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TDM-PON PAM Downstream Transmission for 25 Gbit/s and Beyond

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Abstract: The optical access network is currently driving studies on transmissions beyond 10 Gbit/s. This paper reports an analysis of Pulse Amplitude Modulation (PAM), seen as a promising candidate for future Passive Optical Networks (PON). Previous 25 Gbit/s real-time PAM4 results are extrapolated here with simulations to higher bit rates and a higher number of PAM levels. Our main goal is to evaluate the compliancy of PAM with the existing standards and legacy networks as far as fiber length, optical budget class, and wavelength plan are concerned. The simulations enlighten us as to the challenges of multilevel modulation formats, such as noise and jitter, compared to the currently adopted Non-Return-to-Zero (NRZ).

Keywords: access networks; Intensity Modulation Direct Detection (IMDD); optical fiber communication; Pulse Amplitude Modulation (PAM); Passive Optical Networks (PON)

1. Introduction

The future of access networks is currently motivating research and standardization activities on Time Division Multiplexing Passive Optical Network (TDM-PON) solutions beyond 10 Gbit/s. After the IEEE 10G-EPON [1] and the International Telecommunication Union (ITU-T) XGS-PON (10 Gbit/s symmetrical bit rate capable PON) [2] norms, a new standard has been proposed in the ITU-T roadmap based on TDM-PON with a single channel per stream, which is referred to as High-Speed-capable PON (HS-PON) [3]. Different throughputs are investigated within the HS-PON framework but 25 Gbit/s and 50 Gbit/s seem to be serious candidates for future systems. The evolution towards higher data bit rates is mainly driven by the new mobile interfaces for 5 G, where 25 Gbit/s could be needed soon for either backhauling or high/low layer functional split interfaces. HS-PON could thus allow easier convergence between residential, business, and mobile networks [4]. Another technique to achieve higher bit rates for optical access networks is to use Wavelength Division Multiplexing (WDM). The Next Generation PON 2 (NG-PON2) standard gives specifications for this technique with 10 Gbit/s per wavelength [5]. Nevertheless, NG-PON2 technology is not deployed in access networks and here we focus on future TDM-PON in coexistence with legacy technologies deployed for residential.

Modulation formats other than the standard Non-Return-to-Zero (NRZ) are being considered within the HS-PON study group. Multilevel formats such as Duo-Binary [6–8] and Pulse Amplitude Modulation with 4 levels (PAM4) [9–11], currently used in data center communication [12] and Visible Light Communications (VLC) [13], are good candidates to achieve 25 Gbit/s while keeping 10 GHz optics. State-of-the-art PAM4 reports devoted to optical access networks have, however, been limited in most cases to offline transmissions. Indeed, −14.5 dBm of sensitivity (24.5 dB optical budget) for 28 Gbit/s PAM4 was demonstrated over 20 km [10]. A report on real-time

PON applications demonstrated a 40 Gbit/s downstream PAM4 transmission in C band with 10 and 20 km reach and 26.5 dB and 24.5 dB optical budgets but with rather costly optics (Mach–Zehnder modulator, erbium-doped fiber amplifiers), high-sampling-rate Analog-to-Digital and Digital-to-Analog Converters (ADC and DAC), and equalization [14].

As far as the state of the art for 50 Git/s multilevel transmissions is concerned, the huge majority of assessments are again based on offline transmissions. For instance, 41.85 Gbit/s downstream PAM8 achieving a −13 dBm receiver sensitivity with 10 G optics and Digital Signal Processing (DSP) was demonstrated over 20 km of fiber [15]. Another work showed a receiver sensitivity of −21.4 dBm with 50 Gbit/s Electrical Duo-Binary (EDB) over up to 20 km in O band without DSP [6].

