

Controlling XPM and SPM Nonlinear Effects Impacts in GPON/XGSPON Coexistence System using RZ and NRZ Modulation Formats

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Abstract - This paper discusses a system that combines GPON (2.5 Gbps/1.25 Gbps) and XGSPON (10 Gbps/10 Gbps) in a Passive Optical Network (PON) architecture. The system uses bidirectional optical fiber for data transmission in both directions. Performance assessment involved two modulation formats, Return to Zero (RZ) and Non-Return to Zero (NRZ), with a focus on eye diagram and quality factor (Q). Nonlinear effects like Cross Phase Modulation (XPM) and Self Phase Modulation (SPM) were considered. The study covered network ranges from 10 km to 100 km, using a fixed laser power of 0 dBm. Results favored the RZ format over NRZ, demonstrating reliable transmission up to 100 km distances.

Keywords – NRZ, Q factor, RZ, Simulation, SPM, XPM.

I. INTRODUCTION

In the past five years, there has been substantial growth in optical transmission and networking technologies due to the rise of 5G, IoT, and smart cities. This has resulted in a higher need for bandwidth and data rates of up to 1 Tbps. These advancements have also spurred a more efficient industry, with support from numerous innovative solutions [1]. PON technology has been pivotal for fiber optic network evolution, offering high-bandwidth connectivity through shared optical infrastructure. This has made fiber optic networks crucial for delivering fast and dependable internet services. Two current PON standards are GPON (Gigabit PON) and XGSPON (Extended Gigabit Symmetrical PON). GPON, established, provides speeds up to 2.5 Gbps down-stream and 1.25 Gbps upstream. Meanwhile, newer XGSPON offers symmetrical speeds of 10 Gbps in both directions [2].

This paper aims to select the suitable modulation format between RZ and NRZ for a GPON and XGSPON coexistence system. This

decision involves balancing the effective handling of high-speed Self-Phase Modulation (SPM) and minimizing Cross-Phase Modulation (XPM) when signals overlap [3]. System designers must consider network specifics, transmission distances, data rates, and nonlinear effects for optimal performance. Comprehensive simulations are vital for accurately assessing system performance.

The authors [PAGARE, Rajendraprasad A., KUMAR, Santosh, MISHRA, Abhilasha] introduced an architecture to assess a next-gen passive optical network (NG-PON2) using N1-class hybrid multiplexing (TWDM). This approach accommodates symmetric and worst-case coexistence setups. Their study examined linear and non-linear issues like chromatic dispersion, self-phase modulation, cross-phase modulation, and four-wave mixing in Fiber To The X (FTTX) access networks. The architecture employed On-Off Keying modulation and a hybrid Optical Distribution Network. Results indicated a bit error rate (BER) of $10E-7$ and a quality factor (Q) of 5 for a 10 Gbps channel over a 50 km range [4].

On the other hand, our architecture achieves this by using two modulation formats: RZ and NRZ. The RZ format supports signal synchronization and recovery and offers resistance against noise and nonlinear effects such as XPM and SPM. Conversely, the NRZ format requires less bandwidth due to the absence of zero crossings between bits, making implementation simpler. Managing non-linear effects depends on factors such as the modulation format, range, laser power, and others [5]. We focus on evaluating the performance of the coexistence system, considering nonlinear effects, namely XPM and SPM, with the RZ and NRZ modulation formats over distances ranging from 10 km to 100 km. This work is outlined as follows: Section 1 introduces an overview of the two PON systems (GPON and XGSPON). Sections 2 and 3 delve into defining and analyzing the coexistence and nonlinear effects management using RZ and NRZ modulation formats and chromatic dispersion (CD). Section 4 conducts a simulated and evaluated performance comparison between the GPON and XGSPON systems in both downstream and upstream directions. Lastly, Section 5 provides a summary of the presented studies and contributions. Is the first paragraph of a written research paper, and it should explain the nature of the previous work.

