Real Time 100 Gbit/s/λ PAM-4 Experiments for Future Access Networks over 20 km with 29 dB Optical Budget

Jérémy Potet, Mathilde Gay, Laurent Bramerie, Hallak Hamza, Fabienne Saliou, Gaël Simon, Philippe Chanclou

Real Time 100 Gbit/s/λ PAM-4 Experiments for Future Access Networks over 20 km with 29 dB Optical Budget

Jérémy Potet[(1),(2)], Mathilde Gay[(1)], Laurent Bramerie[(1)], Hamza Hallak Elwan[(1)], Fabienne Saliou[(2)], Gaël Simon[(2)], Philippe Chanclou[(2)]

[(1)] Univ Rennes, CNRS, Institut FOTON - UMR 6082, F-22305 Lannion, France, gay@enssat.fr
[(2)] Orange, 2 avenue Pierre Marzin, 22300 Lannion, France

Abstract *We achieve 29 dB of optical budget and 20 km reach in a 50 Gbaud PAM-4 experiment at pre-FEC BER threshold of 10^{-2}. A PDFA at OLT, a SOA-PIN at ONU are used in a real time experiment.*

Introduction

While the international telecom union (ITU-T) is currently normalizing the 50 Gbit/s/λ higher speed passive optical network (PON)[1], 100 Gbit/s/λ raises increasing interest in the access network community, at a research level. So far, 100 Gbit/s/λ time division multiplexing (TDM)-PON has been demonstrated using coherent solutions [2], [3] or using direct detection associated with off-line digital signal processing, like in the 50 Gbaud 4-level pulse amplitude modulation (PAM-4) TDM-PON experiment of [4], [5] or in the 100 Gbaud PAM-4 experiment of [6].
Real time PAM-4 experiments >50 Gbaud have been performed in the context of data centers [7] where optical power budgets and fibre reaches are far smaller than in the PON context. Indeed, future access solution should rely on the existing fibre infrastructure already deployed for PONs, with an optical budget corresponding at least to the N1 class (13-29 dB) and with typically 20 km of reach.
Also being discussed in the standards, new point to point (PtP) single fibre connectivities are now reaching 50 Gbit/s bitrates with a typical optical budget class of [0-15 dB] for 20 km reach, also named “Class S” in ITU-T G.9806 or “BR20” in IEEE 802.3.cp. These new transceivers types will full-fill the very-high-bitrate demands for radio access equipment in the context of mobile fronthaul and also fixed access equipment with the backhaul of optical line terminal (OLT) shelf to reach metropolitan nodes. So next generation of single fibre bidirectional PtP links also need to be prepared.
In this work, we achieve a 100 Gbit/s single wavelength PAM-4 experiment with optical budgets compatible with N1 class PONs in a real-time setup and without the use of off-line digital signal processing.

Experimental setup

As depicted on Figure 1, at the OLT side, we used a distributed feedback (DFB) laser emitting at 1310 nm, a Mach-Zhender modulator with a 3-dB bandwidth of 40 GHz and an extinction ratio of 8 dB at this wavelength. The praseodyme doped fibre amplifier (PDFA) has a maximum output power of 15 dBm, a small signal gain of 26 dB on a spectral range of 40 nm centered at 1310 nm and a noise figure of 5 dB. The PAM-4 signal was generated by two pulse pattern generators generating pseudo random binary sequences (PRBS) of length 2^{15}-1 at 50 Gbit/s and driving a 50 Gbaud 3-bit digital-to-analog converter (DAC).
The link is composed of a 20 km long section of standard single mode fibre (SMF) together with a variable optical attenuator (VOA) to assess the optical budget limits of this experiment.
At the optical network unit (ONU) side, a semiconductor optical amplifier (SOA) is used as a pre-amplifier with a small signal gain of 18 dB, a noise figure of 6 dB when biased at 90 mA and a polarization dependant gain of 0.5 dB. The PIN photodiode has a bandwidth of 40 GHz and is integrated with a transimpedance amplifier (PIN-TIA). An analog 6-taps finite impulse response (FIR) filter with a tap delay of ~7.5 ps is placed after the detection.
We directly measure the bit error rate (BER) of the PAM-4 signal using a standard commercial

