M-QAM modulation technique effect for an OFDM-RoF/XGS-PON converged network

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***Abstract*—This paper focuses on analyzing, at the simulation level, the effect of the M-ary Quadrature Amplitude Modulation (M-QAM) technique, for an OFDM-RoF converged network infrastructure based on the XGS-PON standard, with a 10 Gbps capacity for a point-to-point downlink and an FTTH application, with an operating wavelength of 1550 nm or 193.4 THz (overlayed OFDM-RoF/XGS-PON system). The above, with the purpose of determining the network performance, as both the order of the M-QAM modulation and the distance of the optical link are increased, considering that the performance of a radio over optical fiber system can be significantly degraded by non-linear phenomena present in the optical link, as well as noise and distortion phenomena that affect the signal quality. In the results of the research, the increase in the order of the M-QAM modulation allows us to represent more bits per symbol, however, a higher transmission power is required. Finally, it is considered that it is possible to develop a robust OFDM-RoF converged network infrastructure for speeds in the order of 10 Gbps for the last mile services, since it uses the advantages of both wireless and optical technologies.**

Keywords—Fiber To The Home, FSAN optical architectures, Quadrature Amplitude Modulation, Last Mile, Orthogonal Frequency Division Multiplexing, Radio over Fiber.

I. INTRODUCTION

Today's next-generation wireless and mobile communication services offer mobility, flexibility, and connectivity to end-users, as well as direct access to a host of new broadband services and applications that require efficient resource utilization [1]. One of the most widely deployed modulation techniques in wireless communications is Quadrature Amplitude Modulation (QAM), which offers a lower probability of Inter-Symbol Interference (ISI) compared to other digital modulation techniques. With the development of advanced modulation formats, such as Orthogonal Frequency Division Multiplexing (OFDM), which allows the simultaneous sending of several independent QAM subcarriers, the overall network performance is improved and a more robust system is created, however, with the development of optic fibers and packet-based networks, modulation schemes such as M-QAM seek to transport more bits per symbol at higher data transmission rates [2]. Therefore, the convergence of these two networks in a technology such as Radio over Fiber (RoF) is currently the subject of constant research.

This paper focuses its study on observing the effects that occur at the simulation level, in a OFDM-RoF converged network infrastructure at a downlink speed of 10 Gbps, implementing the M-QAM modulation technique, by manipulating both the order of modulation and link distance, in order to determine whether an increase in the order of modulation manages to significantly degrade the performance of the RoF converged network. It is important to remark that, the optical core of the network infrastructure is based on the ITU-T G.9807.1 standard, representing XGS-PON type networks. However, in this paper, only the characteristics for the downlink are considered, due to the limitations presented by the simulation tool regarding bidirectional links, without affecting the results obtained.

II. BACKGROUND INFORMATION

A. OFDM

It is a type of Multi-Carrier Modulation (McM), with modulation and multiplexing characteristics, because it divides a high-speed data stream into a set of signals, then modulates each signal to a new frequency using digital modulation techniques, such as Phase Shift Keying (PSK) or QAM. The signals are sent on a set of narrow-band sub-channels, each centered on a sub-carrier, properly spaced and orthogonal to each other. The consequence of transmitting the modulated data in parallel is that the symbol period is extended, so that the ISI within the communication channel only affects a portion of the signal which can be removed using a guard interval called the cyclic prefix [3]. The mathematical expression for the OFDM signal is shown in (1).

$$\phi_n(t) = A(t) * \exp(j2\pi f_n t) = I(t) + jQ(t) \tag{1}$$

Where *fn* is the frequency of the n-th subcarrier, *n* the number of subcarriers and A the amplitude of the signal. The use of Inverse Fast Fourier Transform (IFFT) characterizes the OFDM technology, since it allows the parallel transmission of orthogonal subcarriers, avoiding the problems of multipath propagation [4]. In Fig. 1, an OFDM signal is represented in the frequency domain.

