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Original Article

Performance Analysis of a 200 Gb/s PAM-4 PAM-8 WDM-PON

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Abstract *- Passive Optical Networks allow more and more homes and enterprises to use optic fiber as the transmission medium for access to High-Speed Internet. These kinds of networks are limited by length and data rate due to distortion, noise, and attenuation when light propagates over optic fiber. In this investigation, a simulation of a 200 Gb/s (4x50 Gb/s) WDM-PON with PAM4 and PAM8 modulation without predistortion is performed; it permits transporting more bits over the same bandwidth, increasing spectral efficiency. A scenario was implemented in Optsim® in co-simulation with Matlab® software, and compare the performance over 50%, 60%, 70% and 100% of the necessary bandwidth photodetector. Data was transmitted over a 20 km link, with dispersion compensation with a G.652D standard single-mode fiber. Results show that using PAM-4 against PAM-8 improves 8 dB for objective BER=10^{-3} as the maximum value to implement FEC in the receptors.*

Keywords *- WDM, Pon, Pulse amplitude modulation, Pam-4, Pam-8.*

1. Introduction

When light propagates over a fiber optic link, it suffers dispersion, attenuation, and distortion. This limits length and transmission rate, incrementing the Bit Error Rate (BER). [1] Increasing the optical networks' data rate (bits per second bps) and spectral efficiency (bps/Hz) is the principal scope in developing new technologies and generations of networks. This is achieved by combining some multiplexing techniques and modulation of the optical signal. Wavelength Division Multiplexing- Passive Optical Networks (WDM-PON) combine multiplexing and modulation techniques to increase the bit rate and spectral efficiency.[2,3] These kinds of networks are considered New Generation Networks, and a version is defined by the International Telecommunications Union (ITU) in G.989 recommendations series.[4]

During the COVID pandemic, data traffic had a considerable increment. Thus, more and more homes are using fiber optic cables as transmission mediums.[7] For example, in Latin America, Fiber to the Home/Building (FTTH/B) access networks has had an increase of new users of 40% between 2020 and 2021.[5] In countries like Ecuador, these networks had a rate penetration of 13.09% in 2018 and increased to 24.5% in 2022.[6] Hence, new technologies to increase these networks' performance are required, which is why WDM-PON is considered a new-generation network, allowing better performances and combining time and wavelength multiplexing techniques, which have caused the change of infrastructure of some Internet Service Providers (ISP).[8]

These networks allow to increase in the data transfer speed and spectral efficiency by combining four wavelengths, i.e., a WDM-PON includes four channels with a bit rate of 10 Gb/s each one. This allows transferring a large amount of data with a good cost/performance relation. However, these use two levels modulation scheme as OOK (On-Off Keying) that wastes bandwidth and has low spectral efficiency.[9] To increase spectral efficiency, multilevel amplitude modulation schemes must be implemented. Modulation techniques such as M-level Pulse Amplitude Modulation (PAM-M) are employed to increase the spectral efficiency in optical links. Currently, the most popular are PAM-4 and PAM-8. If PAM-4 is implemented, it allows duplicating of the amount of data transmitted. If PAM-8 is implemented instead, the data amount is triplicated with the same bandwidth compared to a 2-level signal as On-Off Keying OOK or PAM-2.[10] For example, authors in [11] establish that PAM-4 modulation allows reducing the reduction of energy consumption and increases the data transfer. Therefore, this modulation is very useful to implement over 5th generation cellular networks 5G/5G+. In that research work, a WDM-PON with 4x10 Gb/s channels was simulated using Optsim® software, with channels separated with 100 GHz of spectral spacing, according to ITU-T 694.1 recommendation, concluding that using Fiber

Bragg Grating (FBG) based dispersion compensation, allows achieving 15 km extra in an optic link for an objective BER of 10^{-3}, using Forward Error Correction (FEC). In [12], the software VPI Photonics Design Suite® was employed for simulating an 8-channel WDM-PON with 25 and 40 Gb/s of bitrate per wavelength, using PAM-4 modulations. Besides, 10, 12, 20 and 30 GHz 4^{th} order Bessel filters are used in transmission and reception. Results of this paper show that by implementing a 12 GHz filter in transmission and a 10 GHz filter in reception, a 30 km link is achieved with a BER objective of 10^{-3}, with FEC, for a data rate of 25 Gb/s. For a 40 Gb/s data rate for the same BER is necessary the use of 20 GHz filters is. The research work reported in [13,14] details WDM-PON with an 8x2.5 GBaud/s channel, with 100 GHz separation between adjacent channels. The modulation technique employed was PAM-4 over Analog Radio over Fiber (ARoF).

In this millimetric, signals were transmitted with 28 GHz frequency over a 20 km link of standard single mode fiber, obtaining a BER of $4x10^{-3}$ and over a 40 km link with a BER of $2.8x10^{-3}$, which are greater than objective BER for FEC. In [31], authors describe a simulation of a 100 Gb/s WDM-PON simulation using PAM-4, partial-response PAM-4 and PAM-8, including comparing a PIN and an APD receiver and implementing three techniques as no equalization, feed-forward-equalization and decision-feedback equalization. This evaluation concludes that a 20 km optic link is possible with a path loss of 29 dB over a wide range of wavelengths in the O-band. Authors in [15] achieve an objective BER of $3.8x10^{-3}$ working with an 8-channel WDM-PON with 10 Gb/s each and 20 GHz of separation, combined with Hard decision FEC (HD-FEC) that permits to achieve of the objective BER over a 25 km optical link. Besides, in [16], an experimental demonstration is implemented to analyse PAM-4 modulations with predistortion over a 20 km PON, coded with Gray code. This paper concludes that it is possible to achieve a 1 dB improvement for a BER of 10^{-3} with respect to the scenario where no predistortion is used.

In this paper, a WDM-PON is designed and simulated using Optsim® software to analyse the performance using PAM-4 and PAM-8 modulations with a bit rate of 50 Gb/s per channel with four channels over standard single mode fiber and no predistortion using as reference a threshold BER of 10^{-3} used in error correction codes as FEC, unlike of other works, photodetectors with different bandwidth as 100%, 70%, 60% and 50% of necessary bandwidth to transmit PAM-4 and PAM8 signals are used, and due the scarce of investigation using PAM-8 modulations, this paper contributes in that investigation field. In section 2, the fundaments of WDM-PON and PAM modulations are reviewed. In section 3, the parameters of optical simulations and optic networks are presented and analysed. Section 4 details the principal results. Finally, section 5 concludes this paper.

