Performance of Raman Fiber Amplifiers (RFA) in a Next Generation Optical Network XGS-PON

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***Abstract*— This article focuses on analyzing the effects that occur in the downlink of XGS-PON architecture at 10Gbps speed, implementing two different Raman fiber amplifiers (RFA), in order to determine the appropriate amplifier configuration, considering the performance of the optical system can be significantly degraded by the power penalties in presence of non-linear phenomena, such as self-phase modulation (SPM). This type of amplifier is considered the future of optical communications, due to its high power handling to achieve great distances required by the new generation architectures proposed by FSAN.**

Keywords—optical amplifiers, Raman amplifiers, FSAN optical architectures, XGS-PON, power penalties.

I. INTRODUCTION

For the last years, due to the development and appearance of new services and applications, some technologies such as optical fiber, focus on proposing solutions that meet the demands for speed and bandwidth that are continuously increasing, however, these solutions based in modern architectures, have drawbacks to respond to transmission degradations in communication systems. Therefore, it is necessary to implement new stages of optical amplifiers that are more efficient with respect to power penalties and linear and non-linear phenomena, improving the quality of the optical link.

This article focuses its study on observing the effects that occur at the simulation level, in an XGS-PON network architecture, by implementing Raman fiber amplifiers, by manipulating their variables and their configuration modes, in order to determine if the presence of power penalties manages to significantly degrade the performance of the optical system.

II. NEW GENERATION OPTICAL SYSTEMS

A. *FSAN Architectures (Full Service Access Network)*

The Full Service Access Network (FSAN), is a group of tasks made up of operators, laboratories, and telecommunications providers, with the aim of achieving broadband fiber optic access networks based on the evolution of the Passive Optical Network (PON), among which is the technology of Gigabit-capable Passive Optical Network (GPON) [1].

Regarding network architectures, an evolution in two stages is proposed. The first stage is known as Next-Generation Passive Optical Network 1 (NG-PON1) [2], which represents systems that offer low costs, wide coverage and full service, in addition to greater capacity compared to GPON and the possibility of coexisting with this technology, varying only the Optical Line Termination (OLT) and the Optical Network Unit (ONU), in order to take advantage of existing implementations regarding the Optical Distribution Network (ODN). Due to downstream and upstream bandwidth demands, FSAN defines two types of NG-PON1: 10-Gigabit-capable Passive Optical Network (XG-PON) [3], and 10-Gigabit-capable Symmetric Passive Optical Network (XGS-PON) [4].

XG-PON technology is defined as an asymmetric system, with rates of 10 Gbps downstream and 2.5 Gbps upstream [3]. With XG-PON, a fiber optic link of at least 20 km is possible, its architecture can be Point To Point (PtP) or Point To Multipoint (PtMP), and can be considered scenarios of Fiber Through The x (FTTx) such as: Fiber To The Home (FTTH), Fiber To The Cell (FTTCell), Fiber To The Building (FTTB), among others [5].

ITU-T G.9807.1 recommendation describes XGS-PON as a symmetric system with 10 Gigabit capacity. This architecture, like XG-PON, can be point-to-point or point-to-multipoint and supports different FTTx access scenarios, with the difference that it allows a nominal data rate of 10 Gbps both downstream and upstream and a link of fiber of at least 40 km [4]. It should be taken into account that XGS-PON must be capable of supporting multiple existing and emerging services in multiple market segments, moreover, having a symmetric bit rate, new opportunities arise for operators to quickly monetize their networks through business services, residential and mobile [6].

In Fig. 1, an XGS-PON architecture can be observed, where an OLT representing a service provider is implemented, which is connected through an ODN (made up of devices such as optical fiber, compensators, amplifiers and an optical splitter that in point -to-point implementations is not essential) until reaching the end users represented by ONUs [7]. In order to achieve longer distances, the XGS-PON architecture allows the implementation of Reach Extenders (RE) [8]. Being the amplifier, the most used at the moment, which can be of several types and will be treated in detail later.