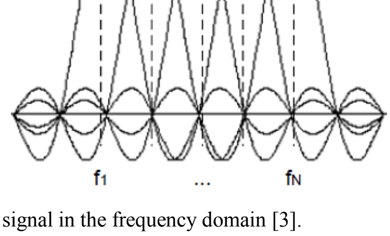


Fig. 1. OFDM signal in the frequency domain [3].

In recent years the progress made in digital signal processing has enabled the introduction of the OFDM modulation scheme in optical communications. The transmission of information in optical networks using a single carrier suggests an inefficient use of the spectrum, however, the demand for higher data rates with high bandwidth requires a search for solutions such as optical bandwidth optimization with dynamic allocations, so OFDM is a promising solution to be implemented in optical communications [5].

There are two types of implementation of the OFDM modulation scheme in the optical medium, according to the technique used for detection in the receiver, such as: direct detection and coherent detection [6]. The former requires electrical-to-optical (E-O) conversion by means of an intensity-modulated laser and a photodetector in the receiver, which gets the pulse optical power and transforms it into an electrical current. In the latter one, the E-O conversion of the OFDM signal in phase and quadrature is performed by means of Mach-Zehnder Modulators (MZM), then the two optical signals are added together and sent on the transmission channel to the receiver. The difference with direct sensing systems is that the optical carrier is not transmitted with the modulated optical OFDM signal, instead, it is generated locally in the receiver by a local laser, with the advantage of using less power to transmit, although it leads to greater sensitivity to phase noise. Also, coherent detection systems require a more difficult transceiver design compared to the direct detection technique [7].

B. QAM

It defines that the information signal is contained in both the amplitude and the phase of the carrier signal, compared to the M-PSK modulation technique, where the points within the constellation are on a fixed amplitude circle. The technique transmits two independent messages from the same carrier signal, where the messages occupy the same frequency band but are offset by 90 degrees from each other. Each message is then modulated independently and transmitted by a single path over the same frequency band and then separated by demodulation in the receiver [8]. The M-ary scheme for QAM, on the other hand, defines that two or 'k' incoming bits of information are represented by a symbol that occupies a point in the complex phase and quadrature constellation. M is the possible output symbols that are transmitted in each Ts symbol period. The mathematical expression for the M-QAM scheme is illustrated in (2).

$$S_i(t) = \sqrt{\frac{2 * E_{\min}}{T_S}} * a_i \cos(2\pi f_o t) + \sqrt{\frac{2E_{\min}}{T_S}} * b_i \sin(2\pi f_o t) \quad (2)$$

This modulation scheme is widely used in the field of modern communications for applications that require high data rates, both in wired and wireless media, e.g., television transmission systems, microwaves, and satellites, since it enables a spectral efficiency improvement in the available bandwidth. Also, M-QAM formats are closer to the Shannon capacity limit when high-spectral efficiency is sought, however, a more complex modem is needed, although in practice, M-QAM exceeds the performance advantages compared to its complexity, and therefore is more widely used than M-PSK formats [8].

C. FSAN

As the transition of telecommunication networks is shifting from circuit-based networks to packet-based next-generation networks (NGN), this migration scenario offers several services on one platform. In turn, NGN are developed to support traditional and emerging packet-based services, as well as all mobile services and applications for residential and business users, with a high quality of service (QoS), bandwidth efficiency and data rates in the order of Gbps, with optical fiber-based telecommunication systems, being important candidates to meet the requirements of an NGN. Some of the requirements according to [9], are: to allow the creation, introduction and management of all types of services, to support, at the transport level, services with different bandwidth demands, to separate services and transport from the network allowing them to evolve independently, among others. On the other hand, the Full Service Access Network (FSAN) task force, created at the end of the 90's to define a family of broadband access architectures based on optical fiber, proposes an evolution to NGN in two stages, such as: New Generation Passive Optical Network 1 (NG-PON1), which comprises PON architectures with a 10 Gbps capacity of symmetric/asymmetric type [10]. Also, NG-PON2 which proposes completely new generation architectures at 40 Gbps [11]. In Fig. 2, an evolution of PON technology is presented in a timeline.