2. WDM-PON and Pulse Amplitude Modulations PAM overview

2.1. Wavelength Division Multiplexing PON

A WDM-PON allows the connection of an Optical Line Terminal (OLT) with an Optical Network Terminal (ONT) for transmitting information over passive optical devices with different wavelengths.[17] In this type of network, it is necessary to use optical combiners working as WDM multiplexers and, alternatively, Arrayed Waveguide Gratings (AWG) as WDM demultiplexers for separating the wavelengths of each channel. A combination of dense WDM (DWDM) downstream is used in WDM-PON to provide services such as High-Speed Internet (HSI), HD-IPTV and other services.[18] In the case of the Next Generation PON 2 (NG-PON2), defined in ITU-T G.989, four L-band wavelengths are used for downstream and other four for C-band wavelengths for upstream, combining WDM and TDM techniques.[19] The bit rate for downstream (DS) and upstream (US) is 10 Gb/s per channel for having up to 40 Gb/s in both directions. The modulation format for US and DS is two-level OOK.[20] Using the same bandwidth for the network transmitter and receiver, the bitrate could have a twofold and threefold increase using other types of modulation as OFDM or PAM-M.[21] Besides, WDM-PON allows the use of power splitters, where all wavelengths are carried to all ONTs, but this technique inserts a lot of insertion loss due to the split rate of up to 1 to 128.[22] Therefore, using a WDM coupler, like an AWG, is a better option.

2.2. Pulse Amplitude Modulation PAM

Pulse Amplitude Modulation uses signals with M-levels like 2, 4 and 8 levels. Each signal level is known as a baud, and it can carry 1, 2, 3 or more bits, depending on the number of levels. Usually, PAM-4 is implemented in short-reach optic links with a high bit rate demand. [23,24] PAM-4 duplicates the bit rate with the same baud rate but decreases the Signal Noise Ratio (SNR) and the length of the optical link. [25] The use of multilevel signals reduces the extinction ratio (ER), or eye aperture, compared to a PAM-2 NRZ modulation, like in the case of PAM-4 and PAM-8 that produce 3 and 7 vertical eyes, respectively, which increase the probability of error (i.e. degradation of the BER).[26,27] Such signals are usually created using external modulation through the use of a Mach-Zehnder Modulation (MZM) and an electrical driver that generates the PAM-M signals. A PAM-M signal is demodulated using a low-complexity direct detection DD technique, possibly employing low-cost photodetectors. [28]

3. Materials and Methods

3.1. Simulation Setup

The network simulation was performed using Optsim® optical system's simulation software in co-simulation with Matlab®. The latter was used for generating the baseband multilevel electric signal. Matlab® was also used for demodulation and data decoding using the electric signal from a PIN photodetector. In Figures 1 and 2, PAM-4 and PAM-8 signals generated by Matlab® modules are shown. The eye diagram of a PAM-M modulation has M levels and M-1 eye apertures. For example, a PAM-4 signal has 4 signal levels and 3 eye apertures, and a PAM-8 have 8 signal levels and 7 eye apertures. [29]