Those new modulation formats for the access network have additional requirements compared to the NRZ. For instance, PAM4 requires a linear driver to maintain equal-amplitude spacing between the four optical levels. However, the most complicated element of the PAM4 system design is the decoder that requires logical gates and limiting amplifiers to adjust the decision threshold. Although the Duo-Binary decoder is simpler with fewer logical gates and decision thresholds, encoding is more complicated especially for Optical Duo-Binary (ODB), which requires a DC biased Mach–Zehnder modulator. Finally, the NRZ format remains the simplest one for PON implementation. Channel equalization is a key solution to enhance the performances of those modulation formats, and is thus the subject of intense studies for either direct detection [16] or coherent detection [17]. Machine learning and deep learning [18] are now being introduced into PON research for efficient design of the equalization procedure. The choice of the modulation format will depend on the difficulties related to the implementation. Upstream and downstream transmissions do not have the same constraints in term of cost and having a Mach–Zehnder modulator is not reasonable in each Optical Networks Unit (ONU) at the user premises. The complexity of the decoder also has an impact on the desired transmission direction. Furthermore, the choice of wavelength will determine the effect of the channel. For instance, chirp intensity modulation might not have the same effect with negative or positive chromatic dispersion. Here, we focus our study for downstream transmissions on a directly modulated laser which reduces the overall cost by sharing the optoelectronics at the Optical Line Terminal (OLT) but requires a linear electrical driver for the PAM4 signal.

The complexity of the DSP and/or equalization techniques could prevent real-time applications in access networks due to the cost of the equipment and the potentially high entailed latencies (for instance, emerging from the processing time needed for a high number of equalization taps). In that sense, in the O band, low-cost, low-latency, high-throughput transmissions would better be reached with either PAM4 on 20–25 GHz optics or higher PAM formats such as PAM8 while reusing 10 GHz optics without DSP.

In a previous work, we demonstrated a real-time 25 Gbit/s PAM4 downstream transmission based on 10 G optics, achieving a 29 dB Optical Budget (OB) corresponding to a −18.5 dBm receiver sensitivity up to 40 km in O band [11]. We use our previous experimental work to fine-tune the proposed simulation model, and we then extrapolate the model results to assess higher bit rates by either adding more amplitude levels on the signal while keeping the same optical bandwidths or by using optics with higher bandwidths to achieve 37.5 Gbit/s and 50 Gbit/s throughputs, which are aligned with target bit rates currently investigated in the normative framework [3]. The novelty in this paper is the extrapolation of a real-time setup to higher bit rates and higher modulation format. This study leads to focusing on or excluding some future research schemes. Most importantly, we focus on keeping simple Intensity Modulation–Direct Detection (IMDD) without signal processing other than Forward Error Correction (FEC), which is essential to assure the interoperability of the physical layer in access networks while allowing low-cost customer premises equipment (CPE).

2. Simulation Setup

The decoding of the received electrical signal is done with 1, 3, or 7 thresholds for NRZ, PAM4, or PAM8. Rectangular masks are implemented to represent the precision of detection on the receiver.

Points falling inside the mask are treated randomly either as above or below the corresponding threshold. The received data are finally compared to the transmitted ones in order to calculate the bit error rate. A loop is implemented in the simulation and the transmission is reiterated until there are at least one hundred errors measured for each Bit Error Rate (BER) value.

All the simulations in this paper rely on a model that was first validated based on the actual real-time experimental results of our previous work [10]. The reference experimental setup (see Figure 1) includes a Pulse Pattern Generator (PPG) generating two Pseudo Random Binary Sequences of $2^{31} - 1$ bits (PRBS31); both generated streams are injected into a PAM4 encoder. The encoder is based on a 6 dB electrical attenuator for the Least Significant Bit (LSB) stream, a tunable phase shifter is used on the Most Significant Bit (MSB) stream to align it with the LSB, and then both of the streams are combined with a power divider. The PAM4 electrical signal is amplified with a linear electrical amplifier before modulating the laser. The laser used is a Directly Modulated Laser (DML) emitting at 1311 nm with 10 GHz bandwidth and with 11.8 dBm optical output power at 90 mA bias current. After Standard Single Mode Fiber (SSMF), a Variable Optical Attenuator (VOA) is used to perform the optical budget measurements. The PAM4 ONU is based on an 8 GHz bandwidth Avalanche Photodiode + TransImpedance Amplifier (APD + TIA). A PAM4 decoder consists of three limiting amplifiers, two eXclusive OR (XOR) gates, and a power divider. Also, a clock recovery module and an error detector are in the decoding part of the real-time 25 Gbit/s PAM experimental setup.