In addition, the European Fiber To The Home (FTTH) committee proposes several network architectures for different scenarios of interconnection and convergence of technologies, with the aim of migrating to NGN and the coexistence of the different proposed standards [12]. The deployment of optical fiber for FTTx networks is limited to a certain point in the network, so the point reached is determined by the last letter, for example: FTTH, Fiber to the Building (FTTB), Fiber to the Node (FTTN), Fiber to the Antenna (FTTA), Fiber to the Distribution Point (FTTDp), among other abbreviations.

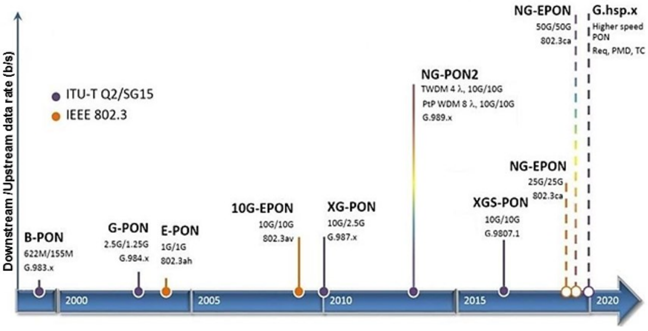


Fig. 2. Evolution of passive optical networks [13].

D. RoF

The transmission of information through the optical fiber is made using as mechanism the adjustment of the light with the RF signal that is desired to emit. RoF is a combination of wireless networks with fiber optic networks, where the RF signals are distributed from a central office through a fiber optic link, to a Base Station (BS). The BS transmits the data to mobile stations or terminals that are within range. Therefore, a RoF system consists of four main elements: the optical transmitter, the optical access network, the BS and the mobile or fixed end [14].

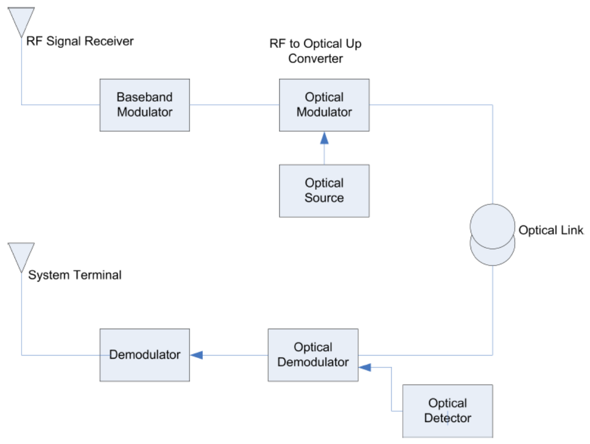


Fig. 3. General RoF architecture [15].

When there are different base stations, the signal is splitted to each one of them by a passive optical splitter. Since the first experiments in the transmission and distribution of RoF signals, the convergence of optical and wireless networks has evolved, so they have been used in a variety of wireless networks, such as outdoor cellular networks and indoor distributed antennas. RoF systems face challenges, such as: to support multiple standards, to reliably and cost-effectively support capacity demands, traffic growth and services in current and future networks [14]. Recently, the region of frequencies that will let the extension of wireless coverage of radio systems for the provision of broadband services is being explored, the great interest has focused on the millimeter wave (mmW), especially in the band of 60 GHz without license and available worldwide, since the existing wireless standards as: Long Term Evolution (LTE), Universal Mobile Telecommunications System (UMTS), Global System for Mobile Communications (GSM), and the IEEE 802.11x standard, work in low frequency ranges from 700 MHz to 6 GHz [16]. The general architecture for a RoF communication system is illustrated in Fig. 3.

III. Simulation Model

For the development of the research, an OFDM-RoF converged network infrastructure based on the XGS-PON standard is defined, with a 10 Gbps capacity for a point-to-point downlink and an FTTH application, with an operating wavelength of 1550 nm or 193.4 THz, which allows the transport of radio frequency video signals over the new generation of passive optical networks (overlayed OFDM-RoF/XGS-PON system).

