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Optical Power Budget of 25+ Gbps IM/DD PON with Digital Signal Post-Equalization

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Abstract: While infrastructure providers are expanding their portfolio to offer sustainable solutions for beyond 10 Gbps in the access segment of optical networks, we experimentally compare several modulation format alternatives for future passive optical networks (PONs) aiming to deliver 25+ Gbps net-rates. As promising candidates, we consider the intensity modulation direct detection (IM/DD) schemes such as electrical duobinary (EDB) and 4-level and 8-level pulse amplitude modulations (PAM-4/8). They are more spectrally efficient than the conventional non-return-to-zero on-off-keying (NRZ-OOK) used in current 10G PONs. As we move to higher rates, digital equalization enhances the performance by smoothening the systems imperfection. However, the impact that such equalization has on the optical power budget remains unclear. Therefore, in this article, we fairly compare the optical power budget values of a time division multiplexed PON (TDM-PON) exploiting a linear digital signal equalization at the receiver side. We consider the conventional PON configuration (20 km of single-mode fiber (SMF), 1:N optical power splitting) with IM/DD and net-rates above 25 Gbps. Furthermore, we focus on a downstream transmission imposing the bandwidth limitations of 10G components using a digital filter before the detection. The obtained results show that the use of a digital post-equalization with 43 feed-forward (FF) and 21 feedback (FB) taps can significantly improve the signal quality enabling new alternatives and enhancing the optical power budget.

Keywords: digital post-equalization; electrical duobinary (EDB); intensity modulation direct detection (IM/DD); non-return-to-zero (NRZ); optical power budget; passive optical networks (PON); pulse amplitude modulation (PAM)

1. Introduction

An immense range of mobile and broadband services, such as Netflix, Spotify, etc., provoke an unprecedented growth of consumer-driven data consumption, which leads to an increase of bandwidth demands in fiber-optic access networks [1]. In this segment, passive optical networks (PON) together with a wavelength division multiplexing (WDM) and a time division multiplexing (TDM) technologies promote a pay-as-you-grow approach in the third generation fiber-to-the-x (FTTH) systems. As 10G PON systems are not capable support future services, especially in the context of the fifth generation (5G) mobile networks, 25G is the next evolution step that must be taken [2]. However, it is not clear which means will be used to make it.

Recent ITU-T recommendations for passive optical networks (PONs), ITU-T G.9807.1 (symmetric 10G PON (XG(S)-PON)) and ITU-T G.989 (next-generation PON2 (NG-PON2)) describe transmission requirements for line rates of up to 40 Gbps per channel, while new recommendations for higher line rates (e.g., G.HSP.Req, G.HSP.comTC, G.HSP.50Gpmd, G.HSP.TWDMpmd) are under active development [3–5]. The enhancements being discussed for the next-generation PON standards include the increase in channel line rates from 10 to 25 Gbps [6]. Now, 100G-EPON standard is still under development by the IEEE P802.3ca Task Force. It is intended to scale up to 25 Gbps or 50 Gbps per single lane capacity while reusing the existing infrastructure of 10G-EPON [1,5,7]. Overall, the future PON is currently under development and standardization for future broadband network solutions beyond 10 Gbps [8–10]. The evolution towards higher line rates is mainly driven by point-to-point (P2P) connections and wireless fronthaul, e.g., the next generation of mobile cellular networks (i.e., 5G and beyond 5G), where a 25 Gbps could be needed soon for either backhauling or new interfaces supporting the functional splits. It is expected that the x-haul of these mobile cellar networks will be centralized and based on a point-to-point (PtP) WDM-PON architecture [3,11,12]. However, due to cost considerations and commercial viability, it is desired to re-use some of the components from 10 Gbps transceivers operating in 10G PONs [13]. Bandwidth limitations from electrical and electro-optical components increase significantly due to the utilization of signals with higher line rates. Nevertheless, such elements/components are crucial for component vendors as their re-use reduce development costs. For example, a cost of an optical line terminal (OLT) transmitter is about twice the cost of the receiver and modulator of the optical network unit (ONU), which represents the major part of the transceiver cost. Therefore, the operational capabilities of the bandwidth-limited transceivers have received considerable attention from component vendors, optical network operators, and research communities [9,14–16]. The choice of a modulation format plays a critical role in the performance of HS-PON systems to provide the necessary line rate for the end-users [17]. It seems unreasonable that coherent technology for such relatively low rates could penetrate this market segment at this time, despite the potential sensitivity and optical power budget (OPB) improvements. Therefore, we assume that IM/DD formats will be used to deliver 25G or even 50G over a 20 km long single-mode fiber, i.e., the conventional PON configuration. For some applications, shorter fibers are also considered (e.g., 10–15 km when PON-based fronthauling solutions for 5G are on the table) but some require a substantially longer reach (up to 40 km) [6,12].

