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Real-Time DSP-Free 100Gbit/s/λ PAM-4 Fiber Access Link using EML and Direct Detection

Jérémy Potet, Mathilde Gay, Laurent Bramerie, Monique Thual, Ivan N. Cano, Giuseppe Caruso, Ricardo Rosales, Derek Nesset, Fabienne Saliou, Gaël Simon, Philippe Chanclou

***Abstract*— A 100 Gbit/s/λ PAM-4 fiber link with an optical budget of 30 dB and 20 km fiber reach is achieved in real time experiments. This is compliant with class A (20 dB) point to point (PtP) applications as mobile fronthaul for example, and with class N1 (29 dB) point to multipoint (PtMP) for residential market. We used an integrated externally modulated laser, an analog pre-equalizer, an optical booster amplifier and/or non-filtered preamplifier and direct detection without any digital signal processing (whether real-time or offline).**

***Index Terms*—Access networks, FTTH, PON, mobile network, PAM-4, EML, Fronthaul**

I. INTRODUCTION

THERE is much interest in increasing the capacity of fiber access links to meet the growing bandwidth demands for both fixed and mobile broadband services. To this end, both the ITU-T and IEEE have initiated standards for bi-directional point-to-point fiber links at 50 Gbit/s line rate [1, 2]. Furthermore, the ITU-T is developing the Higher-Speed PON (HSP) recommendations targeting 50 Gbit/s line rate in passive optical network (PON) systems [3]. Naturally, with the completion of those standards, the research interest moves to the next capacity step for fiber access networks (FANs) e.g., 100 Gbit/s. While 100 Gbit/s is a reality for short range applications as datacenter (DC) [4], the specificity of the access network leads to different constraints, especially in terms of optical budget and reach.

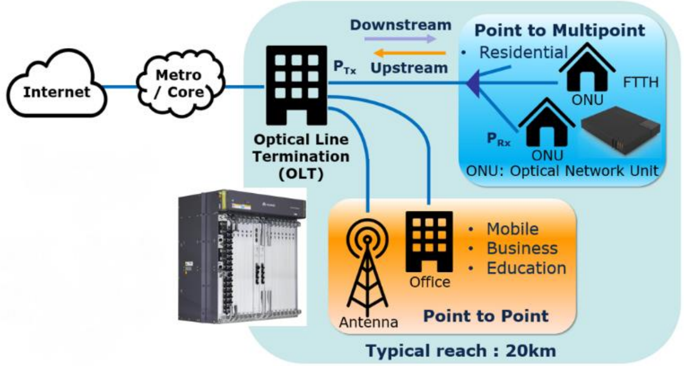

Fig. 1. Access networks topologies overview

An overview of the topologies of the access network is depicted in Fig. 1. Two main architectures exist: point to point (PtP) and point to multipoint (PtMP). The PtP topology is dedicated to mobile, business or specific networks (education, banks). PtMP is well-known for Fiber To The Home (FTTH) using PON. The required link budgets (e.g. 20 dB for PtP (Class A) [1, 2] and 29 dB for PtMP (Class N1) [3]) together with transmission distances covering typically 20 km, are more challenging in FAN than other short reach scenarios.

To meet the link budget, the optical receiver (Rx) sensitivity is a critical issue. For this reason, coherent approaches have been studied for 100 Gbit/s line rate FAN systems [5-8]. However, few reports [8] real time demonstrations due to the development cost of customized digital signal processing (DSP) chips at this bitrate. On the other hand, 100 Gbit/s with 4-level Pulse Amplitude Modulation (PAM-4) has been demonstrated with direct detection (DD) and offline DSP [9-12]. In [13], we showed that using a Mach-Zehnder Modulator (MZM) and DD, PAM-4 could be detected without DSP. Still, it is of further interest to assess if a DSP-free Rx could achieve high link budgets and properly detect a PAM-4 optical signal with a simpler transmitter (Tx) like an externally modulated laser (EML) composed of a monolithically integrated distributed feedback laser and an electro-absorption modulator. The use of such Tx would avoid higher complexity and cost compared to legacy technology such as G-PON and XG(S)-PON.