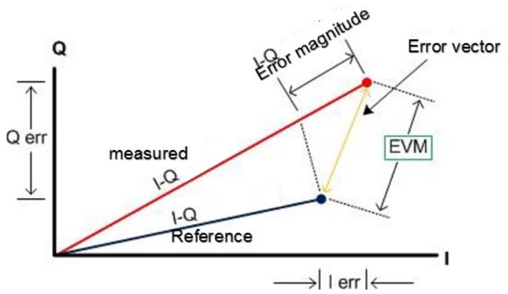


Fig. 4. Graphical representation EVM [15].

The Error Vector Magnitude (EVM), measured in the receiver, seeks to evaluate the quality of a certain signal that has been modulated with some multilevel modulation technique, such as M-QAM or M-PSK. To calculate the EVM, phasors are used in the complex plane, so the EVM is a scale that illustrates the difference between the ideal reference symbol and the real symbol in reception, within the complex constellation [17]. In Fig. 4, the graphic representation of the EVM is illustrated.

In the context of this paper, the EVM is used to calculate the Bit Error Rate (BER), because conceptually a convergent network model with current modulation and direct detection was defined for the OFDM-RoF system, which indicates that the system is not coherent, i.e. there is no synchronization between the transmitter and the receiver, therefore, the signal in reception has amplitude differences and phase shifts, in addition to the noise present in the whole system, causing errors in the BER measurement. According to [15], it is possible to obtain the BER as a function of the SNR for a network model using the M-QAM modulation technique as described in (3).

$$BER = \frac{2*(1-\frac{1}{\sqrt{M}})*erfc(\sqrt{3*\frac{SNR[Linear]}{2*(M-1)}})}{\log_2(M)} \tag{3}$$

It is also possible to obtain a consistent approach to the SNR as a function of the EVM, as described in (4).

$$SNR[dB] = -20\log(\frac{EVM}{100}) = 10\log(SNR[Linear]) \tag{4}$$

The above equations were fully useful for the correct process of calculating the BER. Thus, the methodological process to follow within the OPTSIM software [18] was to measure the EVM in the OFDM-RoF receiver and subtract it with the EVM measured in the back-to-back receiver, later and with the help of MATLAB, the result of the SNR was calculated, for a certain order of M-QAM modulation. On the other hand, the simulation scenario in which the effect of the M-QAM modulation technique was evaluated has the parameters shown in the Table. I, following the FTTH features.

TABLE I. CHARACTERISTICS OF THE SIMULATION SCENARIO.

PARAMETER	VALUE
Data rate	10 Gbps
RF carrier frequency	10 GHz
Modulation formats	4-QAM, 8-QAM, 16-QAM, 64-QAM
IFFT-OFDM Subcarriers	8
Cyclic Prefix	0.25 GHz
Delay	0
Band	C (1530 -1560 nm)
Signal wavelength [nm]	1550 nm (RF video)
CW laser frequency	193.41449 THz (Continuous wave)
CW laser power	0 dBm
Laser wavelength	1550 nm
Optical modulator	LiNb-MZM modulator
Optic fiber	ITU-T G.652 (MSS-28e)
Photodetector	PIN
Photodetector wavelength	1550 nm
Electric filter receiver 1 and 2	Bessel filter with 7 number of poles
Optical filter	Root-raised-cosine filter (roll-off = 0.5)

For the simulation scenario, the general components of a telecommunication system were taken into account: transmitter, channel, receiver. The transmitter consists of two main parts including the RF-OFDM transmitter subsystem and the radio-frequency-to-optical converter (RTO) subsystem. The receiver block comprises two main parts, such as: an O-E converter and an RF-OFDM receiver. The design for the Optical Distribution Network (ODN) was based on an FTTH access network with an XGS-PON type architecture, i.e., optical fiber is laid from the OLT to the ONT. The design parameters to be taken into account were the optical fiber length/type [19]. Since the objectives set for this research were based on the implementation of a OFDM-RoF converged network infrastructure of XGS-PON type (overlayed), a thorough investigation of the maximum distance achieved for this type of converged network was necessary in order to obtain a BER around 10E-3, which is an acceptable bit error probability for cellular radio telephony systems at minimum performance, as recommended by [20]. Fig. 5 illustrates the simulation scenario implemented in OPTSIM for this research.

