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A Real-Time 25/50/100G Flex-Rate PON Implementation

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Abstract *Real-time clock, data recovery and equalization of a mixed 25G/50G/100G downstream PON aligned with ITU-T G.9804 standard requirements is shown. 25G is encoded with delay-modulation for improved timing recovery under mixed signal modulation ©2022 The Author(s)*

Introduction

The 50G PON standard has recently been published in ITU-T G.9804 [1]. It offers a 50G fixed downstream rate by employing NRZ modulation independent of channel conditions. To boost overall throughput a 50/100G Flexible Passive Optical Network (FLCS-PON) was proposed to increase the overall throughput by changing the modulation format to 100G PAM4 for groups of optical network units (ONUs) if channel conditions allow [2]. However, even for today's installed PONs there exist ONUs which might already exhibit marginal channel conditions [3] due to aging and/or reduced installation margins. These ONUs could benefit from a flexible PON which offers higher loss budget and extended reach since adapting the already installed outside distribution network (ODN) to accommodate these ONUs is very costly. To some degree this has been addressed in our FLCS-PON proposal by introducing stronger forward error correction (FEC) codes [2]. We propose to further extend this concept by providing a 25G modulation option as well. In addition to providing extended reach and/or higher loss capability, another use-case of enabling 25G is to provide a safe-mode option for certain ODN fault scenarios. Going to a lower line-rate while keeping the same receiver and modulation normally doesn't improve receiver sensitivity because it is dominated by the noise equivalent bandwidth (NEB) of the receiver front-end. This is a well-known reality for upstream multi-rate burst-mode receivers needing for example bandwidth tuneable frontends to improve performance at the lower rates. However, for 50G PON we have the case where the receiver front-end is still based on 25G class bandwidth limited components which therefore can be exploited to improve receiver performance at the lower 25G rate, similar as was done in [4].

In this paper, we investigated the feasibility of a flexible 25/50/100G PON, that aligns with the ITU-T G.9804 standard, based on a real-time 50 Gbaud clock and data recovery (CDR) integrated with an adaptive T-spaced FFE based equalizer. Because the CDR operates at 50 Gbaud, 50G NRZ and 100G PAM4 are a natural fit. Enabling a 25 Gbaud signal will result in the CDR only seeing 25G transitions while the T-spaced equalizer samples twice for each bit. This might lead to locking issues for both the CDR as well as the equalizer [5]. To overcome this problem, we propose to apply delay modulation, also known as Miller encoding to the 25G signal. In Miller coding, a logic 1 is represented by a mid-bit transition in either direction [6]. Therefore, a Miller encoded 25G NRZ signal looks very much like a 50G NRZ signal in terms of bit transitions while still maintaining many of the benefits of a lower baud-rate signal. Since Miller code is a run length limited code (the longest period possible without a transition is two-bit times) it has very good timing/clock recovery properties and is immune to polarity inversion. Notably it has already been adopted in an ITU-T PON standard (G.989) to reduce the fiber dispersion penalty and mitigate Raman crosstalk of the TWDM-PON signals onto the RF video overlay [7].

Experimental setup

The real-time experimental setup is shown in Fig. 1. At the OLT side it consists of an 25G class electro-absorption modulated laser (EML) based transmitter boosted with a semiconductor optical amplifier (SOA) to ensure a minimum launch power of >+5.5 dBm as specified in G.9804 is satisfied. The transmitter is modulated with mixed signals based on 25G Miller, 50G NRZ, and 100G PAM4 sections each carrying PRBS15(Q) sequences with a duration of about 1.35 μs (see Fig. 3c). A 1358nm EML was used to emulate worst-case fiber dispersion after 20 km of SSMF fiber at 1342 nm (77.1 ps/nm as defined in [1]). The EML transmitter has a chirp close to α=+0.5 at the operating point used in the experiment. The flexible-rate ONU PON receiver has an 25G class SiGe APD-TIA front-end. The real-time 50 Gbaud CDR clock and data recovery loop contains a decision directed symbol-based Mueller-Muller timing error detector with integrated 15-tap FFE equalization. This number of FFE taps is very similar to the specified reference receiver as defined for TDEC in G.9804. Onboard PRBS checkers can be used to evaluate the BER performance of 50G NRZ and 100G PAM4 modulation in real-time.

