10 dBm launch power. The fact that a same sensitivity is obtained for P_{TX} = 11 dBm w/NLPC and for P_{TX} = 10 dBm wo/NLPC, is reflected in the 1 dB overall gain from NLPC.

As shown in Fig. 2(a), for low launch powers, the sensitivity degradation is small (for instance, ~0.2 dB for P_{TX} = 4 dBm) as compared to the BtB situation. Thus, the NLPC gain is also small. For P_{TX} = 4 dBm, the penalty is practically fully compensated by the NLPC block at the BER target. Then, we can assume a full DSP linear impairments compensation, and attribute the remaining 0.2 dB penalty to fiber nonlinearity. The ability of the NLPC scheme to compensate for nonlinearity decreases as the launch power increases, since stronger distortions are induced. For instance, considering a P_{TX} = 11 dBm, the sensitivity degradation, without NLPC, significantly increases to ~3 dB with respect to BtB, as observed in Fig. 2(b). By applying the NLPC, a 1.1-dB improvement is achieved. Considering a launch power of 10 dBm, the power penalty with respect to BtB is ~2-dB wo/NLPC, and using NLPC a 1.0 dB is gained. At higher than 11 dBm launch powers, the NLPC gain is even higher, but the obtained power budget is sub-optimal due to stronger sensitivity degradations.

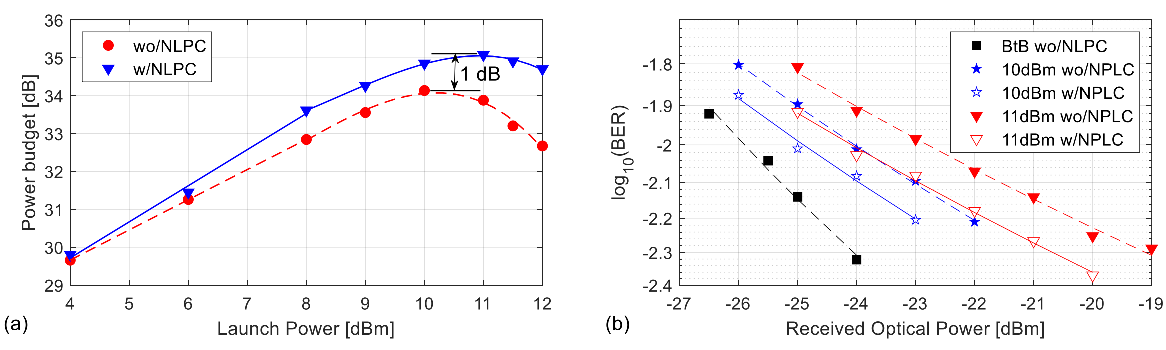

Fig. 2 (a) Power budget at BER = 10^{-2} as a function of launch power for 50 km reach; (b) BER versus ROP curves for BtB and 50 km reach with different launch powers, with and without NLPC.

We repeat the same analysis, but for 25 km reach (the full obtained results are not shown here for space limitations). The effective length of 25 km and 50 km fibers are 14.18 km and 18.19 km, respectively. Then, for the 25 km case, we expect a (moderate) smaller impact due to fiber nonlinearity. In fact, we measured higher (compared to the 50 km case) optimum launch power of 11.5 dBm. The sensitivity degradation is also smaller, resulting in higher achievable power budgets of 34.8 dB (wo/NLPC) and 35.6 dB (w/NLPC). Then, an overall NLPC gain of 0.8 dB was obtained for 25 km.

In a TDM-PON system, a given pre-distortion should work well for all ONUs, irrespective of their distance to the OLT. In Fig. 2, the NLPC parameters were optimized for 50 km. To guarantee feasibility over the full set of possible OLT-ONU distances using a fixed nonlinear pre-compensation, we investigate the following situation. We identified the optimum NLCP parameters for the longest reach at its optimum power (i.e.., L = 50km and P_{TX} = 11 dBm), and we then evaluate the performance of shorter links (0 km and 25 km) keeping fixed the same NLPC parameters. We anticipate a sub-optimal NLPC performance in these conditions, which could be compensated by enabling a higher launch power. We compare against the case without NLPC, using the optimum power of P_{TX} = 10 dBm obtained for 50 km reach wo/NLPC. The resulting measurements are reported in Fig. 3, in form of (a) BER vs. ROP curves and (b) a summarizing graph. We found that the ONU positioned 0 km from the OLT has a sensitivity degradation of around 0.6 dB when applying the NLPC optimized for 50 km. In contrast, the ONU located 25 km from the OLT has a sensitivity gain of 0.3 dBm, with respect to the sensitivity obtained for P_{TX} = 11 dBm when not using any NLPC, even if applying a sub-optimal NLPC. As show in Fig. 3(b), we always have a higher power budget in case of applying NLPC, even for the 0 km case, since the NLPC enable to operate with a 1-dB higher launch power optimum for the longest reach. We thus verified that applying NLPC with optimized parameters for the farthest ONU will not impose power budget losses to the closer ONUs from the OLT.