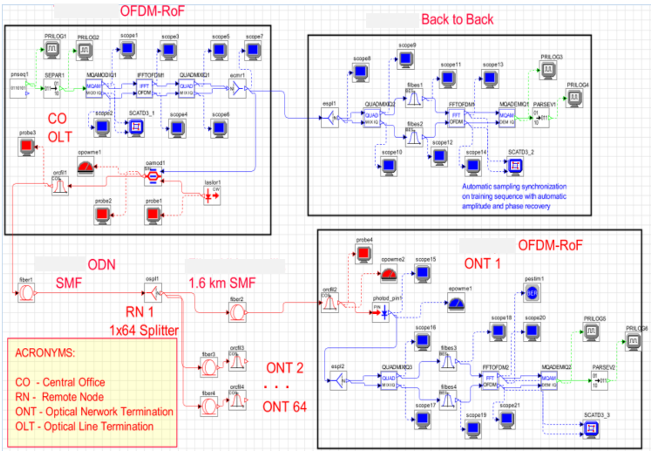
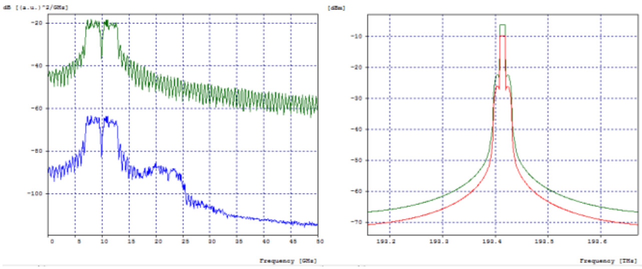


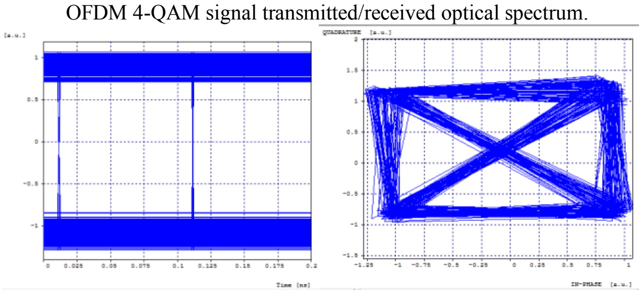
Fig. 5. Simulation scenario.

IV. Simulation Results

For the overlayed **OFDM-RoF/XGS-PON** system with **4-QAM** modulation scheme, a maximum distance of around 3.2 km was achieved, at a data rate of 10 Gbps in the downlink, where it was used for the evaluation of the 4-QAM modulation technique. In Fig. 6 (a), the transmitted (green) and received (blue) RF-OFDM signal spectrum is illustrated for the order of 4-QAM modulation. The RF-OFDM signal is modulated in the optical domain, using the external modulation technique, which is well-known to be used in high-frequency signals. In Fig. 6 (b), the transmitted (green) and received (red) RoF signal is observed. The eye and constellation diagram for the 4-QAM modulation in the OFDM-RoF/XGS-PON system, are detailed in Fig. 6 (c) and 6 (d), respectively.



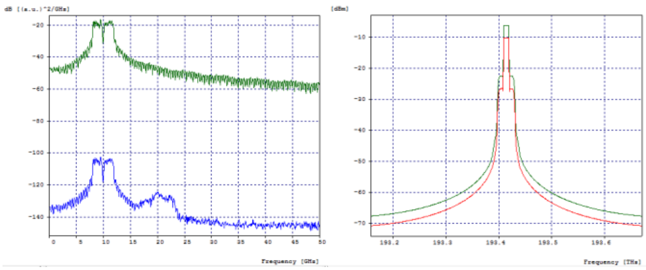
(a) RF-OFDM 4-QAM transmitted/received signal spectrum. (b) RF-OFDM 4-QAM signal transmitted/received optical spectrum.