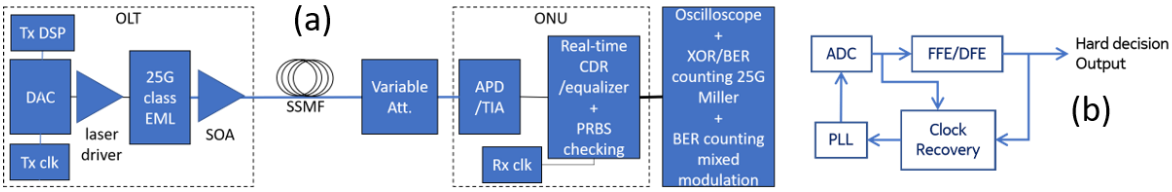
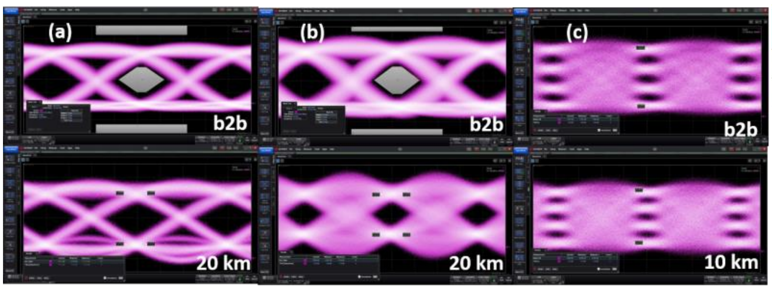


Fig. 1: (a) Real-time experimental FLCS-PON setup. (b) Clock recovery loop with integrated equalization

The received (re-generated) 25G Miller encoded electrical signal after real-time CDR and equalization is captured by an oscilloscope for offline Miller decoding (XORing of two consecutive 50G bits that make up the 25G Miller symbols) and error counting. The BER of each separate modulation section of the mixed signal after real-time CDR and equalization is determined on the electrical re-generated signal in a similar way.

Experimental Results

Fig. 2 shows the measured eye-diagrams of the different modulations after FFE equalization (top=b2b and bottom=after fiber) using a digital communication analyzer (DCA) with CDR and reference receiver as specified in G.9804 standard. The outer optical modulation amplitude (OMA) of the signals was optimized for mixed signal operation and set to the same value while maintaining an extinction ratio ER=7 dB, which satisfies the recommended minimum [1]. It can be observed that the 25G Miller eye (a) resembles a more open 50G NRZ eye (b). The 50G NRZ eye passes the G.9804 mask test with a 6e-6 hit ratio (<max. 5e-5) using a 13 tap FFE and 37 GHz BW reference receiver. The 25G Miller eye passes the same mask with an even lower 6.2e-7 hit ratio. The TDEC and TDECQ after fiber transmission have been evaluated as well using 18.75 GHz reference receiver [1]. The measured increase in TDEC/TDECQ (compared to b2b) after different lengths of fiber at a BER/SER=1e-2 are given in Fig. 2d. The TDEC value after 20 km of fiber (~82 ps/nm at 1358nm) for 50G NRZ is TDEC=5dB which is conform the G.9804 standard (maximum TDEC of 5 dB after 20 km). Fig. 2e shows the magnitude of the FFE filters of the different received modulations after real-time CDR/equalizer. 25G NRZ is shown as a reference as well. It can be observed that the filter response for 25G NRZ is significantly different. This is because for a 25G NRZ signal the 50Gbaud T-spaced equalizer 'effectively' samples the signal at 2 samples per symbol leading to a matched filter response for the 25G NRZ signal (which has Nyquist frequency of 12.5 GHz). However, for the Miller encoded 25G signal the filter response closely matches that of the 50G NRZ and 100G PAM4 signal meaning the equalizer will not have to adapt its coefficients as much under mixed 25G Miller/50G NRZ/100G PAM4 modulation. Fig. 3a shows the measured real-time BER performance for the different mixed signal modulations. The results shown are pre-FEC BERs. First, we measured the b2b performance of the different modulation formats individually (single modulation). A receiver sensitivity of ~-26.5 dBm (25G Miller), -23.7 dBm (50G NRZ) and -14.8 dBm (100G PAM4) at BER=1e-2 has been obtained. 25G NRZ is shown as a reference as well. The obtained receiver sensitivity is impacted by the reduced sensitivity of our APD at 1358nm which response was optimized for 1310 nm (see Fig 3c). At 1310 nm we measured a sensitivity of -25.5 dBm (1.8 dB improvement) for 50G NRZ meeting the -24 dBm requirement at ER=7 dB for G.9804 when factoring in diplexer loss as well. While APDs can deliver high performance for NRZ, they exhibit nonlinearity (see Fig. 3c) due to thermal and space charge effect [8] impeding its performance for 100G PAM4 modulation. The received power