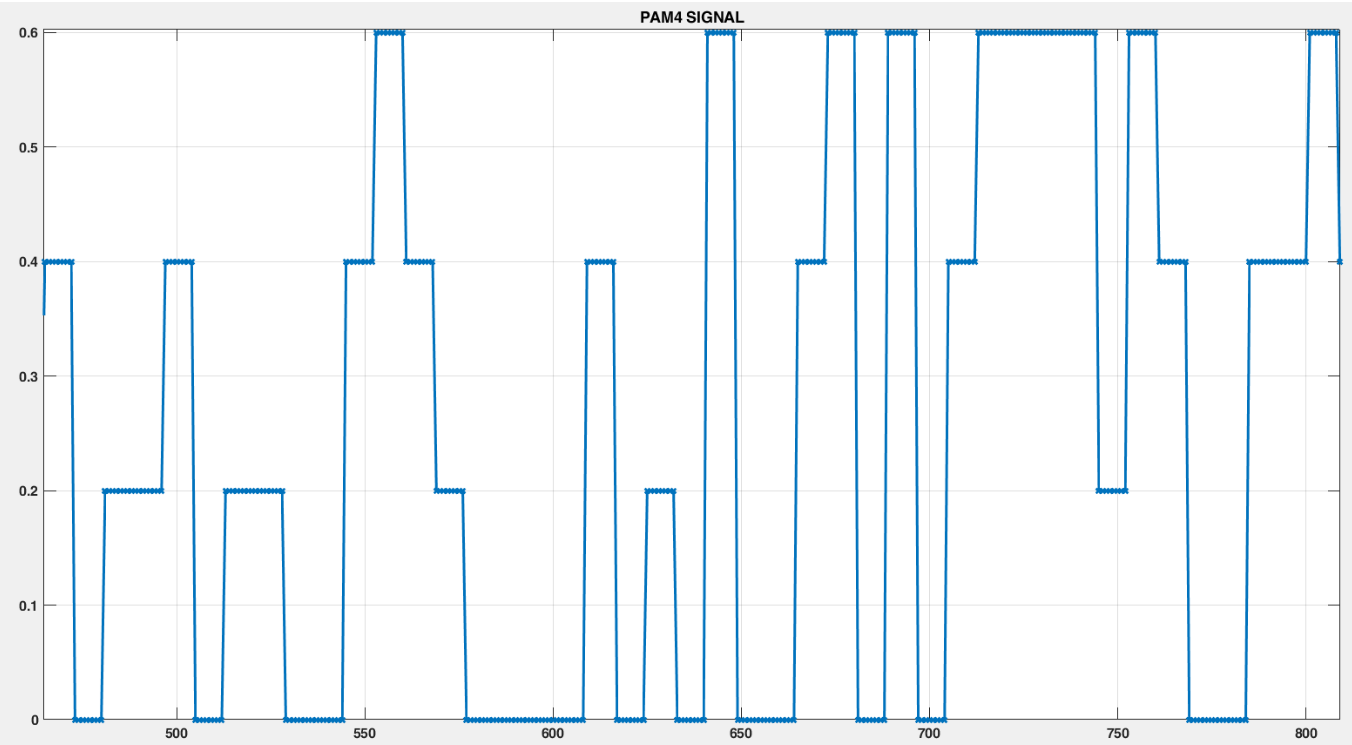

Fig. 1 Pulse Amplitude Modulation signal of 4 levels

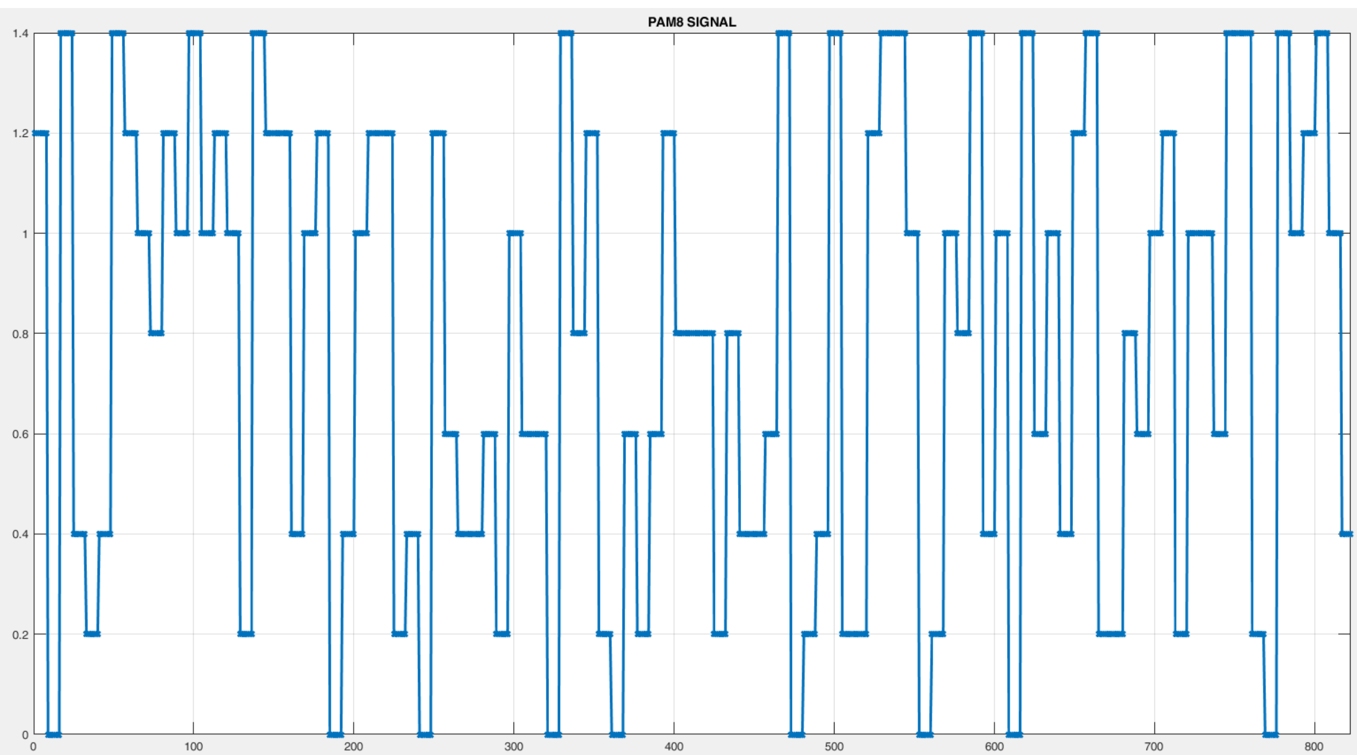

Fig. 2 Pulse Amplitude Modulation signal of 8 levels

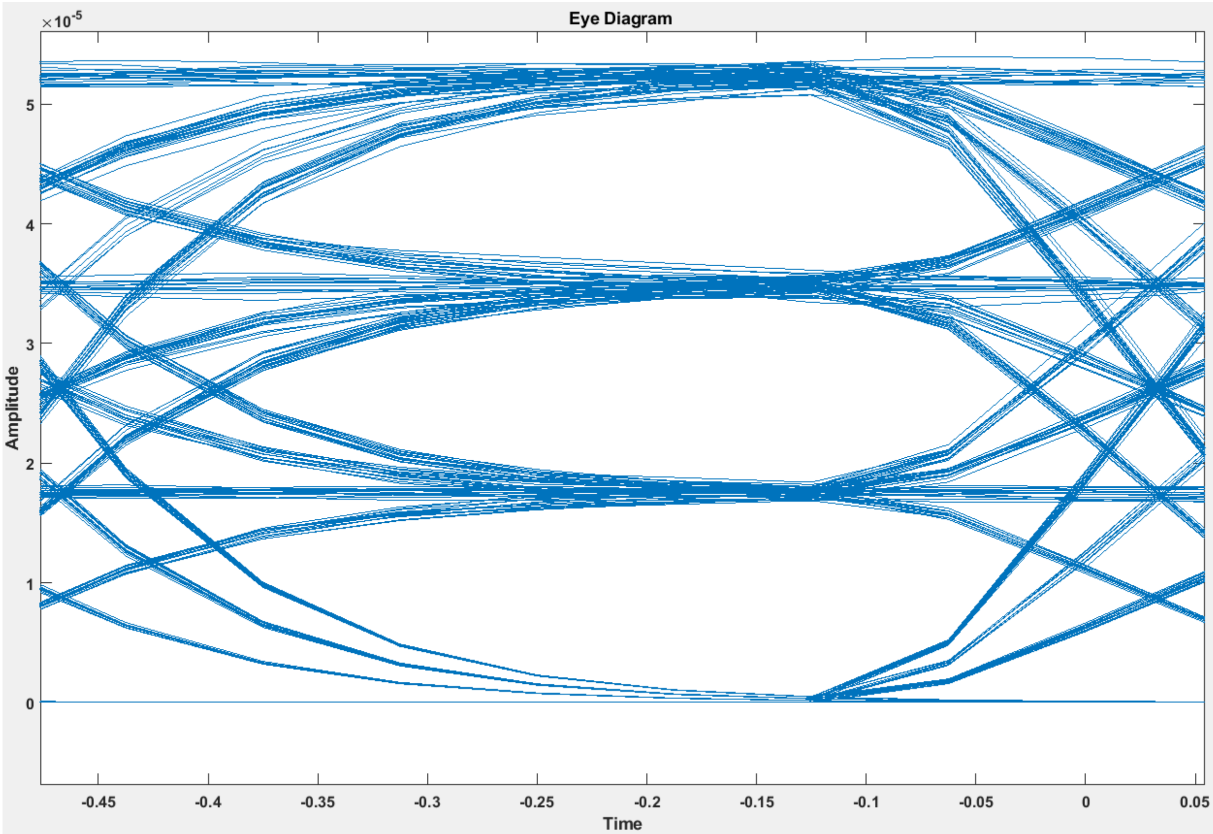

Fig. 3 Eye diagram of a PAM-4 signal

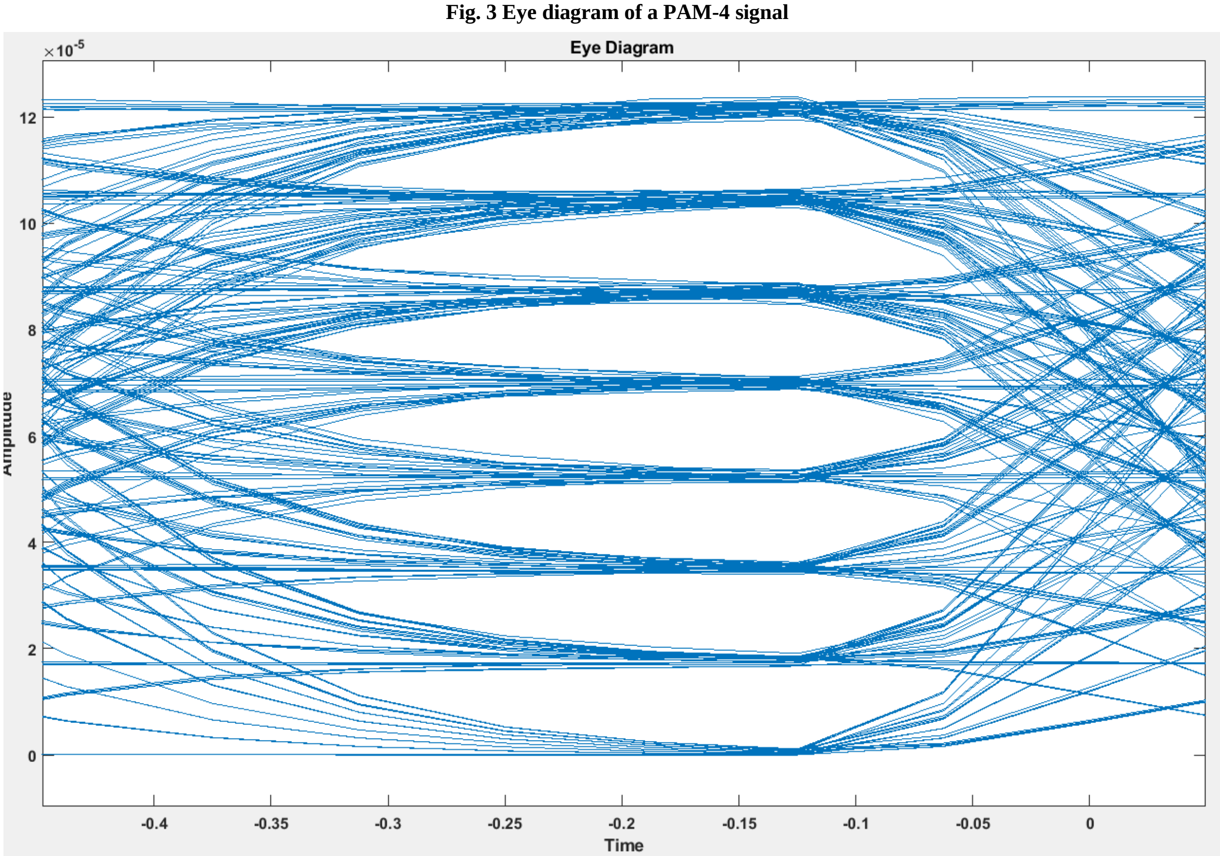

Fig. 4 Eye diagram of a PAM-8 signal

Table 1. Simulation parameters for Optsim®

Parameters	PAM-4	PAM-8
Data Rate	50Gb/s (25 Gbaud/s)	50Gb/s (16.7 Gbaud/s)
Bits transmitted	851952	851952
Samples per bit	8	8
Time span	14176 ns	14176 ns
Central Wavelength	1550 nm	1550 nm

Figures 3 and 4 show eye diagrams of PAM-4 and PAM-8 received signals. These signals and the corresponding eye diagrams, shown in Figures 3 and 4, were generated using Matlab® algorithms that work in co-simulation with Optsim®. For transmission, a PRBS (Pseudo Random Bits Sequence) was generated and coded as a PAM-4 and PAM-8 signal. The parameters used for simulation in Optsim® are detailed in Table 1.

3.2. Network Setup

A WDM-PON works with n-channels with typical separations of 100 GHz, 50 GHz and 20 GHz based in DWDM. [30] A 4-channel WDM-PON with 50 Gb/s one bitrate per channel is employed for this research. For generating the optical PAM-4 and PAM-8 signals, the 1550nm light emitted by a Continuous Wave Laser (CWL) was modulated by a Mach Zehnder Modulator (MZM) using as the driver the electrical signal generated by Matlab®.

Then, the signal is transmitted over a 20 km G562.D standard single-mode fiber, with dispersion compensation based on an FBG filter. The total dispersion compensated in the link was 340 ps/km. The technical specifications of the network are presented in Table 2. An optic combiner was used for the wavelengths' multiplexing, the demultiplexing was implemented, and AWG was used to separate the 4 wavelengths. A Variable Optical Attenuator (VOA) was used to stress the network to simulate the losses in passive elements present in the network, such as power splitters or AWG. In optic reception signals, in different wavelengths were received by a PIN photodetector and then demodulated by the Matlab® module. The scheme of the network is shown in Figure 5. The PIN was configured with 100%, 70%, 60% and 50% of bandwidth necessary to receive a PAM-4 or PAM-8 signal, to analyse the behaviour of WDM-PON under these conditions. First, a comparison between the PAM-4 and PAM-8 modulations was performed, with a photodetector PIN with 100% bandwidth, (i.e. 25 GHz for PAM-4 and 16.7 GHz for PAM-8). Next, it was performed a comparison of the PAM-4 signal reception, with 70% (17.5 GHz), 60% (15 GHz) and 50% (12.5 GHz) of bandwidth in the photoreceiver. Then, the same procedure was carried out for the PAM-8 modulations.