In the second stage, the Next-Generation Passive Optical Network 2 (NG-PON2) is considered, which proposes completely new generation network architectures at 40 Gbps. Regarding the range, these systems support at least 60 km and

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the most important difference from the previous standards is that NG-PON2 is the first PON system that operates with multiple wavelengths per direction of communication, using the Wavelength Division Multiplexing (WDM), thus increasing the total capacity of the system compared to previous technologies [9]. It should be noted that each new generation optical network transmission standard has the same GPON architecture and as they evolve, these PON technologies aim to coexist with previous standards.

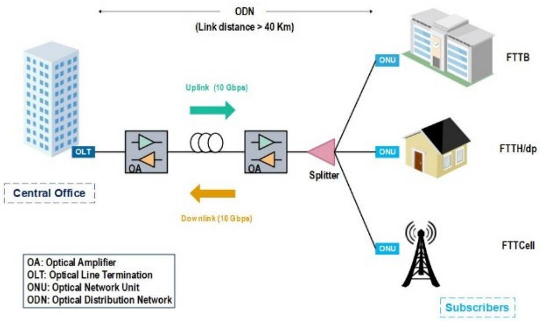

Fig. 1. XGS-PON network architecture.

B. *Optical Amplification Mechanisms*

To satisfy the requirements of optical links over long distances, some type of amplification is required, where an Optical Amplifier (OA) represents a component, module or subsystem that increases the signal power to compensate for the losses presented by other optical elements, that is, it simultaneously amplify all wavelengths, without requiring Optical - Electric - Optical (OEO) conversion, achieving propagations at greater distances [10].

The behavior of optical amplification is determined with respect to factors that produce effects on the system, these variables can be internal to the amplifier with certain degrees of freedom such as: frequency, wavelength, power and gain, among others, and external to the amplifier, which are the network load level (throughput), the proximity of the channels and the amplification mode, which can occur from three points of view i) Booster or power Amplifier (BA) ii) Pre -Amplifier (PA) and iii) Line Amplifier (LA). The booster technique is based on locating the amplifier after the transmitter block followed by the optical source to raise its power level and in the preamplification, it is placed just before the optical receiver; the line amplifier is based on locating the amplifiers at the intermediate points of the fiber link in order to compensate for the losses due to the attenuation that the signals present when they propagate through the medium [11].

In the case of optical amplification, the systems that are on the market are generally Erbium Doped Fiber Amplifier (EDFA), which are devices that allow amplifying signals in the transmission band C, of the spectral region that goes from 1530 nm to 1565 nm; in the same way, the Raman Fiber Amplifier (RFA) is presented, which bases its operation on a non-linear interaction between the optical signal and the high-power pumping signal, these last two amplifiers, according to the ITU-T G.661 recommendation are defined as Optical Fiber Amplifiers (OFA), which have high transparency in the bit rate and wavelength of the digital signal, potentially allowing the design of a flexible network whose capacity may vary depending on the demand for customers [12]. Moreover, the Semiconductor Optical Amplifier (SOA), regenerates signals at different wavelengths simultaneously, and its response time is less compared to OFA [11].

This article focuses on RFAs, which are based on the non-linear physical phenomenon of Stimulated Raman Scattering (SRS), also referred to as the Raman effect, which occurs when high intensity pumping passes through the amplifying medium, this medium is allusive to the fiber optic with a non-linear behavior, so that part of the power from one optical field is transmitted to another field. In other words, it is characterized by obtaining energy from a pumping source to amplify a weak optical signal. The ITU-T G.665 recommendation establishes two types of RFAs that are classified according to their design: Discrete or Lumped Raman Amplifier (LRA) and Distributed Raman Amplification (DRA). In the case of distributed, the same fiber that is used for signal transmission is also used for amplification, while the discrete ones achieve the amplification effect thanks to a shorter fragment of fiber and all the physical elements that are at the inside the device [13].

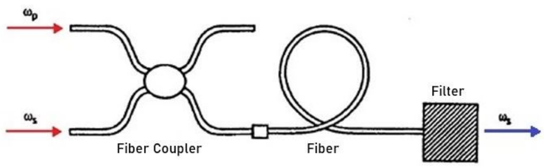

Fig. 2. Raman Fiber Amplifier Scheme [14].