(d)	5km ΔTDEC(Q)	10km ΔTDEC(Q)	20km ΔTDEC(Q)
50G NRZ	0.45	1.06	2.6
100G PAM4	0.87	3.32	-

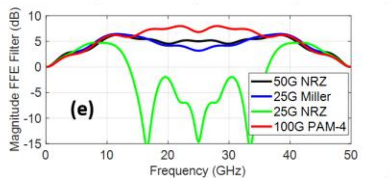


Fig. 2: Measured Eye-diagrams with 1358 nm EML α=+0.5 (a) 25G miller (b2b&20km), (b) 50G NRZ (b2b&20km) and (c) 100G PAM-4 (b2b&10 km) after FFE equalization using DCA with CDR. (d) TDEC results (e) Magnitude of FFE filter response of real-time receiver of Fig 1 of the different modulation formats

needed for PAM4 modulation was measured to be ~9 dB higher than for NRZ. Adopting 25G Miller relaxes the needed received power compared to 50G NRZ by about 2.8 dB(b2b) up to 5 dB (after 20 km) at 1e-2. To further improve the performance at 25G we can elect to adopt a higher input BER FEC code as well [2]. A higher-margin LDPC code of rate 0.733 as proposed for 50G upstream [9] provides an additional ~0.6 dB margin at an input BER of ~1.8e-2. The dispersion penalty of the different modulation formats after fiber transmission at 1358 nm (~82 ps/nm total dispersion) using EML with α=+0.5 has been evaluated as well. The dispersion penalty for 50G NRZ was measured to be ~2.6 dB after 20km of fiber which is below the 3.5 dB maximum dispersion penalty as defined in the standard. For 25G Miller a dispersion penalty of only 0.5 dB was measured after 20 km (see Fig. 3b) confirming its superior dispersion performance over 50G NRZ. This is also visible in Figure 2 when comparing the eye-diagrams after 20 km. The dispersion penalty for 100G PAM4 after 10 km of fiber has been measured to be ~3.5 dB meeting the max penalty as defined in G.9804 as well. We observed a reduction to 1.5 dB after 20 km of fiber by adopting a lower chirp transmitter with α=+0.2 (measured using Mach-Zehnder Modulator based transmitter) as shown in Fig. 3b. The measured dispersion penalties align reasonably well with the measured ΔTDEC(Q) (=TDEC(Q)[20km]-TEC(Q)[0km]) values as in Fig. 2d and depicted in Fig. 3b. Finally, we compared the CDR performance under mixed signal modulation to the performance of single modulation. A 50% 25G Miller/50G NRZ and 50G NRZ/100G PAM4 (see Fig. 3c) mixed modulation signal was transmitted continuously, while at the receive side each PRBS sequence was evaluated for each signal modulation separately to determine its BER. The BER of each modulation is calculated on the entire PRBS stream and no bits are discarded. For all mixed modulation cases a penalty <0.4 dB compared to single modulation at BER=1e-2 was observed, even after 20 km of worse case fiber dispersion. This indicates that the CDR with integrated equalizer is performing well under mixed signal modulation as is also expected based on the equalizer filters the real-time CDR converged to for each single modulation format as shown in Fig. 2b. This indicates feasibility of accurately receiving a mixed modulation signal in real-time under realistic optical physical layer conditions as defined in the ITU-T G.9804 standard.