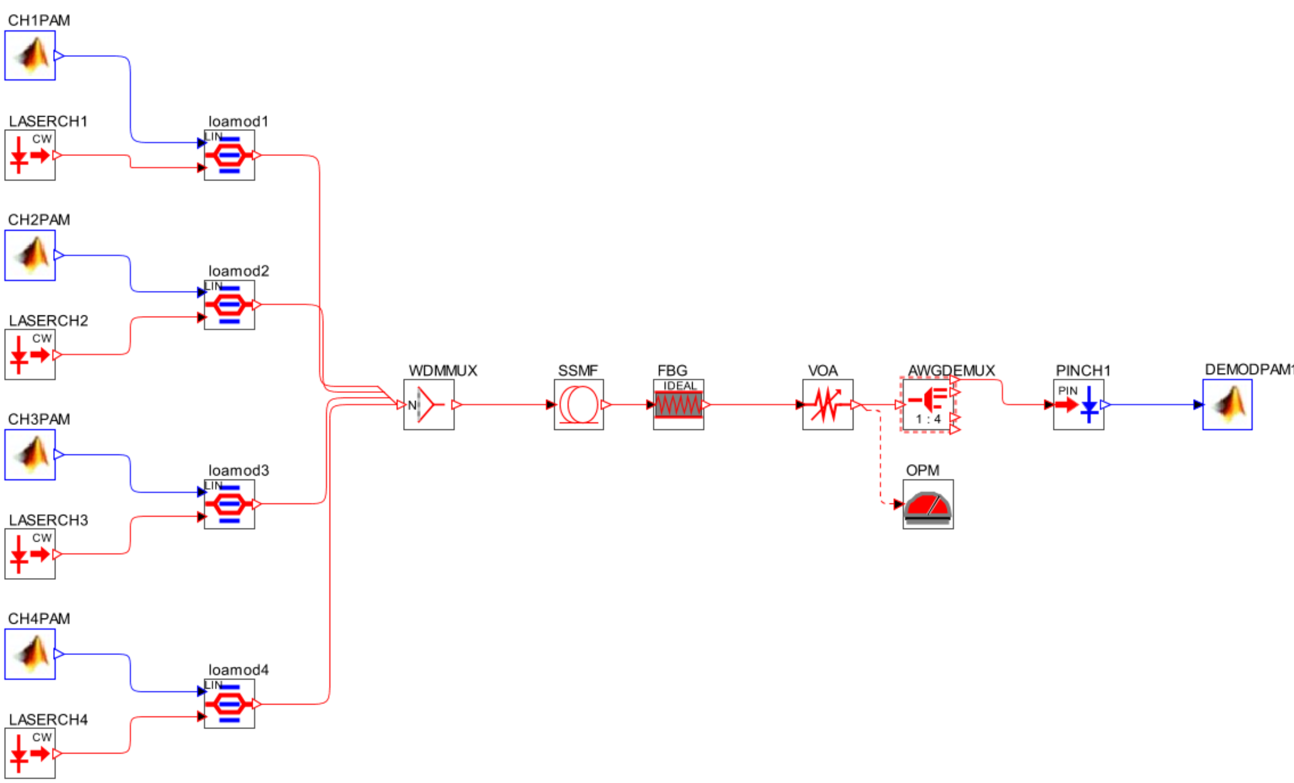

Fig. 5 Screen capture of the scheme of WDM-PON simulated with software Optsim®

4. Results and Discussion

The comparison between PAM-4 vs PAM-8 results are shown in Figure 6, and the data is in Table 3. It can be seen that, for an objective BER of 10^{-3}, there is a penalization of approximately 8 dB if PAM-8 is used instead of PAM-4 modulations. With PAM-4 modulation, the objective BER is achieved with a received signal power of -31 dBm, while for PAM-8, a received signal power of -23 dBm is necessary.

The performance of the PAM-4 signal with different photoreceiver bandwidths is presented in Figure 7, and the data is in Table 4. For PAM-4, there is a penalization of 0.8 dB with bandwidths of 17.5 GHZ, 15 GHz and 12.5 GHz in the PIN photodetector, compared to a PIN photoreceptor with 25 GHz of bandwidth. For the PAM-8 signal, the performance is shown in Figure 8 and Table 5. There is a penalization of 2.6 dB in this signal when transmitting in a PIN photoreceiver's bandwidth of 17.5 GHz, a penalty of 2.8 dB for a bandwidth of 10 GHz, and a penalty of 3.4 dB when using a photoreceiver with 8.35 GHz of bandwidth, all of them compared to a PIN photoreceiver with 16.7 GHz of bandwidth. It demonstrates that an objective BER can be reached by reducing the bandwidth of the photoreceiver with a little penalization of received power. It permits the reduction of the cost of user equipment as ONTs. Authors in [12] use electric filters to limit signal bandwidth but use only PAM-4 modulations.

In this paper, PAM-4 and PAM-8 modulations are used to make this analysis and demonstrate that it is possible to get an objective BER over a WDM-PON with a path loss of 30 dB (PAM-8) and a path loss of 38 dB (PAM-4) and with 200 GB/s of data rate in four channels. The photoreceptor's bandwidth was changed directly in the parameters of the simulation.

Table 2. Technical Specifications of simulated network

Parameters	Characteristic
Optical Fiber	SSMF, G.652.D
Link distance	20 km
Attenuation	0.25 dB/km@1550nm
Chromatic Dispersion	17 ps/nm.km@1550nm
PMD Polarization Mode Dispersion	0.1 ps/km$^{-1/2}$@1550nm
CW laser output power	+7 dBm (C+ class OLT)
Channels Wavelengths (ITU-T G.694.1)	1551.42 nm, 1551.52 nm, 1551.62 nm, 1551.72 nm
Photodetector responsivity	0.8 A/W

Table 3. Bit Error Rate PAM-4 vs PAM-8

Received Signal Power (dBm)	Bit Error Rate (BER) at 100% BW	
	PAM-4	**PAM-8**
-19.05	-	5.88×10^{-6}
-19.54	-	1.41×10^{-5}
-20.58	-	7.88×10^{-5}
-21.58	-	3.07×10^{-4}
-22.56	-	7.00×10^{-4}
-23.56	-	1.59×10^{-3}
-24.56	-	4.07×10^{-3}
-25.56	-	7.20×10^{-3}
-26.55		1.16×10^{-2}
-28.24	9.41×10^{-6}	-
-29.23	7.35×10^{-5}	-
-30.24	6.21×10^{-4}	-
-31.24	1.44×10^{-3}	-
-33.23	6.62×10^{-3}	-
-34.23	1.47×10^{-2}	-