II. COEXISTENCE SYSTEM

The suggested coexistence architecture involves a GPON and XGSPON system. GPON, following the ITU-T G.984.x standard, is a PON network approach. It employs a downstream wavelength of 1490 nm and an upstream wavelength of 1310 nm for data transfer. GPON's downstream speed is 2.5 Gbps, while the upstream speed is 1.25 Gbps. The GPON system employs encapsulation techniques to manage ATM packets, accommodating diverse protocols (Ethernet, IP, TCP, UDP, T1/E1, video, VoIP). AES encryption is utilized in GPON to secure downstream data transmission from the OLT to the ONU [6]. XGSPON, developed in 2016 following the ITU-T G.9807.1 standard, is akin to XGPON. It offers symmetrical bandwidth enhancements compared to GPON. Wide

deployment began in 2018, delivering symmetrical 10 Gbps downstream and upstream rates. For data transmission, it uses 1577 nm (within 1575 nm-1580 nm) wavelength downstream and 1270 nm (within 1260 nm-1280 nm) wavelength up-stream. It employs TDM for downstream transmission from OLT to ONU and TDMA for upstream transmission from ONU to OLT. It accommodates up to 256 ONU across a 100 km ODN distance.

Figure 1 demonstrates how the GPON and XGSPON coexistence system functions using Ethernet and/or TDM [7].

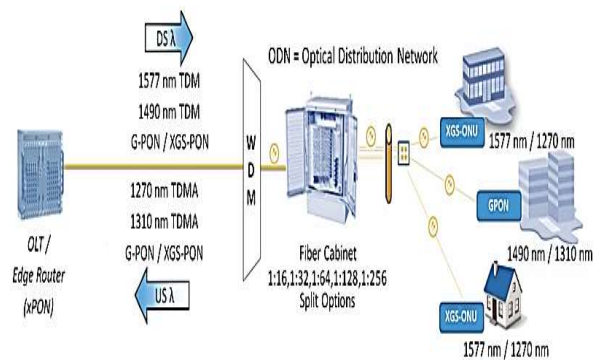


Fig. 1. Principle of coexistence system.

III. NONLINEAR EFFECTS

Nonlinear effects in high-capacity optical transmission systems can cause signal distortions, channel interference, and reduced performance. Designers use nonlinear management techniques like specific modulation formats, dispersion compensators, and optical power management to mitigate XPM and SPM effects. These approaches ensure reliable and efficient optical transmission in fiber optic networks [8].

A) Cross Phase Modulation (XPM)

Cross phase modulation is when a strong optical wave changes the refractive index of an optical fiber, affecting the phase of another parallel optical wave in the same fiber. This can cause interference and distortions in the optical signal [9].

The phase shift induced by cross phase modulation is given by the following formula:

$$\Delta\phi = 2\gamma P_2 L_2 \quad (1)$$

Where :

- γ : is the fiber's nonlinearity coefficient.
- P_2 : is the optical power of the second incident wave (modulating wave).
- L_2 : is the length of the fiber traveled by the second wave.

B) Self Phase Modulation (SPM)

Self phase modulation occurs due to the power-dependent refractive index in a nonlinear medium. When a strong field moves through an optical fiber of length L , it experiences a self-induced nonlinear phase shift due to local index changes.

The nonlinear phase shift, proportional to the wave's intensity, is determined by the equation [10]:

$$\Delta\varphi = \gamma P_0 L_0 \quad (2)$$

Where:

- γ : is the fiber's nonlinearity coefficient.
- P_0 : is the incident optical power.
- L_0 : is the length of the optical fiber.

C) Chromatic Dispersion (CD)

Chromatic dispersion in fiber optics is the phenomenon of different light wavelengths traveling at different speeds through the optical fiber, leading to signal spreading over distance. This dispersion results in signal distortion and imposes limitations on the transmission capacity of optical communication systems.

IV. SIMULATIONS AND RESULTS

A) Measurement of Optical Network Performance Parameters

It indicates the quality of the signal with respect to distance and noise. The Q factor covers noises, scatter, and nonlinearities that degrade signal quality and thus increase the BER. As a result, the higher Q factor, the better signal quality [11].

The eye diagram shows the superposition of all overlapping bits in the signal. The opening of the eye indicates the difference of the bits 1 relative to the bits 0. If the eye is fully open, the difference is great, because the signal-to-noise ratio is better.

The parameters readable by the eye are as follows: Jitter (fluctuation of the delay), inter-symbol interference (ISI), and duration of the rising or falling edge [11].

B) Coexistence System Architecture

The simulated coexistence system combines GPON and XGSPON technologies within a shared PON infrastructure. Through simulation, we can evaluate how these technologies coexist, effectively share network resources, and manage the impact of two nonlinear effects XPM and SPM.