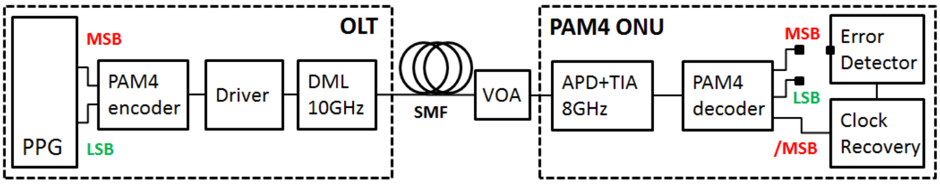

Figure 1. Original experimental setup.

Our system simulation study aims at validating or disproving the concept for higher-bit-rate transmissions. The simulations were implemented with MATLAB© and the main transceiver and transmission system parameters are listed in Table 1. For the sake of simplicity and in contrast with our experimental setup, PAM8 and PAM4 levels were equally spaced. Gbaud rates of 12.5 and 25 were studied here in order to achieve 37.5 Gbit/s and 50 Gbit/s, respectively.

Table 1. Transceiver and transmission parameters.

Parameter	Value
PRBS data sequence length	$2^{15} - 1$ (PRBS15)
Modulation formats	PAM4 {PAM8}
Laser	DFB directly modulated
Wavelength	1311.36 nm
Chirp parameter α	3
Chirp parameter fc	2 GHz
Bandwidth	10 GHz {20 GHz} at 90 mA bias
Electro-optical conversion efficiency	0.15 mW/mA
Threshold current	27.8 mA
Saturation current	138 mA
RIN	−110 dBm (AWGN)
Photodiode + TIA	APD
Responsivity	0.8 A/W
Bandwidth	8.5 GHz {21 GHz}
Transimpedance gain	36 dB
Fiber	SMF
Length	0, 10, or 20 km
Attenuation	0.4 dB/km
Dispersion	0 ps/nm/km

PAM8 has more amplitude levels than PAM4, which will add extra complexity to the encoder and decoder but has the advantage of allowing a 50% increase in the bit rate when using the same bandwidth as a PAM4 signal. Namely, a 12.5 Gbaud PAM8 signal would allow reusing 10 GHz optical components and a lower clock frequency. As far as 50 Gbit/s PAM4 is concerned, four amplitude levels are used and can be decoded following the same principle as that used in the experimental part of our previous work. However, it would require optics and electrical components with bandwidths around 20 GHz, as well as a higher clock reference (25 GHz for 50 Gbit/s).

The first step in the simulation is to generate a PRBS with a Linear Feedback Shift Register (LFSR) function. Then, the PAM4 or PAM8 sequence is built up using two or three versions of the original PRBS sequence, delayed with respect to one another so as to allow proper decorrelation. While opting for Gray encoding would result in a simpler receiver structure, it would be at the cost of a more complicated transmitter in a laboratory implementation. Furthermore, it has been shown that the OB gain when substituting Gray for binary encoding for PAM4 remains small—lower than 0.2 dB at a Bit Error Rate (BER) of 1.10–3 [19]. Here, we decided to study the binary encoding for PAM4 and PAM8, which is closer to our reference study [11].

The combined binary streams are converted into electrical symbols with 32 samples. A low-pass filter is used to simulate the 15 ps rising and falling times (10–90%) of the signal coming from electrical generators used in the reference experimental setup. The 5 Vpp signal then directly drives a virtual Distributed FeedBack laser (DFB) having identical characteristics to that used in the experimentation (see Table 1 for its parameters) and emitting 11.8 dBm mean optical power. The laser signal modeling is based the DFB PI response. A polynomial approximation of the reference experimental curve is generated first, and then the electrical signal is applied on the laser model. Relative Intensity Noise (RIN) is added as an Additive White Gaussian Noise (AWGN). The frequency deviation generated by the chirp is applied following the model depicted in [20]. The 8 GHz cut-off frequency of the photodiode used is lower than the relaxation oscillation frequency of the DFB laser in our experimental setup. So, the equivalent electrical frequency responses of the laser and the photodiode are simulated with a single Butterworth low-pass filter positioned after the optical–electrical conversion, and its -3 dB bandwidth is equal to the smallest bandwidth of both, i.e., 8 GHz.