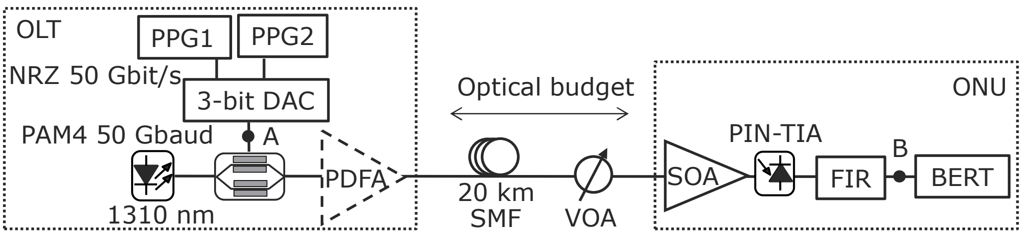

Fig. 1: Experimental setup.

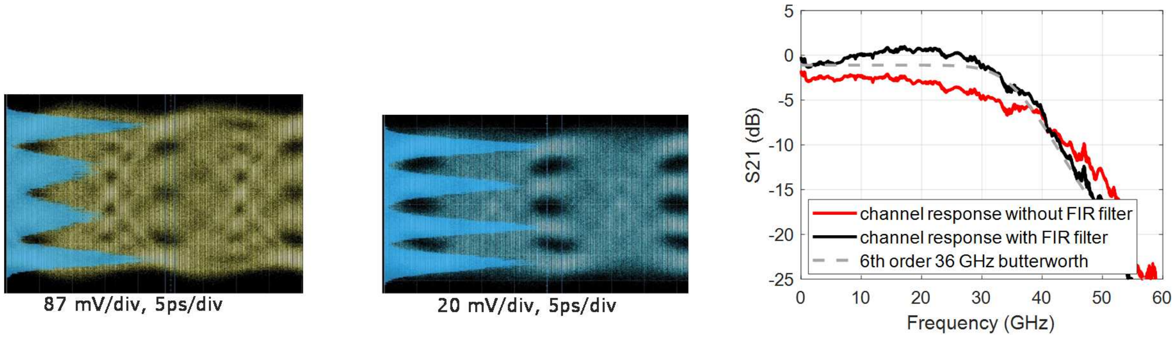

Fig. 2: Eye diagram at the output of the photodiode (left) and at the output of the FIR (middle). Channel response without and with the FIR filter (right).

BER tester without post-processing. As we do not have a full PAM-4 decoder, we measure the BER for each of the three decision levels between a pair of two adjacent symbol levels ($BER_{1,2,3}$) by programming the BERT with patterns corresponding to each level. The aggregate BER is calculated as follow [8]:

$$BER = \frac{1}{2}BER_1 + BER_2 + \frac{1}{2}BER_3$$

Back to back experiment

We first assessed the link without any amplification stage or fibre in order to optimize the FIR filter response. The filter was optimised by minimizing the BER at the receiver sensitiviy and never modified then when varying optical budget and distance. After optimization, we obtain the eye diagrams and corresponding histograms, before (Fig. 2, left) and after (middle) the FIR filter using a 70 GHz sampling oscilloscope. It clearly optimises the symbols distribution.

Fig 2 (right) represents the channel responses without and with compensation measured with a 70 GHz bandwidth vector network analyzer (VNA) between points A (after DAC) and B (after FIR) on Fig. 1. The 3-dB bandwidth is about the same with or without FIR (36 and 33 GHz respectively). We can conclude that the FIR filter main role here is not to improve the channel bandwidth but rather to counter channel distortions. As pointed out by the 6-th order 36-GHz butterworth filter frequency response

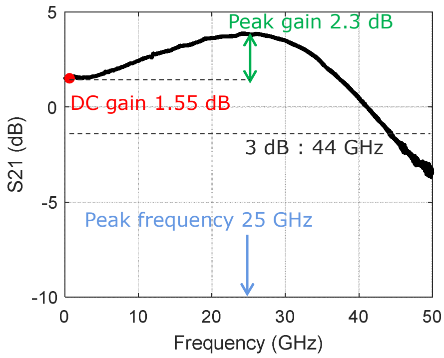

Fig. 3: FIR filter response.

plotted on the same graph, the channel response measured after compensation is not flat as DAC and BERT can not be included in the chain for the VNA measurement.