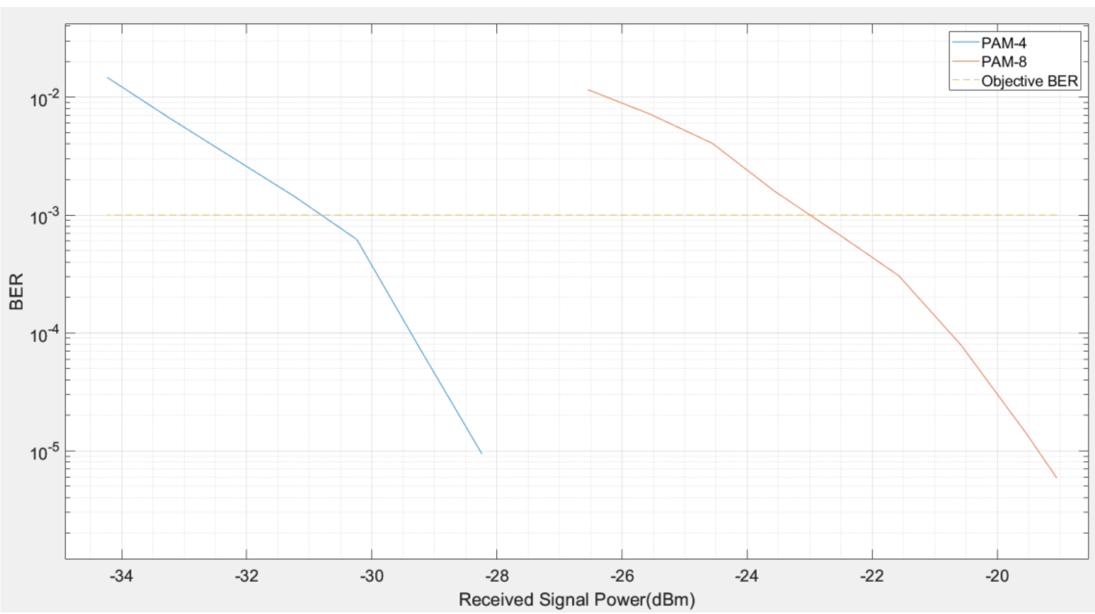

Fig. 6 Performance of PAM-4 modulations vs PAM-8 modulation

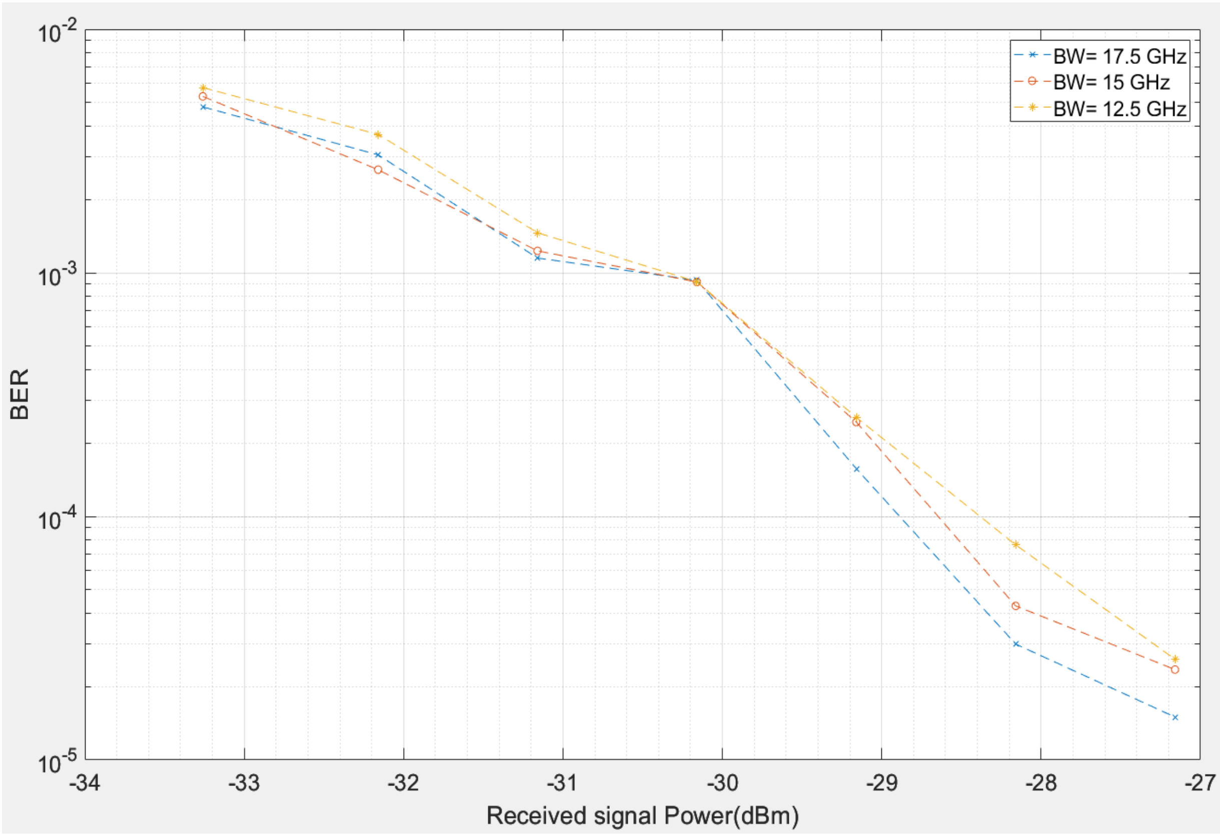

Fig. 7 Performance of PAM-4 modulations with different bandwidths of the PIN photoreceiver