In this paper we demonstrate for the first time to our knowledge, a single wavelength real-time PAM-4 100 Gbit/s/λ fiber access link in O-band generated with an EML Tx and without DSP in the Rx. Fiber transmission over 20 km is realized with an optical budget (OB) of 30 dB using analog pre-equalization, optical amplification, and DD. We study the impact of the optical amplifier location in three configurations: booster, pre-amplifier, and both booster and pre-amplifier targeting PtP and PtMP scenarios. The results are also compared with those obtained previously in [13] with a MZM Tx. The analog electrical finite impulse response (FIR) filter and its impact on the electrical modulation signal at the Tx-side are also presented.

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II. EXPERIMENTS

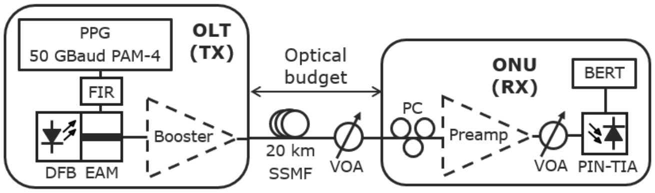

Fig. 2. Experimental setup

The experimental setup is presented in Fig. 2 showing the Optical Line Terminal (OLT), the optical network unit (ONU) and the link. In this work we study different configurations depending on the target optical budget. For the back to back reference (part III.A), no transmission link and no amplifiers are introduced. For the PtP configuration, we have tested the case with a semiconductor optical amplifier (SOA) as a booster (Part III. B), and with a SOA as a preamplifier (Part III.C). Finally, for the PtMP configuration (Part III. D), both booster and pre-amplifier are required in order to reach the optical budget. In this case the booster was a Praseodymium doped fiber amplifier (PDFA) as detailed later.

The detail of the setup is as follows: at the OLT Tx side, we used a Pulse Pattern Generator (PPG) to generate a pair of pseudo random bit sequences of length 2^{15}-1 (PRBS 15) 50 Gbit/s Non-Return to Zero signals. The length of the PRBS sequence was limited by the size of the random access memory of the BER tester programmed for PAM-4 decoding. The PAM-4 100 Gbit/s signal is encoded inside the PPG thanks to a 3-bit digital-to-analog converter (DAC) on which we use 2 inputs. The electrical signal passes through an analog 6-taps FIR filter with 55 GHz -3 dB bandwidth (BW) and time spacing of 7.5 ps. The FIR optimizes the channel response. The equalized electrical signal is amplified and applied to the electro absorption modulator (EAM) section of an EML chip. The laser and the EAM sections of the EML are biased at 92 mA and -2 V respectively, leading to a PAM-4 extinction ratio (ER) of 5.6 dB (defined as the ratio of the outer levels) and an optical modulation amplitude (OMA) equal to 4 dBm. The EML temperature is set and maintained via a temperature controller at 20°C. The EML output optical signal is coupled into a micro-lensed fiber. The optical power coupled into the fiber is +3.5 dBm. This EML emits at 1309 nm and presents a -3 dB electro-optical (EO) BW of 46 GHz. In [13], we used a MZM with 40 GHz BW and 8 dB ER (OMA = 8.1 dBm). After possible amplification (depending on the case study), the optical signal is sent through 20 km of standard single mode fiber (SSMF), leading to a cumulated chromatic dispersion equal to -2 ps/nm (at 1309 nm), and a Variable Optical Attenuator (VOA) is inserted to emulate the losses of an optical distribution network (ODN). The ONU Rx detects the optical signal using a 42 GHz PIN photodiode (PD) coupled with an integrated transimpedance amplifier (TIA). To increase the Rx sensitivity, a SOA is added as a pre-amplifier on the second PtP configuration (Part III. C) and in the PtMP configuration (Part III. D) without an optical filter in between the pre-amplifier SOA and PD. A polarization controller is inserted in front of this SOA to compensate for its 1-dB polarization dependent gain and a VOA in front of the PD protects it from any damage. Finally, the detected signal is sent to BERT for Bit Error Rate (BER) measurement. The BER is measured on each of the three eyes consecutively. We fix the decision time and scan the amplitude decision threshold to determine the minimum BER for each level by programming the BERT with the pattern corresponding to each level (Fig. 3). The corresponding PAM-4 BER is calculated by combining the BER of each eye using the following equation [14]:

$$\mathrm{BER} = \frac{1}{2}\mathrm{minBER}_1 + \mathrm{minBER}_2 + \frac{1}{2}\mathrm{minBER}_3$$

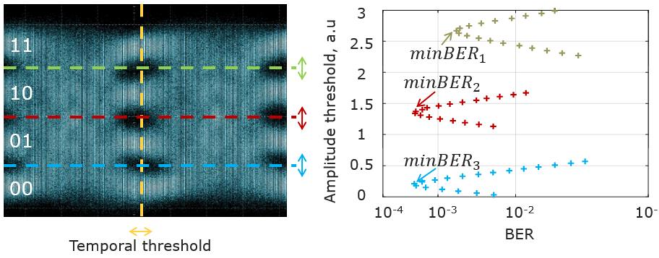

Fig. 3. PAM-4 BER measurement method. The temporal threshold is fixed, the amplitude threshold sweeps on the amplitude of the PAM-4 signal and the BER is measured for each of the three eyes of the signal.