Interestingly, when it comes to the physical (PHY) layer technology and its maturity, three abbreviations (except "NRZ") are met the most often: "Duobinary", "PAM—pulse amplitude modulation", and "OFDM—orthogonal frequency division multiplexing". The desire for multi-level signaling formats such as Duobinary and PAM have been preferred to their advantages in terms of simpler transmitter and receiver structure for HS-PONs. Therefore, they have become a key solution to provide a higher line rate and improve the bandwidth utilization, capacity, and spectral effectiveness [2,13,17–19]. However, they are also more sensitive to driver linearity and have higher sensitivity requirements, which impose additional restrictions and may limit the system's reach. Coexistence with 10G PON technologies and reuse the deployed optical distribution network (ODN) are among the main challenges for upgrading to new generation PON systems. Technically, it requires that the optical budget (OPB), which determines the maximum tolerable optical loss between an optical line terminal (OLT) and an optical network unit (ONU), must be compliant to E1 or E2 class. However, with increased signal baudrates, impairments from both the transceivers and the fiber-link imposed constraints to fulfill the OPB requirement. Firstly, with a larger bandwidth, the receiver sensitivity can be degraded from a higher thermal noise level. Moreover, the bandwidth limitation from the optical and electrical components and the chromatic dispersion (CD) from the optical fiber channel induce more severe inter-symbol interference (ISI) [20,21]. Mitigation techniques from both the optical and the digital domain can be used to maintain or even to improve the OPB level to enable a higher splitting ratio for an ODN, at a higher cost per customer provided equipment (CPE) [22–25]. Firstly, optical amplifications can be performed to compensate for the sensitivity degradation, either with a praseodymium doped fiber amplifier (PDFA) as a booster in the OLT, or with a semiconductor optical amplifier (SOA) as a pre-amplifier in the ONU. The optical power budget of 35 dB is demonstrated in [10,23], where both such optical amplifiers are used for the 25 Gbps PAM-4 downstream transmission. Although they achieve a higher optical power budget, the PDFA provides more than 10 dB gain. Furthermore, the attribution of digital post-equalization is not discussed. Digital equalization techniques, such as linear feed-forward (FF) equalizer or decision feedback (FB) equalizer, can help to overcome the transceiver and link induced ISI. Thus, they deserve the place in future PONs with spectral efficient modulation formats [10,22]. Such a study is performed in [22], where the advantages of electrical duobinary (EDB) schemes and signal post-equalization are discussed for the bandwidth-limited PON. Their results of optical back-to-back sensitivity as a function of the receiver's bandwidth show that (i) the EDB outperforms the conventional NRZ irrespective to the receiver's bandwidth, (ii) the EDB transmission is more dispersion tolerant as compared to the NRZ, and (iii) the NRZ seems unfeasible for the C-band operation, and, thus, the EDB or a multilevel format should be used. Although the extensive comparison between the EDB and the NRZ alternatives is made, the optical power budget considerations remain outside the scope.