In our study, we'll use two methods to manage nonlinear effects. The first simulates the system without compensating for CD, considering nonlinear effects and comparing modulation formats. When signal quality degrades at specific distances, we'll use the second method with CD compensation, choosing the right modulation format while maintaining optimal performance.

Our system architecture comprises three stages: transmitter (OLT), transmission support (Bidirectional Optical Fiber), and receiver (ONU). The coexistence system is a PON network with downstream and upstream transmission directions. We will assess performance by studying the impact of link length (reach), modulation format type and nonlinear effects.

The simulation configuration includes both downstream and upstream channels. The OLT transmits all wavelengths using a single bidirectional optical fiber, covering distances from 10 km to 100 km. Emission power remains at a constant 0 dBm, and two modulation formats (RZ and NRZ) are used.

The figure 2 below, illustrates the coexistence system architecture with two users (1 user for GPON and 1 user for XGSPON).

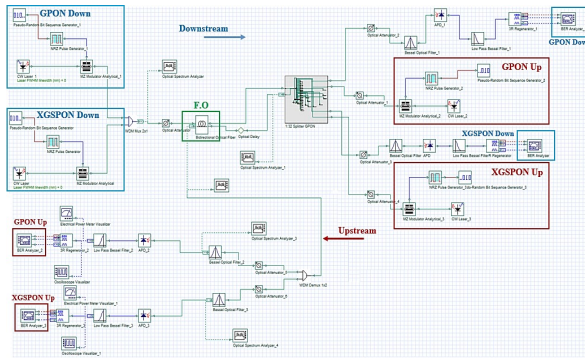


Fig. 2. Overall diagram of the GPON and XGSPON coexistence system.

C) Coexistence System Parameters

Generated data from a Pseudo-Random Binary Sequences (PRBS) generator is optically modulated using an external modulator (Mach-Zehnder Modulator: MZM). This creates RZ or NRZ signals at 2.5 Gbps downstream and 1.25 Gbps upstream per channel for the GPON system. In contrast, the XGSPON system employs a symmetrical 10 Gbps per channel rate for both downstream and upstream. The modulated data is combined through a wavelength division multiplexing (WDM) multiplexer over a bidirectional optical fiber, serving as the transmission support.

The table below, displays the parameters used in our system.

TABLE 1. COEXISTENCE SYSTEM PARAMETERS.

Parameters	Values
Bit Rate	GPON: 2.5 Gbps/canal (Down), 1.25 Gbps/canal (Up). XGSPON: 10 Gbps/canal (Down and Up).
Laser Power	0 dBm.
Pulse Generators	RZ, NRZ.
Fiber SMF Length	10 km, 20 km, 30 km, 40 km, 50 km, 60 km, 70 km, 80 km, 90 km and 100 km.
User Number	2 (1 GPON and 1 XGSPON).
Wavelength (Down)	1490 nm (GPON), 1577 nm (XGSPON).
Wavelength (Up)	1270 nm (GPON), 1310 nm (XGSPON).
EDFA Gain	28 dB.
Chromatic Dispersion (CD)	17 ps/nm/km.
PMD Dispersion	0.5 ps/km ^{1/2} .
Attenuation	0.2 dB/km.
Nonlinear Effects	XPM and SPM

D) Impact of Modulation Format

Our study examines the influence of two modulation formats, NRZ and RZ, on the coexistence system with a 0 dBm laser power. As indicated by figures 3, 4, 5, and 6, both RZ and NRZ formats display enhanced effectiveness within the coexistence system, considering CD, XPM and SPM. Additionally, these formats showcase consistent performance across distances spanning from 10 km to 30 km.

Table 2 illustrates the impact of chromatic dispersion without compensation, XPM and SPM on the overall system performance.

TABLE 2. IMPACT OF CD AND NONLINEAR EFFECTS ON THE Q FACTOR (PRESENCE: CD+NE).