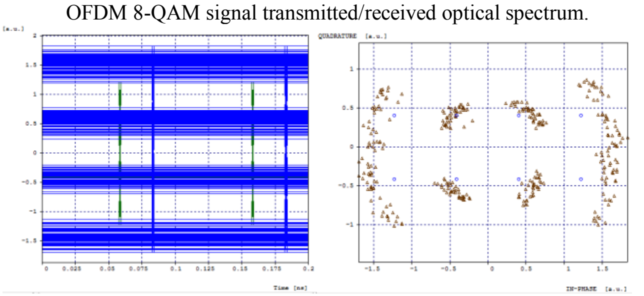
(c) OFDM 4-QAM receiver signal eye 'I' diagram. (d) Receiver 4-QAM signal constellation diagram.

Fig. 6. Graphic results for the OFDM-RoF/XGS-PON system (4-QAM).

For the overlayed **OFDM-RoF/XGS-PON** system with **8-QAM** modulation scheme, a maximum distance of 5 km was achieved, at a data rate of 10 Gbps in the downlink, where it was used for the evaluation of the 8-QAM modulation technique. Fig. 7(a) shows the spectrum of the RF-OFDM signal transmitted (green) and received (blue) for the 8-QAM modulation order. Fig. 7(b) shows the spectrum of the transmitted (green) and received (red) RoF signal. The eye and constellation diagram, for the 8-QAM modulation in the OFDM-RoF/XGS-PON system, are detailed in Fig. 7(c) and 7(d), respectively.



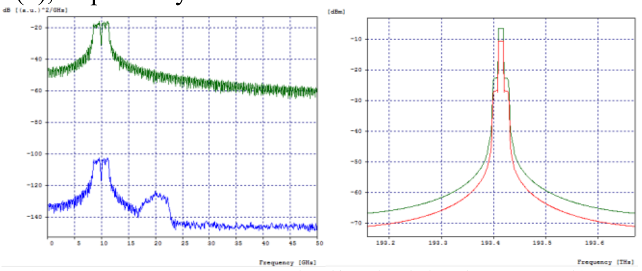
(a) RF-OFDM 8-QAM transmitted/received signal spectrum. (b) RF-OFDM 8-QAM signal transmitted/received optical spectrum.



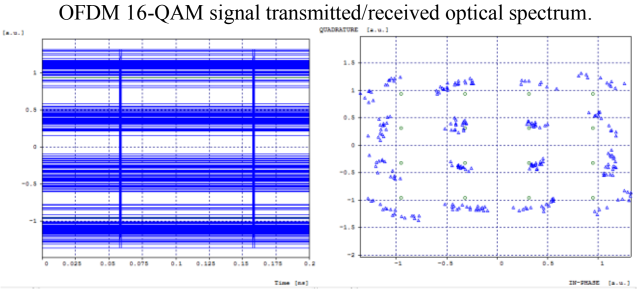
(c) OFDM 8-QAM receiver signal eye 'I' diagram. (d) Receiver 8-QAM signal constellation diagram.

Fig. 7. Graphic results for the OFDM-RoF/XGS-PON system (8-QAM).

In the case of the overlayed **OFDM-RoF/XGS-PON** system with **16-QAM** modulation scheme, a maximum distance of 5.6 km was achieved, at a data rate of 10 Gbps in the downlink, where it was used for the evaluation of the 16-QAM modulation technique. Fig. 8(a) shows the spectrum of the RF-OFDM signal transmitted (green) and received (blue) for the order of 16-QAM modulation. Fig. 8(b) shows the spectrum of the transmitted (green) and received (red) RoF signal. The eye and constellation diagram, for the 16-QAM modulation in the OFDM-RoF/XGS-PON system, are detailed in Fig. 8(c) and 8(d), respectively.