This article aims to bridge the knowledge gap by countifying the gain that digital signal post-equalization has on the optical power budget in IM/DD PONs with NRZ-OOK, EDB, PAM-4, and PAM-8 formats. In this research, we consider a PON architecture based on point-to-multipoint passive optical power splitting in the ODN and focus on the downstream transmission at net-rates above 25 Gbps over a single wavelength in the C-band. Furthermore, as we limit the receiver's bandwidth to 8 GHz, we investigate whether components intended for the 10G operation can be used for 25+ Gbps operation. This enables the full compatibility with XG(S)-PON and 10G-EPON and leads to smooth migration of customers to higher net-rates in a cost-effective way. Our results show that even without any post-equalization, the 28 Gbaud EDB and the 14 Gbaud PAM-4 formats can be used for the downstream transmission allowing us to achieve the optical power budget of 26–27 dB. With the equalization, the corresponding numbers are 27–30 dB. A strong digital post-equalization, using the equalizer with 43-FF and 21-FB taps, enables the 28 Gbaud PAM-4 alternative. It ensures a bit-error-rate (BER) below a 7% hard-decision forward error correction (HD-FEC) threshold of 3.8×10^{-3} and a 23 dB optical power budget. The rest of the paper is organized as follows. Section 2 describes a configuration of the TDM-PON experimental setup used for a fair comparison of the selected IM/DD alternatives. Section 3 discusses the obtained results revealing the impact that signal equalization has on the achievable optical power budget in such PON systems. Finally, Section 4 briefly summarizes the research findings.

2. Experimental Setup and Principles

The experimental setup of a 25+ Gbps IM/DD PON system is shown in Figure 1. It resembles a PON architecture based on point-to-multipoint passive optical power splitting in the outside distribution network. We consider a downstream transmission at net-rates above 25 Gbps over a single wavelength in the C-band. It is fully compatible with XG(S)-PON and 10G-EPON, and thus, it enables smooth migration of customers to higher net-rates without needing to change the ODN. Furthermore, the system's throughput can be increased by exploiting the WDM technique and adding new wavelengths as required. Of course, such a solution requires the wavelength management. In the OLT, the output of a continuous-wave laser source (CW) operating at 1550 nm wavelength is connected to the input of the dual-arm Mach–Zehnder modulator (MZM, Sumitomo, T.DEH1.5-40-ADC). An S_1(t) input of the MZM, having a 3 dB bandwidth of 30 GHz, 9 dB insertion loss, and 15 dB extinction ratio, is driven using analog waveforms from an arbitrary waveform generator (AWG, Tektronix, AWG70001A) having 13 GHz analog bandwidth, up to 50 GSa/s sample rate and 8 bits vertical resolution. These waveforms are obtained using a 2^{15}–1 long pseudo-random bit sequence (PRBS15) and bit-to-symbol (B2S) mapping performed in MATLAB prior to the digital-to-analog conversion (DAC). The electrical signal after the output of the AWG was linearly amplified by an electrical broadband amplifier (EA) and fed into the electrical RF input of one arm of the dual-drive MZM. The second arm was loaded with a 50-Ohm load. To optimize the BER performance, we adjusted a bias voltage of the MZM. In such a way, we impact the MZM's chirp parameter. This adjustment ensures the best possible performance in terms of the dispersion-tolerance, which has a direct impact on signal quality.

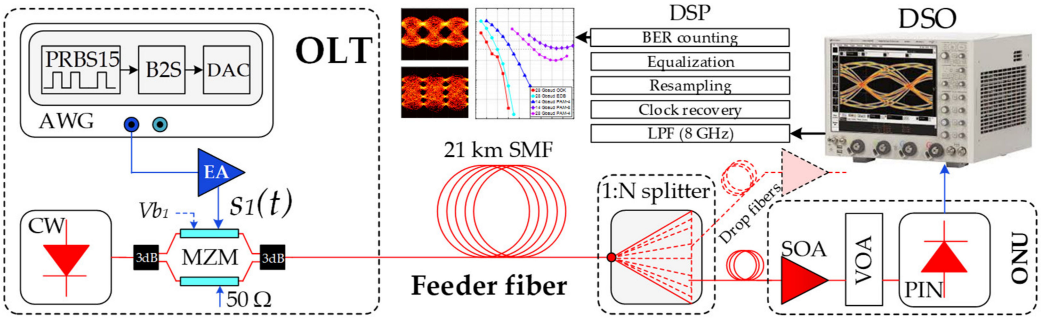

Figure 1. Experimental setup of the 25+ Gbps IM/DD PON system used for the power budget comparison: AWG—arbitrary waveform generator, B2S—bit-to-symbol mapping, CW—continuous wave laser, DAC—digital-to-analog convertor, EA—electrical amplifier, MZM—Mach–Zehnder modulator, SMF—single-mode fiber, SOA—semiconductor optical amplifier, VOA—variable optical amplifier, PIN—(positive-intrinsic-negative) photodiode, DSO—digital storage oscilloscope, DSP—digital signal processing.