Fig. 2 shows the pumping source (wp) that is injected into the fiber, said pumping light can be in the same direction (co-propagation) or in the opposite direction (counter-propagation) of the input signal (ws), it must be fulfilled that $ws < wp$. The co-propagated pumping configuration allows transmission of Dense Wavelength Division Multiplexing (DWDM) channels over long distances, achieving high gains, however, it is critical in terms of transferring noise from pumping sources to DWDM signals, therefore, a careful design must be used to avoid transmission penalties. In the counter-propagated configuration the pumping wavelengths are injected from the end of the fiber span, propagating in the opposite direction to the DWDM signals, thereby ensuring that most of the amplification occurs at the end of the path of the fiber, where the signal levels are weak, avoiding in the same way the non-linear effects, since when amplifying the lower power signals near the end of the span, it causes the power levels at the output of each amplification section do not exceed the threshold of non-linear effects, this propagation scheme provides a high level of output gain, with the consequence of a considerable presence of noise in the amplified signal [15], [16].

It should also be emphasized that, when optical amplification is used indiscriminately, problems such as power penalties occur that refer to the maximum permissible power level before exciting linear and non-linear phenomena, where the change in the propagation regime of the medium harms the performance and quality of the optical signal; the effect of increasing said transmission power in order to achieve long distances, will generate anomalies of more than second order, expressed in the Nonlinear Schrödinger Equation (NLSE), the most important being: Four Wave Mixing (FWM), Cross Phase Modulation (XPM) and Self Phase Modulation (SPM). These phenomena cause the optical signal to degrade, restricting system performance [17].

Regarding previous researches, in [18] a comparative study of different amplifiers of the EDFA, RFA and SOA type is carried out based on some configuration parameters such as

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the operating wavelength, input power and pumping system. On the other hand, in [19] the performance of these three amplifiers is compared, in relation to the transmission distance, with and without the presence of non-linearities at an access speed of 10 Gbps and 16, 32 and 64 optical channels. For its part, in [20], a DRA is designed developing a model that considers effects associated with polarization on signal propagation at different distances, while [21] compares the performance of a DRA and an LRA in a 16-channel system and counter-pumping, by changing the position of the amplifier and the input power to find the right pumping power.

III. SIMULATION MODEL AND RESULTS

TABLE I. GENERAL CHARACTERISTICS OF THE SIMULATION SCENARIO

PARAMETERS	***VALUES***
Band	C (1530 -1560 nm)
Fiber type	Corning SSMF-28e
Attenuation for 1550 nm	0.2 dB/km
Dispersion coefficient for 1550 nm	16 ps/nm.km
Modulation format	RZ-OOK
CD compensation	Ideal
Receiver sensitivity	-24 dBm

For the development of the research, a network architecture based on the XGS-PON standard is defined, which guarantees a 10 Gbps access capacity for a point-to-point type downlink and an FTTH application, in which the 193.4 THz channel is implemented at 10 Gbps and it should be kept in mind that there is not more than one user accessing the network resources. The simulation scenario in which the performance of the network is evaluated has the characteristics of Table I, and following the characteristics of an FTTH application, it is sought to reach a typical distance of 85 km until the end user is found.

When the system does not use any type of amplification, the quality of the received signal is significantly affected as observed in Table II, since it does not comply with the Optical Parameters Monitoring (OPM) established in the ITU-T G.698.1 [22] - ITU-T G. Sup39 [23] recommendations, that is, BER $\leq 1e^{-12}$, Q factor ≥ 7, and receiver sensitivity ≥ -24 dBm with 10 Gbps access.

TABLE II. INITIAL CONDITIONS OF THE MONITORING PARAMETERS (SYSTEM WITHOUT AMPLIFICATION)

Distance 85 Km and Channel 193.4 THz					
BER	***Q Factor [dB]***	***P_{Tx} [dBm]***	***P_{Rx} [dBm]***	***Jitter [ns]***	***$OSNR_{OUT}$ [dB]***
0.019	6.284	0	-34.81	0.023	48.76

In the section below, an analysis of the effect of amplification in an XGS-PON system is performed, due to changes in the pumping source of discrete (LRA) and distributed (DRA) Raman amplifiers.