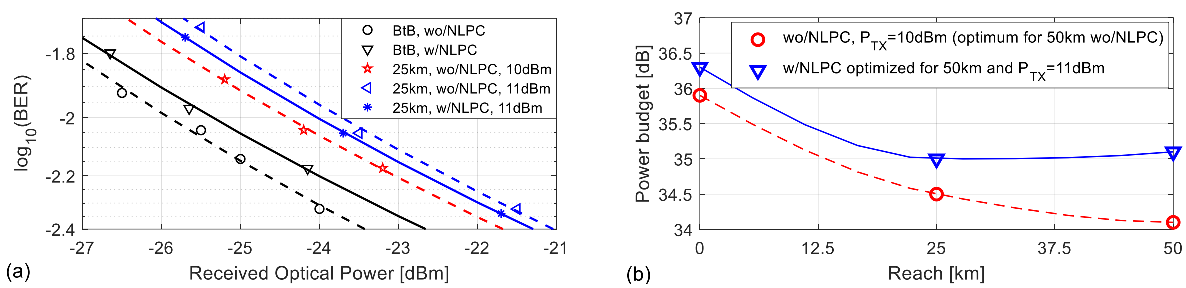

Fig. 3 (a) BER versus ROP curves for BtB and 25 km reach with different launch powers without NLPC and with NLPC having parameters optimized for 50 km reach and 11 dBm launch power; (b) Power budget at BER=10^{-2} versus reach summarizing the cases presented in Fig. 3(a) for BtB and 25 km, and in Fig. 2(b) for 50 km.

4. Conclusion

We have investigated a simple NLPC technique that gains 1.0 dB of power budget in a 200 Gbps/λ PON downstream using a simplified coherent receiver with OLT side Alamouti coding, thus achieving a maximum power budget of 35 dB for 50 km C-band operation. The optimum NLPC parameters for 50 km reach can be used for shorter links without power budget degradation enabled by the optimum launch power increase for the longest reach.

Acknowledgement: P. Torres-Ferrera acknowledges the support of SECTEI, Mexico City. The other authors thank funding from EPSRC grants [EP/S022139/1, EP/R035342/1]. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) license to any Author Accepted Manuscript version arising. Data underlying the results presented here are at https://doi.org/10.17863/CAM.89631

References

[1] M. S. Faruk, et al., "Coherent passive optical networks: Why, when, and how," *IEEE Com. Mag.*, **59** (11), pp. 112-117, (2021).

[2] P. Torres-Ferrera, F. Effenberger, M. S. Faruk, S. J. Savory, R. Gaudino, "Overview of high-speed TDM-PON beyond 50 Gbps per wavelength using digital signal processing," *J. Opt. Comm. Netw.*, DOI: 10.1364/JOCN.468920 [Accepted], (2022).

[3] M. S. Erkılınç, et al., "PON transceiver technologies for ≥50 Gbits/s per λ: Alamouti coding and heterodyne detection [Invited]," *J. Opt. Commun. Netw.* **12**, pp. A162-A170, (2020).

[4] M. S. Faruk, X. Li, S. J. Savory, "Experimental demonstration of 100/200-Gb/s/λ PON downstream transmission using simplified coherent receivers," *Opt. Fiber Comm. Conf.* (OFC), San Diego, CA, USA, **Th3E.5**, (2022).

[5] D. Zhang, et al., "Experimental demonstration of 200 Gb/s/λ coherent PON with a low-complexity receiver and a multi-purpose neural network," *Opt. Fiber Comm. Conf.* (OFC), San Diego, CA, USA, **Th3E.4**, (2022).

[6] X. Liu, F. Buchali, R. W. Tkach, "Improving the nonlinear tolerance of polarization-division-multiplexed CO-OFDM in long-haul fiber transmission," J. Lightwave Technol., **27**, pp. 3632-3640 (2009).

[7] M. S. Faruk, H. Louchet, M. S. Erkılınç, S. J. Savory, "DSP algorithms for recovering single-carrier Alamouti coded signals for PON applications," *Opt. Express*, **24**, pp. 24083-24091, (2016).