The corresponding FIR filter frequency response is represented in Fig. 3. It has a 3-dB cut-off frequency of 44 GHz and a gain at 25 GHz of 2.3 dB compared to DC. The filter shape is very similar to the response of a continuous time linear equalizer (CTLE) with a DC gain of 1.55 dB, a peak gain of 2.3 dB at 25 GHz. Such a CTLE is compatible with CMOS technologies[9] and is a very common equalisation scheme widely used to improve receivers performances.

Fig. 4 presents the BER versus the receiver input power without and with the SOA as a pre-amplifier. The sensitivity at a pre-FEC threshold BER of 10^{-2} falls from –11 dBm to –17 dBm thanks to the addition of the SOA. This corresponds to an optical budget of 22 dB with the SOA. A minimum BER of $1.5.10^{-3}$ is obtained at a received power of -13 dBm and a dynamic range of 10 dB is reached (power excursion below 10^{-2}).

Fig. 5 shows the SOA gain as a function of the

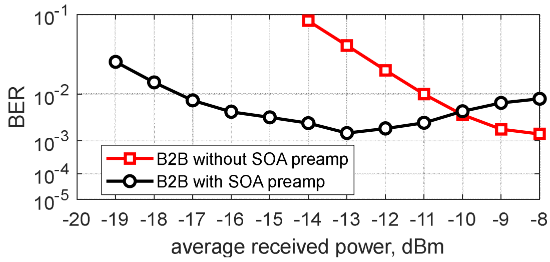

Fig. 4: BER versus received power at 100 Gbit/s in back to back with and without a SOA pre-amplifier.

input power with eye diagrams obtained at -16 and -8 dBm in front of the SOA. The corresponding histograms clearly show the effect of the non-linear SOA gain compression on the 4 levels distribution (3.6 dB gain compression at -8 dBm).

This experiment with a SOA-PIN receiver already demonstrates transmission capabilities that are compatible with future PtP standards needs at

100 Gbit/s, reaching optical budgets of 22 dB.

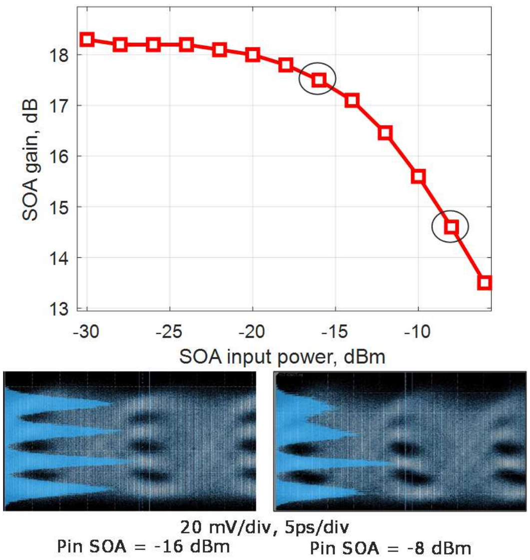

Fig. 5: SOA gain versus input power at 90 mA and eye diagrams at -16 and -8 dBm in front of the SOA.

Higher optical budget and 20 km long links

We then added a PDFA as a booster amplifier in order to reach an optical budget compatible with an N1 class configuration with 29 dB of optical budget. For that, with a sensitivity of -17 dBm obtained with a SOA as a pre-amplifier, we need at least a transmitter output power of 12 dBm. Fig. 6 presents the BER as a function of the

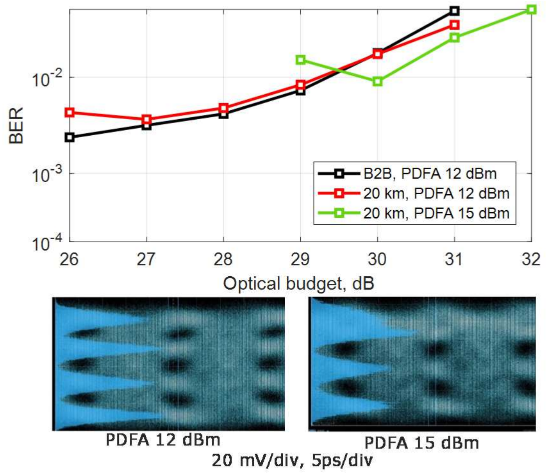

Fig. 6: BER versus optical budget in back to back and after 20km for a PDFA output power of 12 and 15 dBm.