However, commercially available RFA amplifiers are found in Table III and their parameters are taken as a reference for the present research. In the case of discrete RFA, Optilab [24] offers a high-efficiency and low power consumption Raman amplifier for long-distance networks. In the case of distributed RFA, CISCO [25] presents a high power Raman amplifier that operates in the C band of the optical spectrum. Regarding the operating temperature of said amplifiers, this can vary according to the manufacturer's specifications; in this case, the simulation characteristics are defined for a reference temperature of 0 ° C, which is within the real operating conditions of a Raman-type amplifier, where, an interval that varies from 0 ° C to 50 ° C is generally recommended, in order to ensure proper operation of the devices.

TABLE III. RFA PARAMETERS

PARAMETERS	***LRA***	***DRA***
Signal wavelength [nm]	1530 to 1565	1500 to 1567
Pump power [mW]	400	1000
Pump frequency [nm]	1420 and 1455	1428 and 1457
Operating temperature [°k]	273	273
Pump attenuation [dB]	0.2	0.2

A. Discrete RFA Amplification

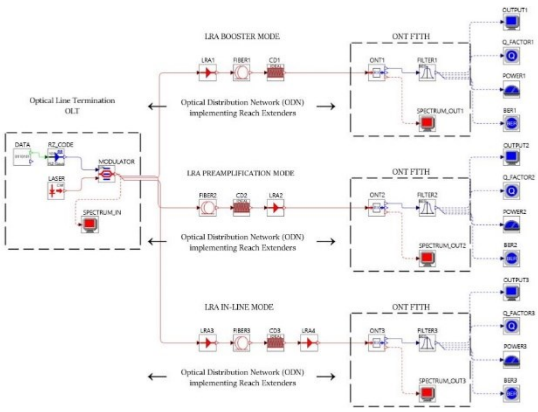

Fig. 3. Simulation scenario for LRA amplification of 1λ x 10 Gbps.

In this case, it should be considered, as observed in Fig. 3, that the device can be configured in three different amplification modes (booster, pre-amplification and in line), and is also taken into account the variables of the pumping source (direction, frequency and pumping power). With this amplification, in spite the fact that with bi-directional pumping, less power is required to achieve good behavior, the best performance is obtained with a counter-propagation source of 1455 nm for pre-amplification and 1420 nm in line, while for booster is achieved with a co-propagated pumping of 1420 nm.

TABLE IV. DISCRETE RFA OPTICAL MONITORING PARAMETERS FOR 1 CHANNEL OF 10 GBPS

P_B [dBm]	***BER***	***Q Factor [dB]***	***P_{Rx} [dBm]***	***Jitter [ns]***	***$OSNR_{OUT}$ [dB]***
Booster mode with 1420 nm co-pumping					
26	0.0002	10.92	-30.70	0.0048	44.47
38	**1e-40**	**38.58**	**-12.60**	**0.0026**	**43.68**
40	1.8e-31	21.34	-2.77	0.0067	29.49
Pre-amplification mode with 1455 nm counter-pumping					
25	1.3e-17	18.54	-27.15	0.0036	39.77
35	**1e-40**	**30.29**	**12.64**	**0.0028**	**40.40**
37	1e-40	30.19	20.02	0.0009	36.28
In-line mode with 1420 nm counter-pumping					
26	0.0105	7.27	-31.11	0.0162	41.88
36	**1e-40**	**22.72**	**-8.52**	**0.0036**	**41.90**
38	6.2e-25	20.33	5.63	0.0205	42.39

Table IV shows the monitoring parameters when the power varies, when the pumping direction and frequency present the best conditions according to previous studies in the different amplification modes [7], and it can be seen that the best behavior in pre- amplification is achieved with 35