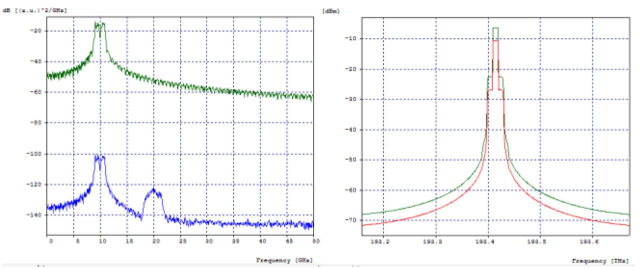


(a) RF-OFDM 16-QAM transmitted/received signal spectrum. (b) RF-OFDM 16-QAM signal transmitted/received optical spectrum.

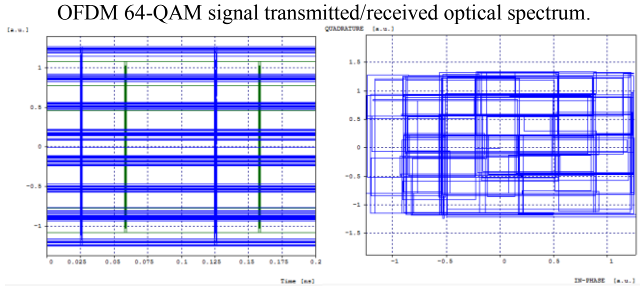


(c) OFDM 16-QAM receiver signal eye 'I' diagram. (d) Receiver 16-QAM signal constellation diagram.
Fig. 8. Graphic results for the OFDM-RoF/XGS-PON system (16-QAM).

For the overlayed **OFDM-RoF/XGS-PON** system with **64-QAM** modulation scheme, a maximum distance of 6 km was achieved, at a data rate of 10 Gbps in the downlink, where it was used for the evaluation of the 64-QAM modulation technique. Fig. 9(a) shows the spectrum of the RF-OFDM signal transmitted (green) and received (blue) for the order of 64-QAM modulation. Fig. 9(b) shows the spectrum of the transmitted (green) and received (red) RoF signal. The eye and constellation diagram, for 64-QAM modulation in the OFDM-RoF/XG-PON system, are detailed in Fig. 9(c) and 9(d), respectively.



(a) RF-OFDM 64-QAM transmitted/received signal spectrum. (b) RF-OFDM 64-QAM signal transmitted/received optical spectrum.



(c) OFDM 64-QAM receiver signal eye 'I' diagram. (d) Receiver 64-QAM signal constellation diagram.
Fig. 9. Graphic results for the OFDM-RoF/XGS-PON system (64-QAM).

According to the analysed data from the M-QAM modulation scheme for the overlayed OFDM-RoF/XGS-PON converged network infrastructure, a graph expressing the SNR versus distance behavior is presented in Fig. 10. Also, a comparative graph of BER versus SNR for the OFDM-RoF/XG-PON system is presented in Fig. 11. A summary of the mathematical results is in Table II.

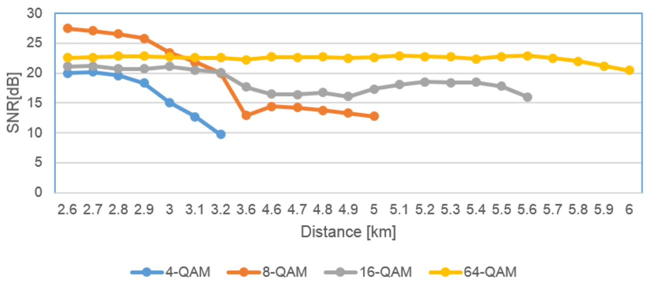


Fig. 10. SNR vs Distance for M-QAM.