L (km)	10	20	30
Q GPON _{Down}	19.9	12.19	7.42
Q XGSPON _{Down}	11.59	6.71	4.24
Q GPON _{Up}	19.25	11.97	7.29
Q XGSPON _{Up}	10.92	6.72	4.19

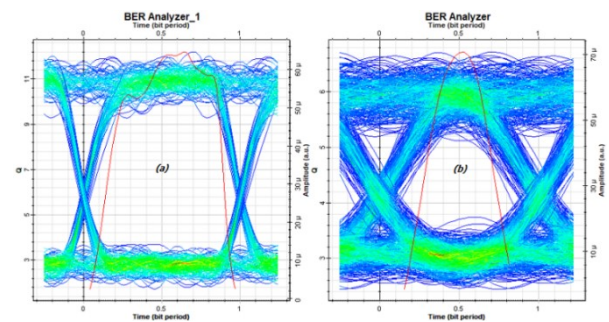


Fig. 3. Eye diagram for GPON_{Down}-NRZ-with-CD-NE with P = 0 dBm and L = 20 km (a), Eye diagram for XGSPON_{Down}-NRZ-with-CD-NE with P = 0 dBm and L = 20 km (b).

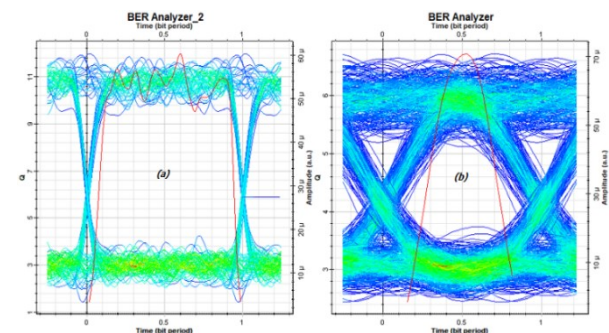


Fig. 4. Eye diagram for GPON_{Up}-NRZ-with-CD-NE with P = 0 dBm and L = 20 km (a), Eye diagram for XGSPON_{Up}-NRZ-with-CD-NE with P = 0 dBm and L = 20 km (b).

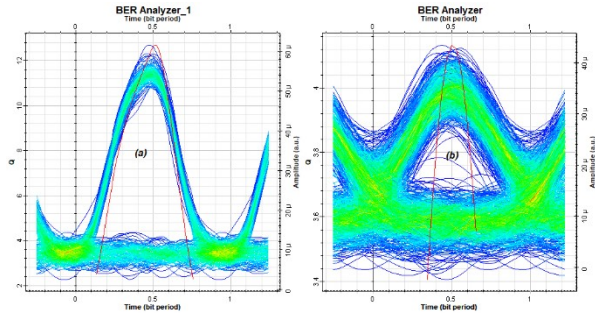


Fig. 5. Eye diagram for GPON_{Down-RZ}-with-CD-NE with $P = 0$ dBm and $L = 20$ km (a), Eye diagram for XGSPON_{Down-RZ}-with-CD-NE with $P = 0$ dBm and $L = 20$ km (b).

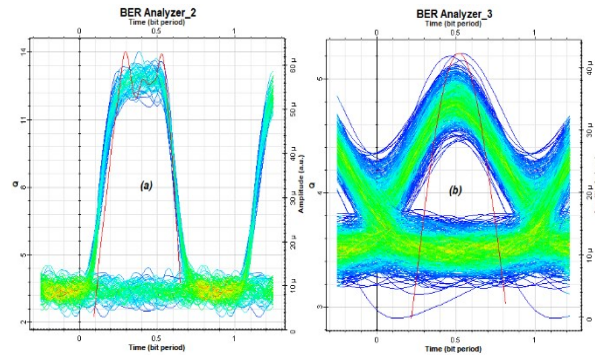


Fig. 6. Eye diagram for GPON_{Up-RZ}-with-CD-NE with $P = 0$ dBm and $L = 20$ km (a), Eye diagram for XGSPON_{Up-RZ}-with-CD-NE with $P = 0$ dBm and $L = 20$ km (b).

At distances beyond 30 km, a decline in system performance becomes noticeable, both upstream and downstream (refer to Figure 7 and 8). This finding underscores the crucial role of selecting the right modulation format for our system. Analyzing Figures 7, 8, and 9 reveals an improvement in transmission quality when compensating for chromatic dispersion through the utilization of a Dispersion Compensating Fiber (DCF), coupled with the choice of the RZ format over NRZ.