Fig. 4 a) shows the modulating electrical eye diagram without and with the FIR analog compensation. The S_{21} measurements shown on Fig. 4 b) are done with a 70 GHz vector network analyzer (VNA). The red dot curve is the Tx (RF chain and EML) response without compensation (3 dB EO BW of 38 GHz), and the black dash curve is the FIR filter response with the parameters used in this work. Finally, the blue full curve is the compensated transmitter response, the FIR filter enhances spectral components between 10 GHz and 30 GHz.

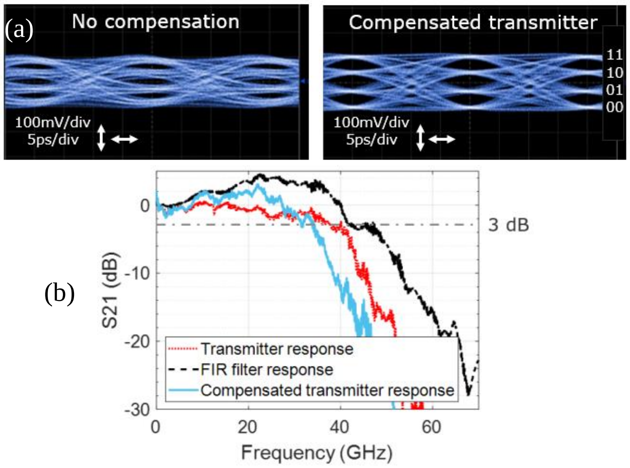

Fig. 4. (a) Electrical eye diagrams of modulating signal without and with compensation. (b) Analog FIR filter S_{21} response (black), transmitter response before (red) and after compensation (blue).

The tap coefficients are optimized through the observation of the eye diagram and measured BER. The effect of equalization is clearly observed in the quality of the eye diagram in Fig. 4 a). After compensation, the trajectories are cleaner, and the eyes are more balanced and symmetric.

III. RESULTS AND DISCUSSION

A. Back to back

Fig. 5 presents the reference BER measurement in back-to-back (BtB) without optical amplification. We measure a reference Rx sensitivity of -10.2 dBm at a pre-FEC (Forward Error Correction) threshold considering a value of BER = 10^{-2} based on the latest 50 Gbit/s HSP ITU-T standard [3]. An error floor is observed at BER = 5.10^{-3}. Fig. 5 also shows the electrical eye diagram at the output of the PIN-TIA at a received power of -8 dBm. In this configuration, the OB is limited to 13.5 dB.

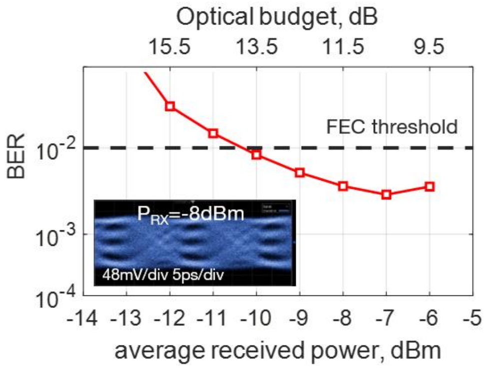

Fig. 5. BER versus average received optical power and optical budget (top axis). The insert is the optical eye diagram at the PD output at a received power of -8 dBm.

B. Booster SOA (PtP)

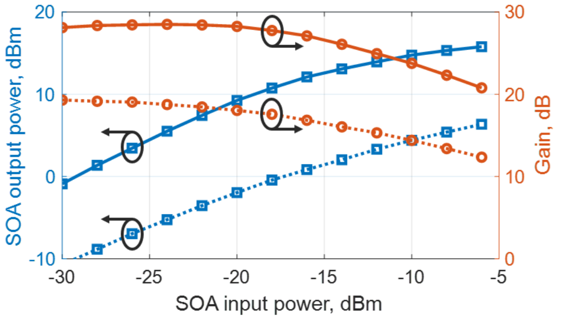

Fig. 6. Booster SOA (SOA1) (full curve) and pre-amplifier SOA (SOA2) (dot curve) characterization at 1309 nm: output power versus input power (blue square) and gain versus input power (red circle).