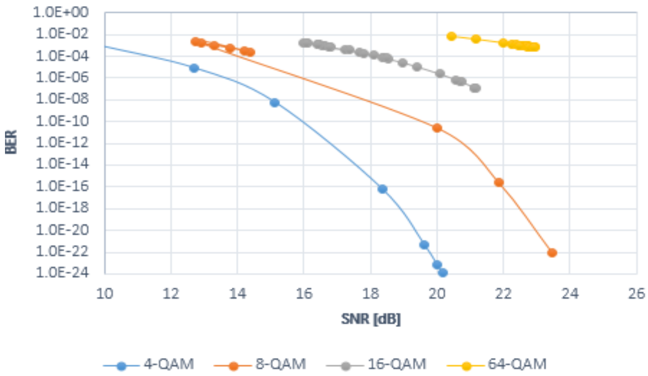


Fig. 11. BER vs SNR for M-QAM.

TABLE II. DATA OBTAINED IN THE SIMULATION SCENARIO.

Overlayed OFDM-RoF/XGS-PON		
4-QAM	Maximum distance [km]	3.2
	Minimum SNR [dB]	9.7
	Maximum acceptable BER	1.1E-3
	Transmission power [dB]	-18.1961
	Received electrical power [dB]	-63.3462
	Received optical power [dBm]	-9.8339
	Received OSNR [dB]	61.1341
8-QAM	Maximum distance [km]	5
	Minimum SNR [dB]	12.75
	Maximum acceptable BER	1.9E-3
	Transmission power [dB]	-16.5547
	Received electrical power [dB]	-102.3441
	Received optical power [dBm]	-10.1427
	Received OSNR [dB]	60.6494
16-QAM	Maximum distance [km]	5.6
	Minimum SNR [dB]	16.047
	Maximum acceptable BER	1.7E-3
	Transmission power [dB]	-15.6287
	Received electrical power [dB]	-102.2173
	Received optical power [dBm]	-10.3202
	Received OSNR [dB]	60.7606
64-QAM	Maximum distance [km]	6
	Minimum SNR [dB]	20.441
	Maximum acceptable BER	6.3E-3
	Transmission power [dB]	-13.7371
	Received electrical power [dB]	-100.2540
	Received optical power [dBm]	-10.4693
	Received OSNR [dB]	61.2886

According to the results, it can be seen that with an increase in the order of M-QAM modulation, for the OFDM-RoF network infrastructure, at a 10 Gbps downlink data rate, it is possible to represent more bits per symbol, however, as the proximity of the symbols within the constellation increases, it is susceptible to higher BER due to noise and distortion phenomena, which requires a higher level of transmitted signal power. Moreover, it is observed that 8-QAM is the order of modulation that presents a greater performance in power over the region between 4 and 5 km of optical fiber length approximately, however, there is a penalty in the spectral efficiency and data transmission speed compared to 64-QAM.

CONCLUSIONS

The results presented in this paper allows us to verify that the performance of an OFDM-RoF converged network infrastructure for a downlink speed of 10 Gbps is affected by varying the order of modulation M-QAM, because an increase in the order of modulation leads to represent more bits per symbol and reach a greater distance without losing the transmitted information, but, a higher transmission power is required, since the proximity of the symbols within the constellation and signal degradation along the transmission channel, generates detection errors in the receiver.

The M-QAM multi-carrier modulation scheme can be implemented in OFDM-RoF converged networks together with XGS-PON access networks, as it efficiently uses the available bandwidth, as it uses the advantages of both radio and optical fibre technology. It is also clear that an XGS-PON solution provides scalability by being inherently transparent to the channel bit rate, so in an overlayed OFDM-RoF/XGS-PON system, there is no significant loss in the optical link.

The present research is a reference for future work and development of the OFDM-RoF converged network model in wireless and broadband communications, concluding that, the OFDM-RoF converged network model can be implemented on telecommunication networks to obtain benefits, such as: bandwidth increase, low attenuation due to the optical fiber link, and low BER using the M-QAM modulation technique, taking into consideration that PON combine the high capacity given by the optical fiber with the low cost of installation and maintenance of a passive infrastructure. It should be noted that the line of research can be extended as future work with the use of the XGS-PON standard for a two-way symmetrical link.

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