optical budget in back to back (B2B) including the PDFA at 12 dBm and after 20 km of SMF fibre for a PDFA output power of 12 and 15 dBm. In B2B and after 20 km with a transmitter output power of 12 dBm, the sensitivity remains unchanged (-17 dBm) and an optical budget of 29 dB is obtained. In the case of 15 dBm output power, the 10^{-2} threshold is hardly reached, the sensitivity shifts by 2 dB and the optical budget hardly reaches 30 dB. We can clearly observe that non-linear effects in the SMF start to become detrimental in this case as shown on insets eye diagrams.

Conclusion

We experimentally demonstrated for the first time a PAM-4 transmission at 100 Gbit/s/λ in real time using a PDFA as a booster and a SOA-PIN receiver. An optical budget compliant with the N1 class of PONs was achieved up to 20 km. The results pointed out the strong sensitivity to non linearities of PAM-4 modulation.

Without the PDFA, we also demonstrated that PAM-4 single wavelength transceivers could be implemented with a SOA-PIN to achieve 22 dB of optical budget for 100 Gbit/s PtP transmissions, for upcoming radio access network needs.

Acknowledgements

The authors would like to thank the french research program ANR under contract EAM-VCSEL ANR-19-CE24-0018.

References

[1] G.9804.1 : Higher Speed Passive Optical Networks: Requirements; online : https://www.itu.int/rec/T-REC-G.9804.1-201911-I/en.

[2] K. Matsuda and N. Suzuki, "Hardware-Efficient Signal Processing Technologies for Coherent PON Systems," in *Journal of Lightwave Technology*, vol. 37, no. 6, pp. 1614-1620, 15 March15, 2019.

[3] J. Zhang, J. S. Wey, J. Shi and J. Yu, "Single-Wavelength 100-Gb/s PAM-4 TDM-PON Achieving Over 32-dB Power Budget Using Simplified and Phase Insensitive Coherent Detection," *2018 European Conference on Optical Communication (ECOC)*, 2018.

[4] J. Zhang, J. Yu, H. Chien, J. S. Wey, M. Kong, X. Xin, and Y. Zhang, "Demonstration of 100-Gb/s/λ PAM-4 TDM-PON supporting 29-dB power budget with 50-km reach using 10G-class O-band DML transmitters," in Proc. *Opt. Fiber Commun. Conf.* (OFC'2019), paper Th4C.3, 2019.

[5] R. Borkowski *et al.*, "World's First Field Trial of 100 Gbit/s Flexible PON (FLCS-PON)," *2020 European Conference on Optical Communications (ECOC)*, post-deadline session, 2020.

[6] D. Che, Y. Matsui, R. Schatz, R. Rodes, F. Khan, M. Kwakernaak, T. Sudo, S. Chandrasekhar, J. Cho, X. Chen, and P. Winzer, "Direct modulation of a 54-GHz distributed Bragg reflector laser with 100-GBaud PAM-4 and 80-GBaud PAM-8," in Proc. *Opt. Fiber Commun. Conf.* (OFC'2020), paper Th3C.1, 2020.

[7] J. Verbist *et al.*, "Real-Time and DSP-Free 128 Gb/s PAM-4 Link Using a Binary Driven Silicon Photonic Transmitter," in *Journal of Lightwave Technology*, vol. 37, no. 2, pp. 274-280, 15 Jan.15, 2019.

[8] K. Szczerba, P. Westbergh, J. Karout, J. Gustavsson, Å. Haglund, M. Karlsson, P. Andrekson, E. Agrell, and A. Larsson, "30 Gbps 4-PAM transmission over 200 m of MMF using an 850 nm VCSEL," *Opt. Express,* vol. 19, B203-B208, 2011.

[9] R. Tang, K. Wang, D. Li, L. Geng and X. Gui, "A 100-Gb/s PAM-4 CTLE in 28-nm CMOS with Coarse-Fine Gain Adjustment," *2020 IEEE International Conference on Integrated Circuits, Technologies and Applications (ICTA)*, 2020.