The signal propagation in the optical fiber is modeled using the Slowly Varying Envelope Approximation (SVEA) [21]. Indeed, this relatively simple model can be adopted without loss of generality since optical nonlinear effects are expected to be negligible considering the relatively low optical power launched into the fiber and the short distances in single-channel access networks. A 0.4 dB/km fiber attenuation was applied and no chromatic dispersion was added since the laser emits at 1311.36 nm (in the O band), near the zero-dispersion wavelength for the SSMF.

In the following analysis, different fiber lengths are considered up to 20 km, which is the typical range of currently deployed access networks. Longer segments would bring no degradation other than attenuation at the tested wavelength. A VOA was simulated to perform OB measurements. The photodiode model mimics the experimental Avalanche PhotoDiode + Transimpedence Amplifier (APD + TIA) used (see Table 1). Both shot noise and thermal noise were simulated, according to [21]. The homemade decoder of the reference experimental setup generates an additional noise that is added to the model as a Gaussian noise whose standard deviation, expressed in arbitrary amplitude units (a.a.u.), varies as depicted in Figure 2. It should be noted that the realistic noise distribution is slightly broader from the higher levels to the lower ones of the PAM signals due to the differences in optical power. Here, the same noise distribution is implemented for all levels.

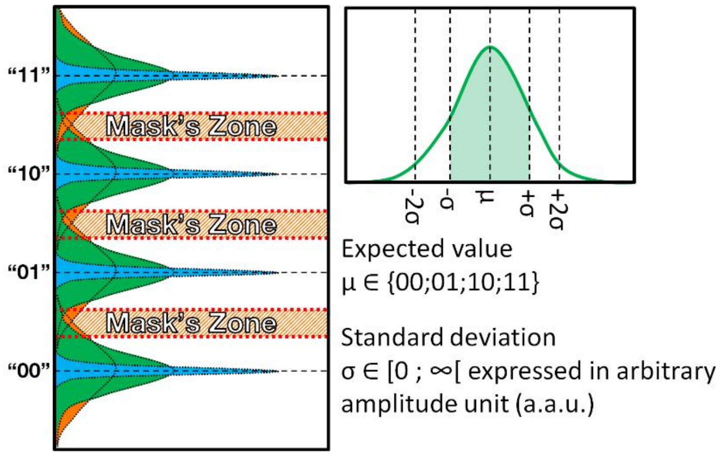

Figure 2. Gaussian noise representation on each PAM4 level for different standard deviations (blue: low standard deviation; green: medium; orange: high).

3. Simulation Results

3.1. Simulation Model Fine-Tuning

In order to correctly simulate our experimental setup, we first measured a new BER curve for an equally spaced PAM4 generated with a data sequence of length $2^{15} - 1$ bits (PRBS15) on the existing experimental setup described in Section 2. The reduced PRBS length was imposed by memory constraints on our simulated PRBS sequences. Using equally spaced PAM formats allows a more straightforward and fair comparison between PAM4 and PAM8.

The size of the masks is the major parameter that determines the optical budget in our model. The masks have fixed sizes, and according to the XG(S) PON standard [2], they are set similarly to the rectangular mask of the OLT's signal (see Figure 3a). In order to correctly calibrate its size for a 3.8×10^{-3} target BER, its width matches the standard, i.e., 20% of the eye diagram width. The mask's height should be 50% of the eye's height to comply with the standard. However, since PAM4 includes three amplitude levels, a new mask has to be defined. We propose three identical masks with heights equal to 50% of the amplitude of each eye, which gives us around 16% of the total eye diagram's height, as shown in Figure 3b. In order to be closer to the experimental curves, the masks' height is set to 14% of the total eye diagram's amplitude in our simulations.