Note that the modulator's chirp is a key factor enabling dynamic tunability of the transmission reach in IM/DD-based optical fiber links [26]. After the MZM, the modulated optical signal is coupled into the feeder fiber and transmitted over a 21 km long standard single-mode fiber (SMF) link. The input optical power of +4 dBm ensures the ODN compliance to the E1 (18–33 dB) power budget class for several modulation format alternatives. After the downstream transmission, the optical signal is passively split by a 1-to-N (1:N) optical power splitter. In an ONU, the split optical signal is pre-amplified by a SOA(Samsung Electronics, OA40B3A, InP/InGaAsP, 1550 nm) prior to the detection. The variable optical attenuator (VOA), placed before the receiver, is used to adjust a received optical power required for the OPB assessment and to protect it from the overload. The receiver consists of a PIN photodiode (Discovery, DSC-R409, 30 GHz, 0.7 A/W) and a digital storage oscilloscope (DSO, Agilent Technologies, DSOX93304Q, 33 GHz, 80 GSa/s). The DSO is used to limit the receiver's minus 3 dB bandwidth to 8 GHz using a using a 4th order Bessel–Thompson filter, to digitize the received waveforms and to store the digitized for further post-processing. The applied low-pass filtering (LPF) is imposed to emulate the bandwidth limitations at the receiver's (Rx) side aiming to investigate whether components intended for the 10G operation can be used for higher line rates. The offline digital signal processing (DSP) module consists of clock recovery, resampling, linear post-equalization (if considered), and bit-error-rate (BER) estimation. The signal is post-equalized by a linear symbol-spaced equalizer that uses feed-forward and feedback taps to compensate for analog imperfections. For BER estimation, we use a direct error counting. It relies on the bit-by-bit comparison of the transmitted and received bit sequences. More than 10^5 bits are available for the BER estimation at the receiver.

3. Results and Discussion

In this section, we reveal how the signal post-equalization impacts the achievable optical power budget of the IM/DD PON system. Before moving to the optical power budget analysis, we summarize the pros and cons of transceivers exploiting the modulation formats of the interest (see Table 1). We judge aspects such as spectral efficiency of the modulation scheme, power consumption (as a line card must supply enough electrical power), transmission reach (considering an MZM with non-zero chirp factor), and simplicity of the transmitter and receiver (considering the complexity of the driving circuits and pre-/post-processing requirements).

Table 1. Pros and cons of transceivers exploiting the considered intensity modulation direct detection (IM/DD) schemes.

Modulation Format	Spectral Efficiency	Transmission Reach	Power Consumption	Transmitter Simplicity	Receiver Simplicity
NRZ	−	−	+	++	++
EDB	+	++	−	−	−
PAM-4	++	++	−−	−−	−−
PAM-8	+++	+	−−	−−	−−

For the optical power budget assessment, we use the conventional BER curves showing how a pre-FEC BER values change with the received optical power. Two different a pre-FEC BER criteria are considered: (i) a 7% overhead (OH) HD-FEC threshold of 3.8×10^{-3} and (ii) a 20% OH soft-decision (SD) FEC threshold of 2×10^{-2}. If the first one is used as a benchmark for the performance and optical budget comparison, then the second one is mainly used for illustration purposes. We assume that all errors can be corrected by a FEC code for the pre-FEC BER below 3.8×10^{-3}, which leads to the background block error BBE = 0 and thus no service disruption. Additionally, we present eye diagrams so the reader could make the judgment about the signal quality in a such bandwidth-limited IM/DD PON solution.

Figure 2 shows BER curves and eye diagrams for the 28 Gbaud OOK/EDB/PAM-4 and 14 Gbaud PAM-4/8 modulated signals in the IM/DD PON systems. First, we analyze the system performance without any post-equalization (Figure 2a,c), and then, we focus on improvements that the linear post-equalization offers (Figure 2b,d). The optical power budget values (together with the corresponding values of the available power margin) obtained for all considered cases are summarized in Table 2. For the power margin calculation, we assume the insertion loss of 4.4 dB for the feeder fiber, 17.3 dB for the 1:32 optical power splitter, and 2.2 dB for the drop fiber. A negative power margin (as for the 28 Gbaud PAM-4) means that the splitting ratio of 1:32 is not supported. Note that the average insertion loss of 1:16 splitter is at least 3 dB lower, which enables the 28 Gbaud PAM-4 alternative.