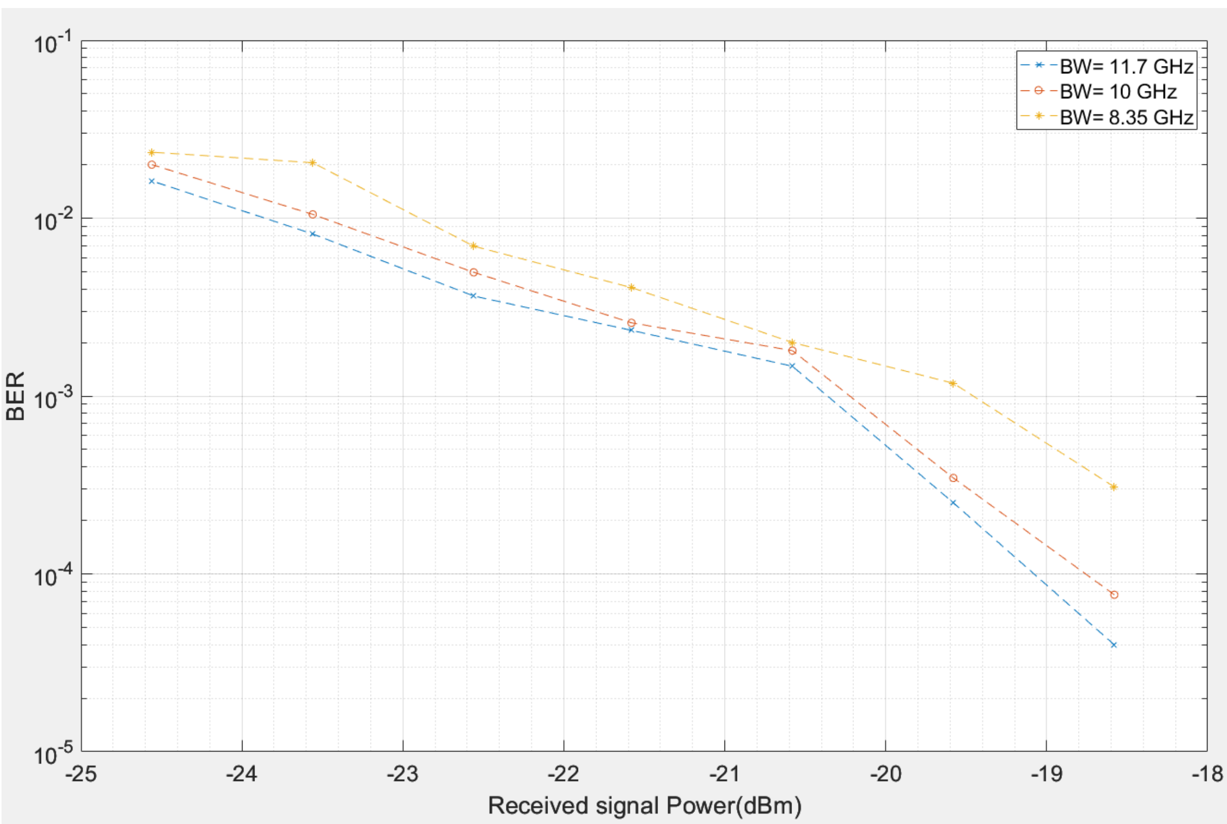

Fig. 8 Performance of PAM-8 modulations with different bandwidths of the PIN photoreceiver

Table 4. Bit Error Rate PAM-4 with different bandwidths

Received Signal Power (dBm)	Bit Error Rate (BER)		
	70% of BW (17.5 GHz)	60% of BW (15 GHz)	50% of BW (12.5 GHz)
-27.16	$1x10^{-5}$	$2.35x10^{-5}$	$2.59x10^{-5}$
-28.16	$2.99x10^{-5}$	$4.29x10^{-5}$	$7.64x10^{-4}$
-29.16	$1.57x10^{-4}$	$2.44x10^{-4}$	$2.55x10^{-4}$
-30.16	$9.31x10^{-4}$	$9.17x10^{-4}$	$9.19x10^{-4}$
-31.16	$1.15x10^{-3}$	$1.23x10^{-3}$	$1.46x10^{-4}$
-32.16	$3.05x10^{-3}$	$2.65x10^{-3}$	$3.7x10^{-3}$
-33.26	$4.80x10^{-3}$	$5.30x10^{-3}$	$5.76x10^{-3}$

Table 5. Bit Error Rate PAM-8 with different bandwidths

Received Signal Power (dBm)	Bit Error Rate (BER)		
	70% of BW (17.5 GHz)	60% of BW (15 GHz)	50% of BW (12.5 GHz)
-18.58	$3.99x10^{-5}$	$7.63x10^{-5}$	$3.08x10^{-4}$
-19.58	$2.51x10^{-4}$	$3.46x10^{-4}$	$1.18x10^{-3}$
-20.58	$1.47x10^{-3}$	$1.8x10^{-3}$	$2x10^{-3}$
-21.58	$2.34x10^{-3}$	$2.58x10^{-3}$	$4.07x10^{-3}$
-22.56	$3.65x10^{-3}$	$4.96x10^{-3}$	$6.96x10^{-3}$
-23.56	$8.15x10^{-3}$	$1.05x10^{-2}$	$2.05x10^{-2}$
-24.56	$1.6x10^{-2}$	$2.0x10^{-2}$	$2.35x10^{-2}$

5. Conclusion

PAM-4 and PAM-8 modulations allow to increase in spectral efficiency and data rate, and their implementation is feasible over WDM PON because of received signal power is in operation range of commercial ONT for an objective BER of 10^{-3}. Of course, these modulations must be combined with FEC and HD-FEC techniques. In the case of HD-FEC, the objective BER is $3.8x10^{-3}$.

The PAM-8 modulation needs a greater received signal power than PAM-4 modulations, in approximately 8 dB. Besides, the bandwidth reduction has a 3.4 dB maximum penalization for an objective BER of 10^{-3} in PAM-8 modulations and 0.8 dB in PAM-4 modulations, which permits cheaper receiver equipment using Direct Detection DD and Intensity Modulation IM. Because of the smaller Extinction Ratio ER or eye aperture, PAM-8 modulation is more affected by noise and distortion than PAM-4 modulation. Hence, it is very necessary to implement electric filters to minimize the noise effect, as seen in the works previously reviewed, especially if PAM-8 or PAM-4 are implemented and using photodetectors with adequate bandwidth is better than limiting it by electric filters.

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References

[1] Pimchanok Montha, Rachata Maneekut, and Pasu Kaewplung, "The Performance Limitation of 10-Gbps-Per-Channel-Based Coarse Wavelength Division Multiplexed Passive Optical Network," *16th International Conference on Advanced Communication Technology,* pp. 1089–1092, 2014. *Crossref,* http://doi.org/10.1109/ICACT.2014.6779127

[2] V.S.R Kumari, and V.Suresh, "WDM-OFDM-PON to Enhancing Band Width in High-Speed Communication Systems," *SSRG International Journal of Electronics and Communication Engineering,* vol. 2, no. 1, pp. 9–13, 2015. *Crossref,* http://doi.org/10.14445/23488549/IJECE-V2I1P104

[3] Tomáš Huszaník, Ján Turán, and Ľuboš Ovseník, "Utilization of 10 Gbps DWDM System with Duobinary Modulation into Passive Optical Network," *Journal of Communications Software and Systems,* vol. 14, no. 4, pp. 367-375, 2018. *Crossref,* http://doi.org/10.24138/jcomss.v14i4.644

[4] ITU-T-G.989, "40-Gigabit-Capable Passive Optical Networks (NG-PON2): Definitions, Abbreviations and Acronyms," 2022.

[5] SmC+ Digital Public Affairs, "FTTH Deployment in the Latin American Region," 2022.

[6] FTTH_Council_Europe, FTTH/B Global Ranking 2022, 2022. [Online]. Available: https://www.ftthcouncil.eu/knowledge-centre/all-publications-and-assets/1463/ftth-b-global-ranking

[7] Stackscale, Internet Traffic is Increasing at IXPs around the World, 2021. [Online]. Available: https://www.stackscale.com/es/blog/crecimiento-trafico-internet-2020-2021/

[8] Puza Roy et al., "Symmetric Wavelength Reused Bidirectional RSOA Based WDM-PON with NRZ Data in Downstream and Upstream," *2021 International Conference on Automation, Control and Mechatronics for Industry 4.0*, pp. 1-5, 2021. *Crossref,* http://doi.org/10.1109/acmi53878.2021.9528112

[9] Isiaka Alimi, Paulo P. Monteiro, and António L. Teixeira, "Telecommunication Systems - Principles and Applications of Wireless-Optical Technologies," *IntechOpen*, 2019. *Crossref,* http://doi.org/10.5772/intechopen.80140