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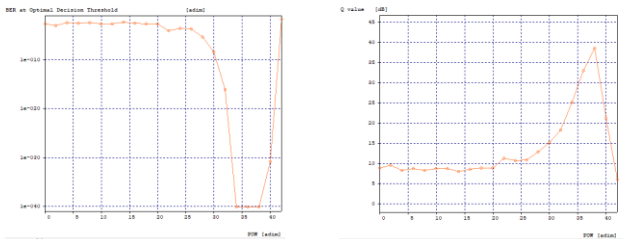
dBm, in line with 36 dBm and in booster with 38 dBm, obtaining in booster a better signal quality and therefore the best performance of the three, in this mode it has a BER region of 1e -40 between 34 dBm and 38 dBm as seen in Fig. 4. (a) and (b). B, for pre-amplification this region is from 27 dBm and in line, at 36 dBm only.



(a) (b)

Fig. 4. (a) BER vs. Pumping power (b) Q Factor vs. Pumping power for LRA in booster with 1λ x 10 Gbps and co-pumping of 1420 nm.

In Table V, it can be seen that for a 1-channel system at 10 Gbps, with discrete Raman amplification, the configuration that presents a better performance at the OPM level and the absence of non-linear (such as SPM) is the booster mode in 1420 nm co-propagation, which presents a robust system and less sensitive to power variations compared to the other configurations. In respect of the effect of the non-linear phenomenon SPM, in booster for a power below the ideal pumping region, the signal does not have good OPM, but no pulse spreading is generated until 40 dBm, where the effect of self-phase modulation is noticeable, therefore, it is recommended to work with the pumping value found in the previous analysis (38 dBm).

TABLE V. DISCRETE RFA OPERATION REGION FOR 1 CHANNEL OF 10 GBPS

Power penalties for LRA			
Configuration	***Meets OPM objective***	***Optical spectrum without penalties [dBm]***	***Ideal Pumping Region [dBm]***
Booster	(34, 40]	[0, 38]	(34, 38]
Pre-amplification	> 27	[0, 35]	(27, 35]
In-line	[32, 38]	[0, 38]	[32,38]

B. Distributed RFA Amplification

With the simulation scenario in Fig 5, the study of the DRA amplifier is carried out, for a 1-channel system at 10 Gbps. The analysis is performed considering the same variables as in 1-channel discrete RFA (direction, frequency and pumping power).

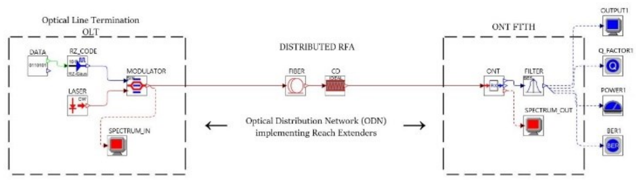
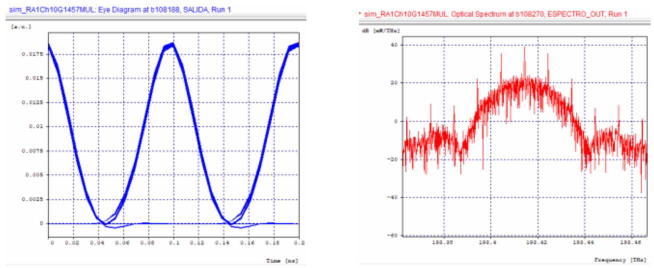


Fig. 5. Simulation scenario for DRA amplification of 1λ x 10 Gbps.

In Fig 6 (a) and (b), the eye diagram and optical spectrum with a power of 34.7 dBm can be seen, where the behavior of the amplifier with an ideal bit error rate is shown, without the presence of degradations or phase deviation in the eye diagram.



(a) (b)

Fig. 6. (a) Eye diagram (b) Optical Spectrum for DRA with 1λ x 10 Gbps for a bidirectional source of 1457 nm and power of 34.7 dBm.