Table 2. Optical power budget and available power margin for the explored alternatives and post-equalizer structures (number of FF and FB taps).

Signals	w/o	4-FF	9-FF&5-FB	43-FF&21-FB
28 Gbaud OOK	-	29 dB/5.1 dB	31 dB/7.1 dB	31 dB/7.1 dB
28 GBaud EDB	27 dB/3.1 dB	29 dB/5.1 dB	30 dB/6.1 dB	30 dB/6.1 dB
14 Gbaud PAM-4	26 dB/2.1 dB	27 dB/3.1 dB	27 dB/3.1 dB	27 dB/3.1 dB
14 Gbaud PAM-8	-	-	-	-
28 Gbaud PAM-4	-	-	22 dB/−1.9 dB	23 dB/−0.9 dB

In the configuration without the post-equalization, the HD-FEC requirements are met for two cases: (i) 28 Gbaud EDB and (ii) 14 Gbaud PAM-4. These signal formats allow achieving the HD-FEC requirements and the optical power budget of 27 dB and 26 dB, respectively. Such performance could be considered as expected, but the level distribution between eyes in the eye diagrams shows evidence of driver's linearity. Even for the 14 Gaud PAM-8, the linearity is acceptable, and only a high signal-to-noise ratio (SNR) requirement hinders to reach the HD-FEC performance. For the 28 Gbaud OOK and PAM-4, a dispersion-induced power fading degrades the performance, and chromatic dispersion compensation or signal equalization must be applied to reach the BER threshold of 3.8×10^{-3}. To test this, we have chosen a linear equalizer whose structure consists of 43-FF&21-FB taps.

The number of taps is chosen in a way to maximally improve the system's performance by tackling the bandwidth limitations due to the receiver's side bandwidth and chromatic dispersion. Further increase of the filter tap number does not improve BER values but only adds the complexity. Note that linear equalization using FF taps only is implemented to overcome bandwidth limitations and ISI, whereas FB taps are added to the structure to improve the performance in the presence of noise.

The results show that such post-equalization (43-FF&21-FB taps) significantly improve the BER performance, and thus, it enhances the optical power budget as compared to the previous case without the post-equalization. The optical power budget of the 14 Gbaud PAM-4 is increased by 1 dB. The corresponding value for the 28 Gbaud EDB is 3 dB. More importantly, the post-equalization enables more options of the modulation format alternatives. The HD-FEC requirement is met for the 28 Gbaud OOK and 28 Gbaud PAM-4 modulations. Moreover, the signal quality is so good that it allows achieving the optical power budget of 31 dB and 23 dB, respectively. Although the BER improvement is not enough to meet the HD-FEC requirements for the 14 Gbaud PAM-8 signals, its BER curve approaches to the threshold and a slight SNR improvement, e.g., using a nonlinear equalization, would aid in meeting this requirement. Figure 2d shows the corresponding eye diagrams captured for received optical power values that allow detecting signals with the BER below 3.8×10^{-3} or close to it as in the 14 Gbaud PAM-8 case.