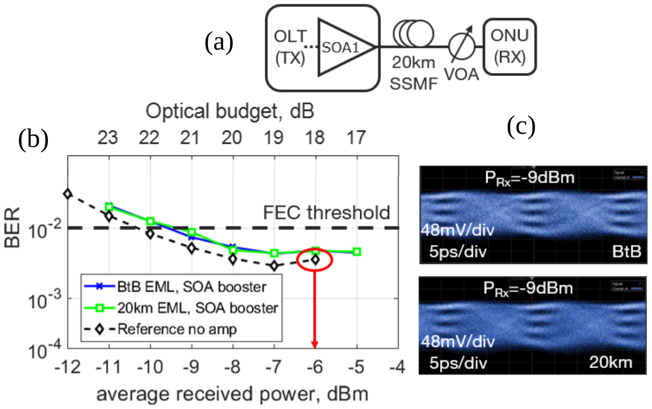

Fig. 7. (a) Experimental setup with boosted transmitter. (b) BER versus average received optical power and optical budget (top axis), with 20 km SSMF propagation and BtB. (c) Optical eye diagrams at received optical power of -9 dBm.

To reach an OB suitable for PtP Class A (i.e., 20 dB), we add a SOA as a booster amplifier (SOA1) i.e. at the OLT Tx side (Fig. 7 a)). Fig. 6 presents the booster (SOA1) output power (full blue square curve) and the gain (full red circle curve) as a function of the SOA input power. SOA1 has a small signal gain of 28 dB, a saturation input power of -16 dBm at 1 dB gain compression and a noise figure (NF) of 7 dB at 1309 nm wavelength, for bias current of 444 mA at 20°C. In our previous work [12], to avoid nonlinear effects during fiber propagation, the launched power had to be limited to 12 dBm [9]. We thus add an attenuator before the SOA to reduce the input power to -17 dBm and obtain a Tx output power of 12 dBm (Fig. 6). In this way, SOA1 works very close to its linear regime which limits both the gain compression in the amplifier to 0.5 dB and the fiber nonlinearities. As observed on the BER measurements on Fig. 7 b), the ASE noise introduced by the SOA leads to a ~1 dB penalty on the Rx sensitivity compared to the reference measurement (no SOA). In Fig. 7 b), the reference measurement is only relevant to the received optical power and not to the OB. We measure an Rx sensitivity of -9.5 dBm and a corresponding OB of 21.5 dB both in BtB and after 20 km of SSMF. The chromatic dispersion has a negligible effect after 20 km transmission at the operating wavelength (1309 nm) as seen on the eye diagrams of Fig. 7 c) captured in BtB (up) and after 20 km (down) for a received power of -9 dBm.

C. Pre-amplifier SOA (PtP)

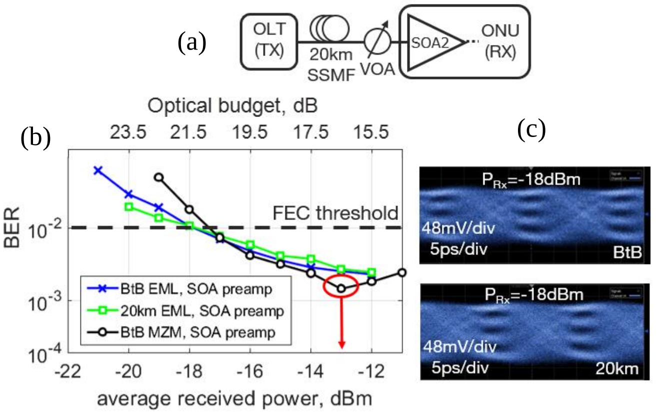

Fig. 8. (a) Experimental setup with pre amplified receiver (b) BER versus average received optical power and optical budget (top axis), with 20 km SSMF propagation and BtB. (c) Optical eye diagrams at a received power of -18 dBm.