In Table VI, the OPM are found for the pumping frequency of 1457 nm, at a distance of 85 km and channel of 193.4 THz, it is appreciated that with bidirectional pumping, less power is required to achieve better performance. At both pump frequencies, the best condition is obtained with bidirectional pumping, with an ideal BER and quality factor. Furthermore, the received power is within the sensitivity range, however, it is observed that the best performance of the system is obtained when the power is 34.7 dBm for a bidirectional frequency of 1457 nm.

TABLE VI. DISTRIBUTED RFA OPTICAL MONITORING PARAMETERS FOR 1 CHANNEL OF 10 GBPS

P_B [dBm]	***BER***	***Q Factor [dB]***	***P_{Rx} [dBm]***	***Jitter [ns]***	***$OSNR_{OUT}$ [dB]***
Co-pumping					
24	2.7e-20	19.26	-28.65	0.0026	54.38
30	1e-40	27.23	-23.68	0	52.29
34	**1e-40**	**40.00**	**-13.48**	**0**	**49.09**
Counter-pumping					
24	5.9e-14	17.58	-28.73	0.0023	47.04
30	1e-40	25.81	-24.10	0.0009	42.99
36	**1e-40**	**31.60**	**-5.36**	**0**	**43.05**
Bidirectional pumping					
30	1e-40	35.13	-17.83	0	49.14
34.7	**1e-40**	**40.00**	**3.35**	**0**	**51.89**
36	1e-40	38.25	6.17	0.0034	48.05

In Table VII, the ideal region in which the DRA amplifier works was determined without penalties taking into account the shape of the output spectrum and the optical monitoring parameters. For counter-propagation, the ideal region in which it must work will be from 38 dBm to values less than or equal to 44 dBm; for co-propagation, powers greater than or equal to 30 dBm up to 34 dBm and for bidirectional, values from 30 dBm to 36 dBm, the latter being the best option, because it presents an ideal pumping of 34.7 dBm, where it has an ideal behavior with a BER of 1e-40 and a quality factor of 40 dB.

TABLE VII. DISTRIBUTED RFA OPERATION REGION FOR 1 CHANNEL OF 10 GBPS

Power penalties for DRA			
Configuration	***Meets OPM objective***	***Optical spectrum without penalties [dBm]***	***Ideal Pumping Region [dBm]***
Counter with 1428 nm	(38, 45]	[0, 44]	[38, 44]
Co with 1457 nm	[30, 36]	[0, 34]	[30,34]
Bi with 1457 nm	[30, 36.9]	[0, 36]	[30,36]

When doing point-to-point deployments using a single ODN that connects to an ONT, it is not necessary to consider

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a splitter device, however, to meet the characteristics of an XGS-PON network architecture, a 2.5 Gbps DWDM network was defined with speed of access and a throughput of 10 Gbps through the implementation of 4 optical channels with a maximum of 4 end users implementing a 4:1 type splitter device, with an attenuation of 6 dB per user, performing the analysis for one of them and considering a symmetrical behavior of the network. Regarding the frequency response due to the amplification stages, it was observed that with 4 channels at 2.5 Gbps, using a discrete Raman amplification (LRA), the configuration with the best performance, at the OPM level and penalties of power, is the in-line mode counter-pumping (1455 nm and 32 dBm), while using a distributed Raman amplification (DRA), the configuration that presents the best performance corresponds to bidirectional pumping (1428 nm and 34.7 dBm). The results obtained imply that it is a robust system and that it does not present a considerable Raman inclination (tilt-amplification), given that no significant changes in power are observed across the bandwidth of the four simulated channels [7].

IV. COMPARATIVE ANALYSIS

The following is a comparative analysis of the case studies developed with respect to the two types of Raman fiber amplifiers in different amplification modes for an XGS-PON network environment, where the best configuration is selected for each case.

TABLE VIII. TABLE WITH SYNTHESIS OF AMPLIFIER PERFORMANCE RESULTS FOR 1Λ X 10 GBPS.