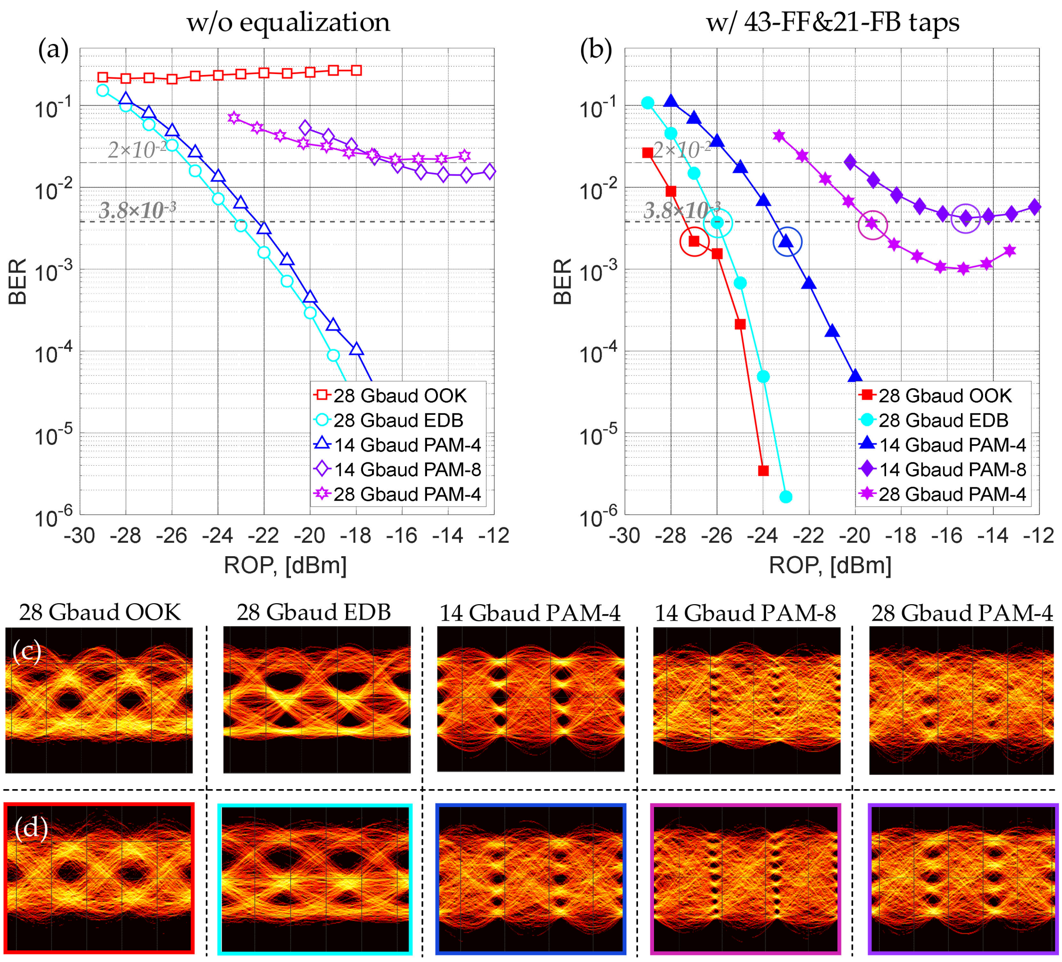

Figure 2. Quality of transmission (QoT) characteristics for the 28 Gbaud OOK, 28 Gbaud EDB, 14 Gbaud PAM-4, 14 Gbaud PAM-8, and 28 Gbaud PAM-4 signals in the IM/DD PON system: (**a**) BER vs. received optical power (ROP) before the digital post-equalization; (**b**) BER vs. ROP after the digital post-equalization employing 43-FF&21-FB taps; (**c**) eye diagrams captured in the ONU at the highest ROP and before the digital post-equalization; and (**d**) eye diagrams captured in the ONU and ROP values that ensure BER < 3.8×10^{-3} after the digital post-equalization.

Next and to better explore the impact that post-equalization has on the optical power budget and to emphasize its importance, we use three equalizer configurations and compare the OPB for each of them: (i) without post-equalizer, (ii) post-equalizer with only 4-FF taps, (iii) 9-FF&5-FB taps. The obtained results are benchmarked to the previous case, i.e., with the equalizer having 43-FF&21-FB taps. Figure 3 presents the results for scenarios whose combination of data rates and modulation formats ensures line rates no higher than 28 Gbps—28 Gbaud OOK/EDB and 14 Gbaud PAM-4, while Figure 4 includes the 14 Gbaud PAM-8 and 28 Gbaud PAM-4. The first is used to stress the bandwidth limitations of the system components and the second to test linearity of the MZM drivers and the system's SNR.