[10] Robbert van der Linden et al., "Optimization of Flexible Non-Uniform Multilevel PAM for Maximizing the Aggregated Capacity in PON Deployments," *Journal of Lightwave Technology,* vol. 36, no. 12, pp. 2328–2336, 2018. *Crossref,* http://doi.org/10.1109/JLT.2018.2809966

[11] Toms Salgals et al., “Investigation of 4-PAM Modulation Format for Use in WDM-PON Optical Access Systems,” *2017 Progress In Electromagnetics Research Symposium - Spring (PIERS),* pp. 2450-2454, 2017. *Crossref,* http://doi.org/10.1109/piers.2017.8262162

[12] Sandis Spolitis, Inna Kurbatska, and Vjaceslavs Bobrovs, “Evaluation of the Impact of MZM Frequency Response on BER Performance of PAM-4 Modulated WDM-PON,” *PhotonIcs & Electromagnetics Research Symposium – Spring,* pp. 2037-2042, 2019. *Crossref,* http://doi.org/10.1109/piers-spring46901.2019.9017581

[13] Toms Salgals et al., “Research of PAM-4 Modulated WDM-PON Architecture for 5G Millimeter-Wave Hybrid Photonics-wireless Interface,” *2019 Photonics & Electromagnetics Research Symposium - Fall (PIERS - Fall),* pp. 728-734, 2019. *Crossref,* http://doi.org/10.1109/PIERS-Fall48861.2019.9021846

[14] Deepak Jain, and Brijesh Iyer, "Design and Analysis of 8-Channel WDM-RoF Using the C and L Band for 5G and Beyond Applications," *International Journal of Engineering Trends and Technology,* vol. 71, no. 1, pp. 41-52, 2023. *Crossref,* https://doi.org/10.14445/22315381/IJETT-V71I1P205

[15] Jiajun Zhou et al., “8 x10 Gb/s Downstream PAM-4 Transmission for Cost-Effective Coherent WDM-PON Application,” *Journal of Lightwave Technology,* vol. 39, no. 9, pp. 2837–2846, 2021. *Crossref,* https://doi.org/10.1109/jlt.2021.3064590

[16] Germán V. Arévalo, Marco Villavicencio, and Gladys Flores, “Experimental Demonstration of a PAM-4 based 20 Gb/s PON using Dispersion Pre-Compensation,” *2019 XVIII Workshop on Information Processing and Control (RPIC),* pp. 283–285, 2019. *Crossref,* https://doi.org/10.1109/RPIC.2019.8882165

[17] NamUk Kim et al., “Advanced Multicast Service Scheduling Mechanism with IGMP Snooping in WDM-PON,” *The 7th International Conference on Advanced Communication Technology, ICACT 2005*, vol. 1, pp. 298–302, 2005. *Crossref,* https://doi.org/10.1109/ICACT.2005.245852

[18] Vivek Kachhatiya, and Shanthi Prince, “Wavelength Division Multiplexing-Dense Wavelength Division Multiplexed Passive Optical Network (WDM-DWDM-PON) for Long Reach Terrain Connectivity,” *2016 International Conference on Communication and Signal Processing (ICCSP),* pp. 104–108, 2016. *Crossref,* https://doi.org/10.1109/ICCSP.2016.7754518

[19] Acosta O. María et al., “Experimental Evaluation of a NG-PON2 Network,” *2018 IEEE Third Ecuador Technical Chapters Meeting (ETCM),* pp. 1-4, 2018. *Crossref,* https://doi.org/10.1109/ETCM.2018.8580339

[20] R. Bonk et al., “Beneficial OLT Transmitter and Receiver Concepts for NG-PON2 Using Semiconductor Optical Amplifiers [Invited],” *Journal of Optical Communications and Networking,* vol. 7, no. 3, pp. A467–A473, 2015. *Crossref,* https://doi.org/10.1364/JOCN.7.00A467

[21] C. W. Chow et al., “Enabling Technologies and Signal Processing for NG-PON2 and Future WDM-PON,” *2013 9th International Conference on Information, Communications & Signal Processing,* pp. 1-2, 2013. *Crossref,* https://doi.org/10.1109/ICICS.2013.6782794

[22] Rongqing Hui, *Introduction to Fiber-Optic Communications,* Elsevier Inc., 2020.

[23] Liuyan Chen et al., “A Low-Latency Real-Time PAM-4 Receiver Enabled By Deep-Parallel Technique,” *Optics Communications,* vol. 508, p. 127836, 2022. *Crossref,* https://doi.org/10.1016/j.optcom.2021.127836

[24] Cheng-Yi Huang et al., “Comparison of High-Speed PAM4 and QAM-OFDM Data Transmission Using Single-Mode VCSEL in OM5 and OM4 MMF Links,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 26, no. 4, pp. 1–10, 2020. *Crossref,* https://doi.org/10.1109/JSTQE.2019.2903754

[25] Alberto Paradisi et al., *Optical Communications: Advanced Systems and Devices for Next Generation Networks - Telecommunications and Information Technology*, Cham: Springer International Publishing, 2019.

[26] Y. Shao, F. Chen, A. Wang, Y. Luo, and L. Chen, “Application Research on 4-Pulsed Amplitude Modulation in 10 Gb/S Passive Optical Access Systems,” *Optik,* vol. 146, pp. 63–68, 2017. *Crossref,* https://doi.org/10.1016/j.ijleo.2017.08.072

[27] Aanchal Sharma et al., “Investigation of WDM-MDM PON Employing Different Modulation Formats,” *Optik,* vol. 257, p. 168855, 2022. *Crossref,* https://doi.org/10.1016/j.ijleo.2022.168855

[28] Nan Feng, and Xiang Sun, “Nyquist Four-Level Pulse Amplitude Modulation Scheme (PAM-4) Based on Hierarchical Modulation in IM/DD-TDM PON with Hybrid Equalization,” *Optics Communications,* vol. 457, p. 124609, 2020. *Crossref,* https://doi.org/10.1016/j.optcom.2019.124609

[29] Ute Troppenz et al., “1.3 μmElectroabsorption Modulated Lasers for PAM4/PAM8 Single Channel 100 Gb/s,” *26th International Conference on Indium Phosphide and Related Materials (IPRM),* pp. 1-2, 2014. *Crossref,* https://doi.org/10.1109/ICIPRM.2014.6880562

[30] ITU-T-G.694.1, “Spectral Grids for WDM Applications: DWDM Frequency Grid,” 2020.

[31] Pablo Torres-Ferrera et al., “100 Gbps/λ PON Downstream O and C Band Alternatives Using Direct-Detection and Linear-Impairment Equalization [Invited],” *Journal of Optical Communications and Networking*, vol. 13, no. 2, pp. A111-A123, 2021. *Crossref,* https://doi.org/10.1364/jocn.402437