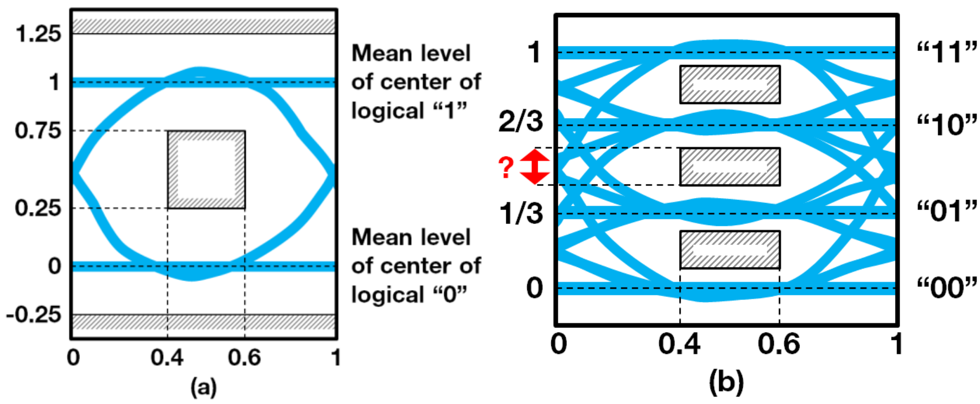

Figure 3. Mask of the eye diagram for OLT transmitter (**a**) and proposition for PAM (**b**).

The encoder noise setting that allows the best resemblance between experimental and simulation results was found to be 500 a.a.u, which represents a noise amplitude of ~18 mVpp on each level for a 120 mVpp PAM4 signal. Figure 4 shows a quite good match between the simulated and the experimental back-to-back BER curves for a transmitted PRBS15 sequence. The 12.5 Gbit/s NRZ curve shows the detection of the MSB in both experimentation and simulation.

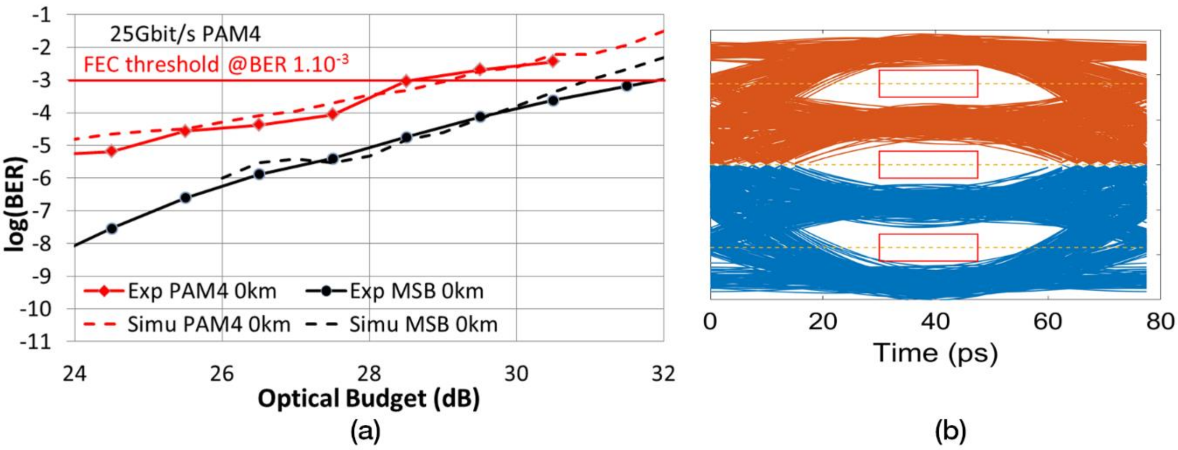

Figure 4. (**a**) Calibration of the simulation with experiment for PAM4 transmission in optical back to back at 25Gbit/s with a PRBS15; (**b**) Eye diagram with rectangular decision masks.

3.2. 37.5 Gbit/s PAM8

PAM8 is generated from three PRBS15 data streams. The amplitudes of two of the streams are attenuated, the former by half and the latter being divided by 4. A different timing delay equal to an integer number of bits is applied on each PRBS15 in order to decorrelate the streams. Natural labeling PAM8 decoding is based on seven decision thresholds and eight exclusive-OR operations (Figure 5).