Conclusions

We experimentally demonstrated real-time operation of a flexible downstream 25/50/100G PON aligned with the ITU-T G.9804 50G PON standard. Good performance (sensitivity) and correlation between dispersion penalty and ΔTDEC(Q) is shown. By enabling 25G Miller we demonstrated extended reach and up to ~5 dB loss capability improvement over 50G NRZ for enhanced reliable transmission to high loss and/or far away ONUs in the network. By switching to 100G PAM4 the data-rate can be doubled for ONUs that are nearby and/or experience low loss, at the expense of ~9 dB optical power penalty.

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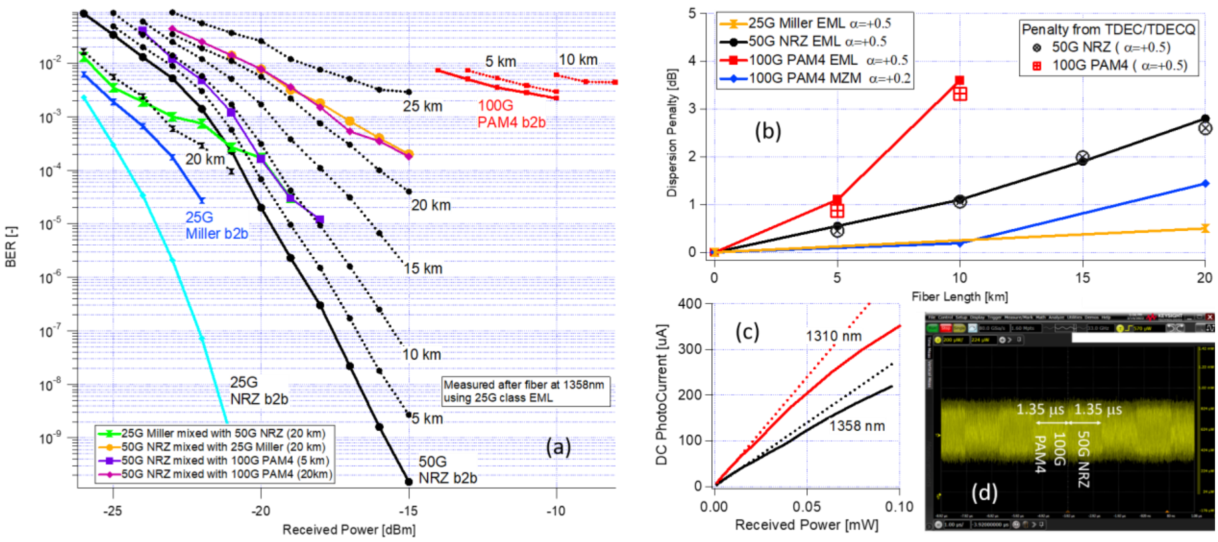

Fig. 3: (a) Measured real-time BER curves for 25,50 and 100G single and mixed modulation, (b) dispersion penalty (c) APD response (d) Time-domain signal of transmitted mixed 50G NRZ/100G PAM4 signal

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