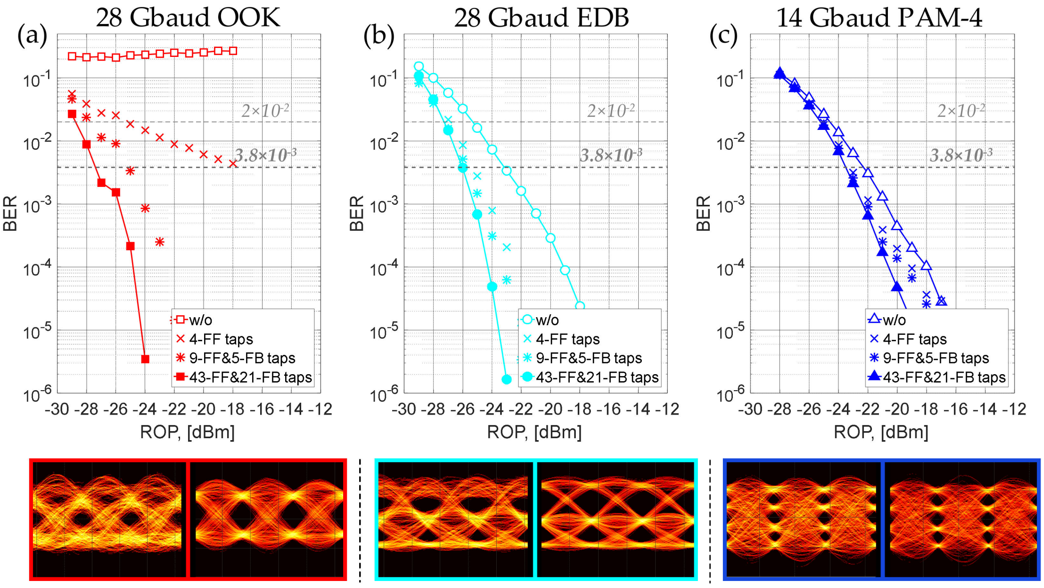

Figure 3. Plots of BER vs. ROP and post-equalizer structure for the (**a**) 28 Gbaud OOK, (**b**) 28 Gbaud EDB, and (**c**) 14 Gbaud PAM-4 signals accompanied by the corresponding eye diagrams captured in the ONU before and after digital post-equalization employing 43-FF&21-FB taps.

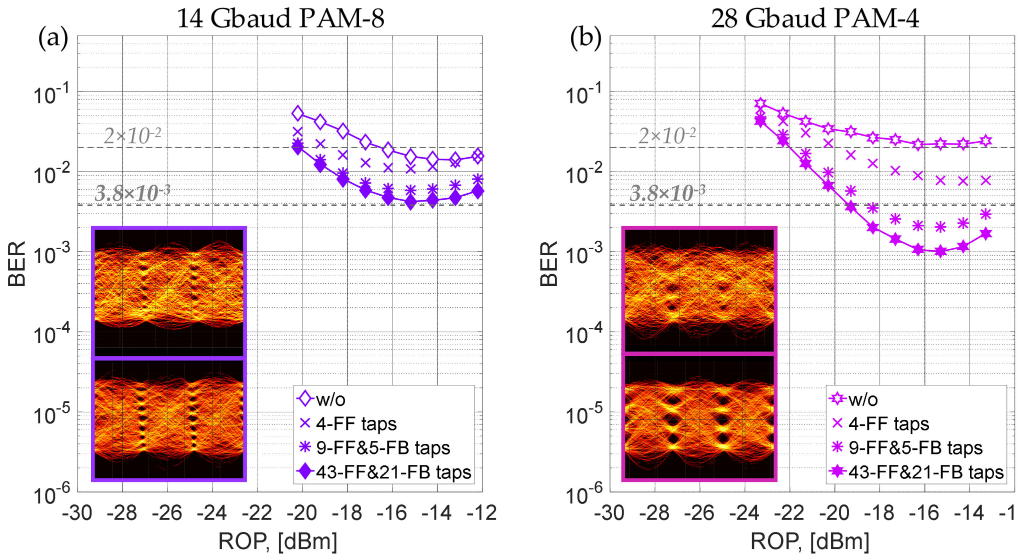

Figure 4. Plots of BER vs. ROP and post-equalizer structure for the (**a**) 14 Gbaud PAM-8 and (**b**) 28 Gbaud PAM-4 signals accompanied by the corresponding eye diagrams captured in the ONU before and after digital post-equalization employing 43-FF&21-FB taps.