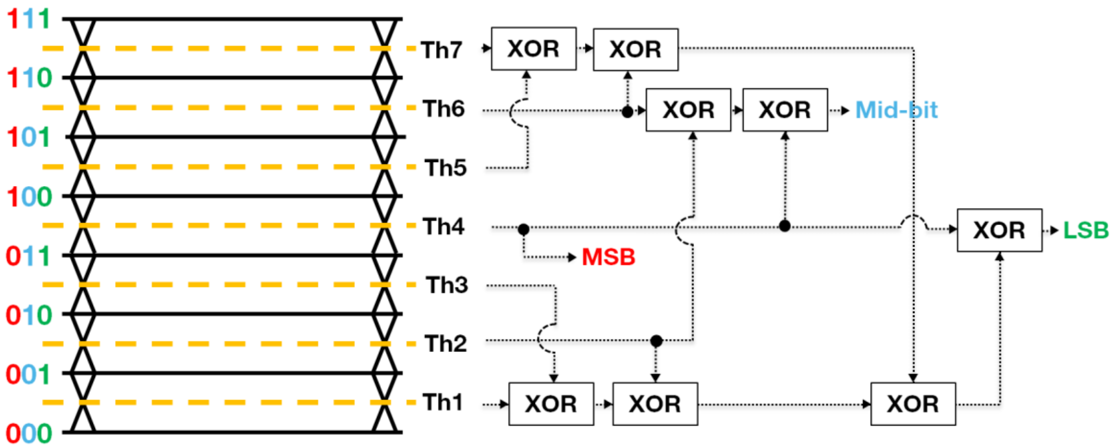

Figure 5. Natural labeling PAM8 decoder.

We observe that a 37.5 Gbit/s PAM8 transmission cannot be correctly performed using the simulation parameters issued from our 25 Gbit/s PAM4 calibration. This is mainly due to the noise added to emulate our homemade decoder. The amplitude levels are too close from one another to be correctly distinguished from each other; thus, the BER never falls below the FEC threshold, whatever the OB (see Figure 6a and "500" a.a.u. curve in Figure 6d).

In order to evaluate how a better-quality decoder device would mitigate the observed drawback and allow a 37.5 Gbit/s system, the standard deviation of the decoder noise was decreased progressively (see eye diagrams in Figure 6a–c). The first OB curve that does not exhibit a pronounced error floor is obtained for a Gaussian noise standard deviation equal to 140 a.a.u. (which represents a noise amplitude around ~6 mVpp on each level for a 120 mVpp PAM8 signal). In this configuration, PAM8 still does not reach a 28 dB OB (see Figures 6d and 7) and is not compliant with any of the budget classes depicted in the standard. We can thus fairly say that realizing PAM8 IMDD transmission compliant with ODN class N1 would only be possible with a far better decoder or at least with DSP or equalization procedures, which should be avoided to allow cost-efficient CPEs.

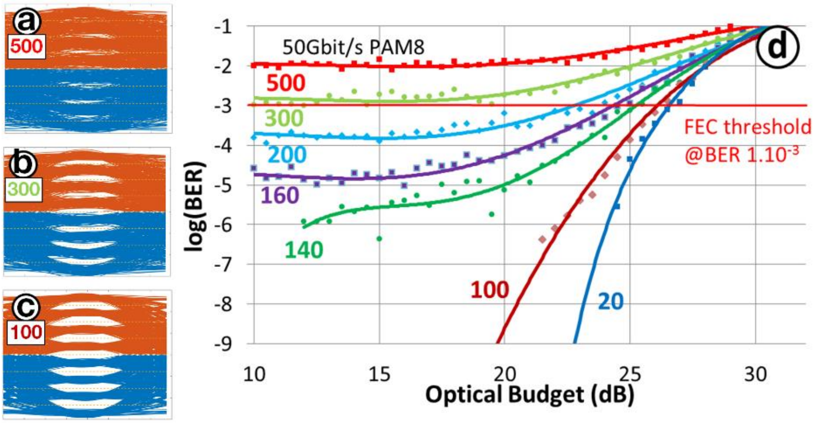

Figure 6. PAM8 eye diagrams for standard deviations of the decoder's Gaussian noise of (**a**) 500 a.a.u., (**b**) 300 a.a.u., and (**c**) 100 a.a.u. (**d**) Simulated and polynomial approximations of BER versus Optical Budgets for different standard deviations of the simulated decoder's noise.