An alternative to the amplified Tx for PtP links is a pre-amplified Rx as depicted in Fig. 8 a). The pre-amplifier (SOA2) presents a small signal gain of 19 dB, an input saturation power of -20 dBm as shown on Fig. 6 (dot curve), a NF of 5.9 dB and 1 dB polarization dependent gain. Fig. 8 b) plots the measured BER and Fig. 8 c) presents the detected electrical eye diagrams at BER = 10^{-2} in BtB and after 20 km. In this setup, we obtain a Rx sensitivity of -18 dBm at BER = 10^{-2}, corresponding to an OB of 21.5 dB (Tx power of +3.5 dBm). We also show on Fig. 8 b), results from [12] with a MZM at the Tx. The MZM has a higher ER (8 dB) and is chirp free, however it has a higher cost than an EML. We note from Fig. 8 b) the sensitivity measured with the MZM based Tx is almost the same as with EML. Hence, at this bit rate and operating wavelength, the Rx noise is the main limiting factor.

D. Booster and preamplifier (PtMP)

Finally, we study a future single wavelength 100 Gbit/s PtMP residential scenario. To meet the required OB, we insert in this case both a booster and a pre-amplifier (Fig. 9 a)). SOAs exhibit a larger noise figure than fiber amplifiers; hence, to limit the optical noise we use a PDFA as booster. The PDFA has a noise figure of 5 dB, and its output power is set to 12 dBm to avoid nonlinearities in fiber propagation [12]. The detected electrical eye diagrams are open (Fig. 9 c)) and we measure a Rx sensitivity of -18 dBm in BtB and after 20 km (Fig. 9 b)). Despite the presence of a second amplifier which introduces more noise in the link compared to the case without booster, the Rx sensitivity remains the same as the case with only pre amplified Rx. We reach an OB of 30 dB, which is compatible with N1 Class (14-29 dB) OB for PONs [3]. The black curve gives the performances obtained previously with the MZM. Despite the lower OMA from the EML, the performance is comparable.

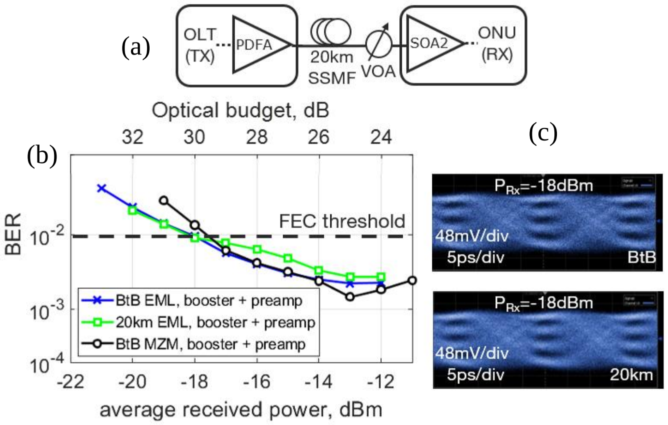

Fig. 9. (a) Experimental setup with boosted transmitter and pre amplified receiver. (b) BER versus average received optical power and optical budget in back-to-back and with 20 km fiber propagation. (c) Optical eye diagram at received power of -18 dBm.

IV. DISCUSSION AND CONCLUSIONS

While the association of two non-optically filtered amplifiers as booster and pre-amplifier provides the best results, having both simultaneously remains questionable for residential broadband applications due to the cost constraints. The experiments show that with a SOA either as a booster or pre-amplifier, the OB for PtP can be achieved. However, since monolithic integration on a single chip of a SOA with an EML is easier than with a PIN diode, the booster SOA seems more technically feasible. Moreover, it is more reasonable to add an optical amplifier at the OLT because of the controlled environment operation and energy consumption.

We demonstrate a real time single wavelength 100 Gbit/s/λ PAM-4 transmission using only analog pre-equalization and optical amplification. The equalization scheme used in this work is relatively simple with a 6-tap analog FIR filter, showing that a 100 Gbit/s/λ IM/DD link is achievable without complex DSP. We test three different non-filtered optical amplifier configurations -booster, preamplifier, and both-, and thus achieve OB of 20.5 dB, 21.5 dB and 30 dB respectively (higher than ITU-T budget class N1) with an integrated O-band EML in BtB and through 20 km of SSMF. The use of fiber amplifier in access network has not been deployed, mainly due to cost and integration issues, recent works on Bismuth doped fiber amplifier [15] further open this possibility. These results demonstrate a way forward for bidirectional PtP standards along with illustrating what could be possible at 100 Gbit/s in PON applications.

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