Figure 3 shows that equalizer with just 9-FF&5-FB taps significantly improves the performance of the 28 Gbaud OOK system. The optical power budget is 29 dB, which is by 2 dB smaller as compared to the case with 43-FF&21-FB taps. Unfortunately, only FF taps are not able to provide the required improvement to meet the pre-FEC BER requirement. At −18 dBm of the received optical power, the BER approaches but not crosses the defined threshold. As for the 14 Gbaud PAM-4 and 28 Gbaud EDB, an equalizer with just 4-FF taps is enough to improve the performance and leads to a higher sensitivity—by 1 dB and by 3 dB, respectively. The use for a more complex structure with more taps does not enhance the performance, and the optical power budget remains unchanged.

Further, we explore two scenarios—14 Gbaud PAM-8 and 28 Gbaud PAM-4—ensuring a higher line rate (42 Gbps and 56 Gbps, respectively). Figure 4a shows results for the 8-level PAM signals, 14 Gbaud PAM-8, which was used to test the MZM driver linearity. The obtained eye diagrams evidence their good linearity as signal levels are equally distributed, but we see that the system is SNR limited as the upper and lower eyes are noisy. Therefore, applying even strong linear post-equalization (i.e., using 43-FF&21-FB taps) does not improve the quality significantly to fulfill the performance requirement although the BER approaches the threshold of 3.8×10^{-3}. Finally, Figure 4b shows that the linear equalization with 9-FF&5-FB taps is sufficient to fulfill the HD-FEC BER requirements and reach the optical power budget of 22 dB for the 28 Gbaud PAM-4 alternative. A more complex structure of the equalizer does not provide significant improvements neither in terms of the signal quality nor in the optical power budget. The system is a partially SNR limited. Insets in Figure 4b show the best eye diagrams for the configuration without the equalizer and with 43-FF&21-FB tap equalizer. The latter has a relatively large eye opening. The fact that the BER threshold of 2×10^{-2} is met for all considered modulation format alternatives proves the viability of IM/DD formats to be used in HS-PON solutions delivering 25+ Gbps or even 50+ Gbps in commercial PONs if SNR improvement and modulator chirp management are achieved.

4. Conclusions

The optical power budget is analyzed for the bandwidth-limited IM/DD PON exploiting the digital signal post-equalization at ONUs. We compare the optical power budget values and the available power margins for the conventional TDM-PON configuration (20 km long feeder fiber, 1:N passive optical power splitting before ONUs) with NRZ-OOK, EDB, PAM-4, and PAM-8 formats at net-rates above 25 Gbps. These signal formats are chosen thanks to their simplicity, the possibility to re-use some of the transceiver's elements (e.g., electrical drivers, amplifier, and photodiodes), and compatibility with the deployed PON infrastructure. We consider only a downstream transmission over a single wavelength in the C-band. To investigate whether components intended for the 10G operation can be used for 25+ Gbps operation, we limit the receiver's bandwidth to 8 GHz before the estimation of the optical power budget. The obtained results show that (i) 10G PON component bandwidth is enough to achieve net-rates above 25 Gbps; (ii) linearity of the optoelectronic components allows operating them using schemes with multilevel modulation formats; and (iii) in combination with the digital signal post-equalization, the obtained optical power budget is compliant with E1 class (OPB = 18–33 dB). More specifically, we reveal that the 28 Gbaud EDB and 14 Gbaud PAM-4 schemes could be used in PONs even without any post-equalization. The signal quality is such that it fulfills the HD-FEC requirement and ensures the power margin of 3.1 dB. For the 28 Gbaud NRZ-OOK, an equalizer with FB taps is required; a 9-FF&5-FB tap equalizer helps to overcome ISI in the presence of noise, which leads to the optical power budget of 29 dB. Finally, line-rates up to 56 Gbps can be supported by the PON employing the PAM-4 modulation. Although a 1:32 splitting ratio might not be feasible due to high insertion loss of such a splitter, it provides the optical power budget of 23 dB. Therefore, the considered IM/DD PON alternatives together with digital signal equalization has the potential to ensure the sustainability for future PONs with line rates well beyond 25 Gbps in the access segment of optical networks.

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