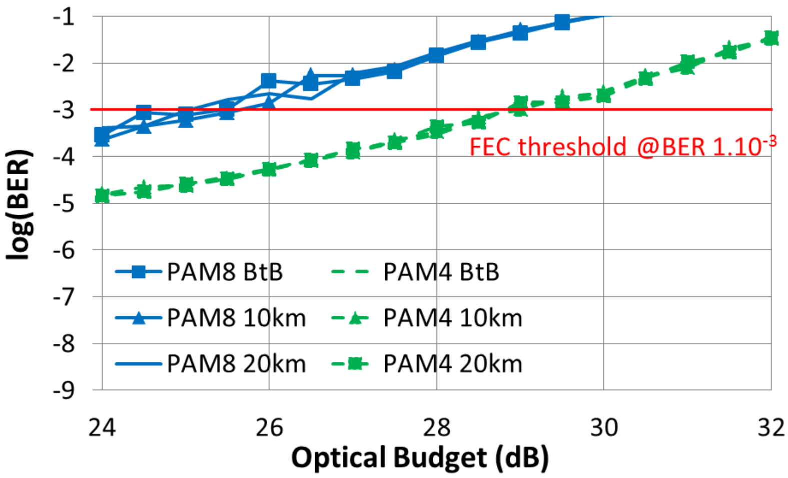

Figure 7. BER of 37.5 Gbit/s PAM8 and 50 Gbit/s PAM4 versus Optical Budgets for 0, 10, and 20 km.

3.3. 50 Gbit/s PAM4

In this part, the electrical bandwidths of the optical components are enhanced in order to upgrade the rate from 25 Gbit/s to a target bit rate of 50 Gbit/s. The results are therefore akin to 25 Gbit/s and better than the optimized 37.5 Gbit/s PAM8 (Figure 7).

Compared to 25 Gbit/s PAM4, a small change in the eye diagram is noticeable in terms of rising and falling time because of the higher limiting bandwidth of the transceivers: at 25 Gbit/s (12.5 Gbaud), the photodiode used in the experimental setup had a 8.5 GHz bandwidth (68% of the baud rate), whilst in the simulated 50 Gbit/s (25 Gbaud), the laser is the limiting bandwidth element at 20 GHz (80% of the baud rate).

Contrary to the 25 Gbit/s PAM4 simulations, which were based on actual measurements from our experimental setup, it should be noted that here we rely only on the datasheets of the 20 GHz optics that we took as a reference.

Another approximation in our model regards chromatic dispersion. Although weak, depending on the emitting wavelength in the O band, it could reach up to ±3 ps/nm/km. The recent normalization recommendation [3] states that for chirpless 25 Gbit/s NRZ transmission, the dispersion tolerance is around 190 ps/nm, which means that wavelengths between 1260 and 1410 nm are usable over up to 20 km of fiber without dispersion compensation. For 50 Gbit/s PAM4, the usable spectrum might be restrained due the higher number of amplitude levels. This means that the simulated results might be valid on a narrower wavelength spectrum.

4. Conclusions

In this article, we studied the feasibility of downstream PAM TDM-PON with either 50 Gbit/s PAM4 or 37.5 Gbit/s PAM8 to achieve higher bit rates than 25 Gbit/s.

While PAM8 can reuse the 10 GHz optics designed for previous PON generations, this modulation format appears to be too constraining in terms of noise sensibility and receiver complexity for access network CPEs. A PAM8 decoder should have 3 times less noise than an actual real-time PAM4 decoder, and it would still not be compliant with the ODN classes depicted in the standards of the legacy access network technologies.

PAM4 is a very good candidate to solve the bit rate growth problem in both fixed and mobile access networks. In O band, where the chromatic dispersion is low, it preserves the IMDD transmission simplicity with no heavy signal processing or equalization requirements. However, bit rate enhancement up to 50 Gbit/s would require higher bandwidth for optoelectronics components up to 25 GHz.

Author Contributions: S.B., L.A.N. and F.S. conceived of the presented idea. S.B. and L.A.N. developed the theory and performed the computations. S.B. carried out the experiments. L.A.N., F.S., P.C. and D.E. verified the analytical methods. All authors discussed the results and contributed to the final manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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