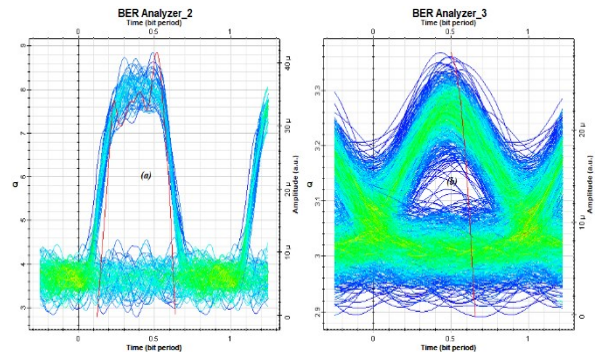


Fig. 7. Eye diagram for GPON_{Down-RZ}-with-CD-NE with $P = 0$ dBm and $L = 100$ km (a), Eye diagram for XGSPON_{Down-RZ}-with-CD-NE with $P = 0$ dBm and $L = 100$ km (b).

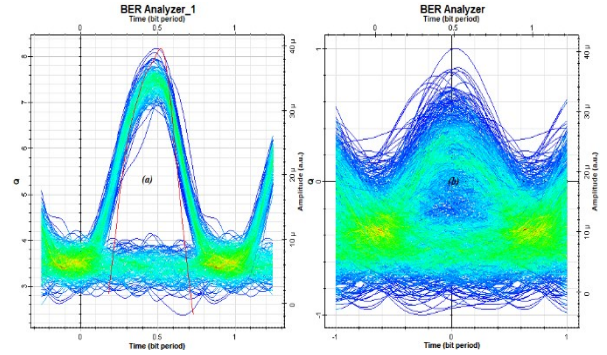


Fig. 8. Eye diagram for GPON_{Up-RZ}-with-CD-NE with $P = 0$ dBm and $L = 100$ km (a), Eye diagram for XGSPON_{Up-RZ}-with-CD-NE with $P = 0$ dBm and $L = 100$ km (b).

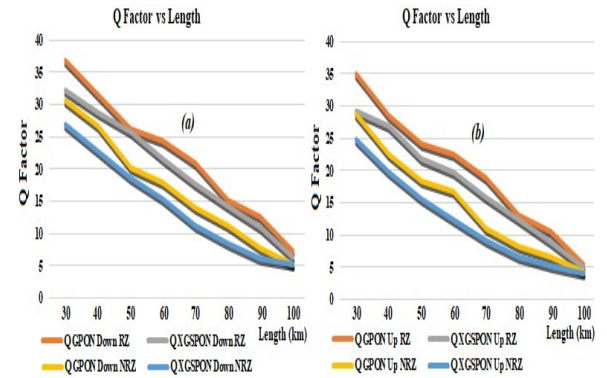


Fig. 9. Impact of modulation format (down) (a), Impact of modulation format (up) (b).

V. CONCLUSION

Employing an Optisystem simulator, we conducted simulations involving both technologies in a unified system, considering factors like length, modulation formats (RZ and NRZ), nonlinear effects (XPM, SPM), and chromatic dispersion [12]. This work aims to contribute to improving the performance of the PON network through the integration of a new coexistence system. The two optimization methods without amplifier, CD and nonlinear effects allowed us to choose a coexistence system with better performance with a maximum range of 30 km and a minimum power of -12 dBm, which allowed us to efficiently optimize the energy consumption of the overall system. In the second part with amplifier, CD compensation and nonlinear effects, XPM has no effect, which leads to the conclusion that the ideal modulation format for this scenario is RZ because the duration of the pulse for this modulation format is shorter, which helps mitigate SPM effects by distributing the

optical power over shorter pulses, thereby reducing fiber induced nonlinearity [13]. However, the longer pulse duration of the NRZ format reduces XPM effects due to reduced signal overlap and increases SPM effects compared to the RZ format, because longer pulses concentrate optical power and increase fiber induced nonlinearity [13]. Through both optimization methods, we've chosen a coexistence system that exhibits enhanced performance, with a BER below $10E-9$, a Q factor surpassing 6, and an extended range of 100 km.

VI. ACKNOWLEDGMENT

This work was supported by the Laboratory of Electromagnetism, Photonics, and Optronics L.E.P.O, at Djillali Liabes University of Sidi Bel Abbes, Algeria.

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