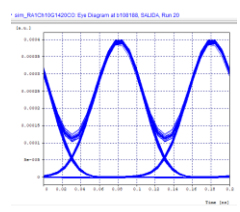
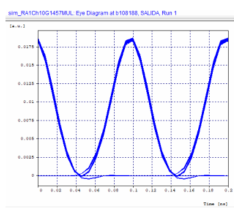
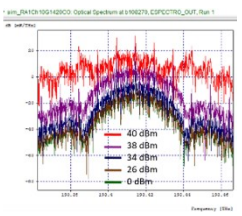
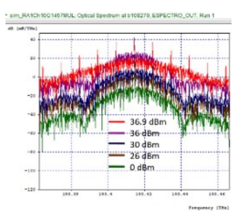
	LRA	*DRA*
Ideal mode	Booster	Doesn't apply
Ideal pumping	Co- propagated of 1420 nm and 38 dBm	Bidirectional of 1457 nm and 34.7 dBm
Eye diagram for 85 km		
Optical spectrum		
Power penalties	Not very susceptible	Not very susceptible
Cost	High	High
Performance	Good	Very good
linear effects	Moderately tolerable	Moderately tolerable
Maximum distance reached	Good (145 km)	Good (115 km)

Table VIII summarizes the simulation performance of RFA optical amplifiers in an XGS-PON network, where it is evident that although for each amplification system a different ideal pumping is found, in general, a robust link is guaranteed with these configurations, with good performance and allowing long propagation distances without exceeding power limits that significantly degrade signal quality, concluding that:

- RFAs are classified according to their design, in two types of amplifiers: LRA and DRA, which allows verifying that DRA achieves the amplification effect due to the same fiber that is used for signal transmission.
- The RFA amplifier configured in the different modes with the values established by the manufacturer does not correspond to the best performance and generates power penalties.
- Regardless of whether you are dealing with a 4-channel or 1-channel system, susceptibility to RFA power penalties is low.
- RFA amplifiers working in their ideal configuration, obtain better performance in the network with the reference frequency (193.4 THz).
- At values below the ideal working range of the amplifiers, there are very low power levels that do not allow any channel to be detected and at higher values, power penalties are excited.
- The eye diagrams, allow us to deduce that the performance of the system is not affected by attenuation, ISI or noise and do not show changes in the signal phase that cause problems and transmission errors.
- The analysis of the maximum distance reached by each of the amplifiers allowed us to conclude that with LRA a greater distance is achieved for a system of 1λ x 10 Gbps.
- In general, in relation to the analysis of linear effects, it was found that Raman fiber amplifiers are moderately tolerable to these first order degradations.
- Under the characteristics designed for the link, where it want to analyze the performance of the optical amplifiers in the network, it is determined that effects such as PMD, CD, XPM and attenuation, do not contribute significantly.

V. CONCLUSIONS

The results presented in this article allow verifying that the performance of an XGS-PON network architecture, in which Raman optical amplification is used, is affected by varying parameters of the pumping source of the amplifier, mainly by varying the pumping power, so working with powers outside the established operating range can migrate the system from a predominantly linear to non-linear propagation regime, generating signal degradation and detecting errors in the receiver.

From the research carried out, it is recommended to use Raman-type amplifiers for metropolitan or long-range networks, since for short distances due to the high cost of these Raman devices (either LRA or DRA), other optical amplifiers are used to present a good cost-performance ratio in these cases. On the other hand, although DRA, being an amplified fiber is more attractive because it needs fewer network elements, it may be more economically feasible to implement LRA in a fiber optic link, however, for the next evolution of

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systems at speeds of 40 Gbps Raman-type links represent a more attractive solution.

This research project allowed to establish the most convenient configurations of the Raman amplifiers studied under the established network conditions, taking into account that the characteristics of real devices were considered, so it was possible to verify that the configuration parameters of the amplifiers can vary according to the needs of the network, since the pumping parameters of commercial devices, both LRA and DRA, in most scenarios do not agree with the value found according to the monitoring parameters obtained.

Similarly, it can be concluded that this type of research, analysis and results around advanced optical amplifiers, contributes to the updating of next-generation DWDM networks, since currently, this type of optical amplification is one of the most studied proposals to achieve XGS-PON type communication systems with high data transmission rates and long distances, defining the conditions in which the network is least affected by optical degradations.

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