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BER REDUCTION FOR MQAM HIGH-SPEED TRANSMISSION IN OPTICAL FIBER NETWORKS USING CONVOLUTIONAL, BCH, RS AND LDPC ERROR CORRECTING CODES

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ABSTRACT

A comparative study of digital m-ary Quadrature Amplitude Modulation (mQAM) channel coding signals for optical high-speed transmission is presented in this article. The needs to transmit information at high speed are topical and relevant to the images, the sounds, and data of any kind, etc. The photonic networks are the subject of much research on the application in optical domain of techniques already used in wireless networks such as mQAM digital modulations and error correcting codes. The mQAM digital modulations interest lies in the fact that they are now being used as subchannel modulation techniques in other advanced modulations such as Othogonal Frenquency Division Multiplexing (OFDM). Indeed, OFDM using mQAM modulation seems to be a good candidate in high speed networks. This allows considering transmission systems at very high speeds in optical transmission networks. The performance of channel coding is based on the estimation of the Bit Error Rate (BER) implementing techniques of Convolutional codes, Bose Chaudhuri Hocquenghem (BCH) codes, Reed-Solomon (RS) codes and Low Density Parity Check (LDPC) codes in a 10Gbps transmission. The BER is estimated as a function of the OSNR and also as a function of the transmission distance.

The study was conducted in a software cosimulation environment with VPITransmissionMaker and Matlab software. The simulation results showed that error correcting codes and particularly LDPC codes are effective and provide satisfactory solutions to reduce the BER by fighting against optical transmission channel disturbances such as chromatic dispersion and nonlinearities.

KEYWORDS: mQAM, broadband, BER, optical fiber, error correcting codes.

I. INTRODUCTION

The transmission of digital signals in high-speed telecommunications optical networks is of increasing interest with the use of high spectral efficiency mQAM modulations. mQAM modulations are been studied in many applications to maximize transmission rates on various media such as wireless channels (Proakis, 2001), (Hara and Prasad, 2003) or optical fiber (Qian, 2005), (Lowery and Armstrong, 2006), (Shieh and Djordjevic, 2010).

The most commonly used modulations in the optical fiber transmission modulations are RZ, NRZ and DPSK. Nowadays most advanced modulation schemes are studied.

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mQAM modulation solutions prove to be potentially suitable for high-speed transmission over optical fiber as they can be associated with a channel coding that can be defined according to the characteristics of the transmission medium.

In this study, we use 4QAM, 16QAM, 64QAM and 256QAM modulation with channel coding to fight against the imperfections of the optical fiber transmission, that is to say, the Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD), nonlinearities and InterSymbol Interference (ISI). The error correcting codes used are discussed in a comparative approach.

In the second section, we present the different parts of the mQAM optical transmission chain. The performance evaluation based on bit error rate (BER) is presented in Section 3. In Section 4, the error correcting codes used are presented and their characteristics. We focus on these four error correcting codes because they are widely studied in the research and thus are potential candidates for improving the quality of transmissions in high speed optical networks. In Section 5, simulations are described and their results are given. Finally, in Section 6, the conclusion is deducted, which contains a summary and perspectives for future works.

II. mQAM OPTICAL TRANSMISSION CHAIN

The optical digital transmission system is presented as follows:

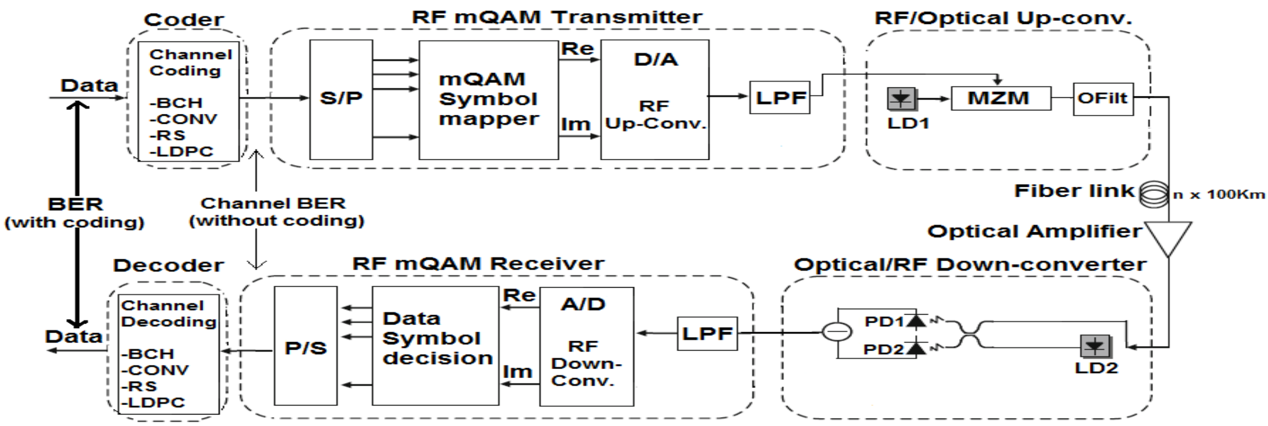


Figure 1: mQAM optical transmission chain

In this diagram, the data are randomly generated, and then successively coded by convolutional, BCH, RS and LDPC codes. mQAM modulation is applied followed by a digital to analog conversion (D/A). The obtained electrical signal can be filtered and sent to the Mach-Zender modulator for a RF/optical convertion. An optical filter is applied before routing the signal on a standard mode optical fiber SMF on a distance of 1000 Km. The optical receiver, consisting of photodiodes, receives the optical signal and converts it to electrical signal and then transmits it to the mQAM receiver. After demodulation and extraction of the received bit sequence, channel decoding is applied. BER calculation is performed before and after the channel decoding according to the OSNR and distance. 4QAM, 16QAM, 64QAM and 256QAM modulations are successively used to compare the different channel coding techniques in the mQAM optical transmission chain.

III. BER ESTIMATION WITH OSNR

The determination of the Bit Error Rate (BER) is based on the probability that the bit being transmitted will be mistaken by the decision circuit (Shieh and Djordjevic, 2010):

$$BER = \Pr(0/1)\Pr(1) + \Pr(1/0)\Pr(0) \quad \text{(1)}$$

Pr(0/1) is the conditional probability that bit 1 was transmitted by the decision circuit decided in favor of 0, Pr(1/0) is the conditional probability that bit 0 was transmitted by the decision circuit decided in favor of 1, and Pr(0) and Pr(1) are a priori probabilities of bits 0 and 1, respectively.

We assume that we have an equiprobable transmission, so Pr (1) = Pr (0) = 0.5 The probability density functions (PDF) for bit 0 and bit 1 are considered Gaussian (Cvijetic M., 2004), (Agrawal G. P., 2002), (Keiser G., 2000) and the conditional error probabilities can be determined by :

$$\Pr(0/1) = \frac{1}{2} erfc\left(\frac{I_1 - I_{tsh}}{\rho_1\sqrt{2}}\right) \quad ; \quad \Pr(1/0) = \frac{1}{2} erfc\left(\frac{I_{tsh} - I_0}{\sigma_0\sqrt{2}}\right) \quad \text{(2)}$$

with the complementary error function erfc(x) defined by: $erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^{+\infty} e^{-z^2} dz$; I_1 and I_0 represent the average photocurrents corresponding to bit 1 and bit 0 levels, I_{tsh} is the photocurrent threshold level, and σ_1 and σ_0 are corresponding standard deviations. The resulting BER can be obtained by:

$$BER = \frac{1}{4}\left[erfc\left(\frac{I_1 - I_{tsh}}{\rho_1\sqrt{2}}\right) + erfc\left(\frac{I_{tsh} - I_0}{\sigma_0\sqrt{2}}\right)\right] \quad \text{(3)}$$

After minimizing the BER and assuming that $\sigma_1=\sigma_0$, we can approximate the value of I_{tsh} and the BER becomes:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \quad \text{(4)}$$

with $Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}$ introducing the Q-factor.

Given the theoretical complexity of evaluating BER depending on the type of transmission channel, the simulation software can also evaluate the BER at the receiver side by the direct counting of erroneous bits. In this case, BER can be expressed by:

$$BER = \frac{Erroneous\_bit\_number}{Transmitted\_bit\_number} = \frac{N_{err}}{N} \quad \text{(5)}$$

This equation requires the simulation to be done with a large number of symbols to ensure the results.

To overcome this problem, we use a Monte Carlo approach. The simulation method of Monte Carlo (Jeruchim et al., 2000) relates to a stochastic simulation technique wherein a large number of random symbols are used to estimate the behavior of a system. We can deduce that:

$$BER_{MC} = \lim_{N \to +\infty}\left(\frac{N_{err}}{N}\right) \quad \text{(6)}$$

The simulation is performed under the effect of the Chromatic Dispersion (CD) and the Optical Signal to Noise Ratio (OSNR). In our context, OSNR is determined and calculated at the receiver side at the entry of the Optical/RF Down-converter (*Figure 1*). The OSNR is the ratio of the optical signal power and the noise power:

$$OSNR = \frac{P_S}{P_{Noise}} \quad \text{(7)}$$

with P_s the power of the optical signal, P_{Noise} the total power noise which models the accumulation of all the noise associated with optical transmission chain. Then in dB:

$$OSNR(dB) = 10\log_{10}\left(\frac{P_S}{P_{Noise}}\right) \qquad (8)$$

In our context, we monitor the OSNR so as to secure successive values that can influence the calculation of BER for modeling the variable effect of imperfections in the optical transmission channel. In reception we measure the OSNR before the entry at the photodiode.

IV. THE CONVOLUTIONAL, BCH, RS AND LDPC ERROR CORRECTING CODES

The principle of channel coding techniques is to introduce redundancy in information to be transmitted in order to detect and correct errors at the receiver side. The error correcting codes have been created to achieve channel coding as the process consist on encoding information messages, and at the receiver side after crossing the channel, on achieving the reverse process to restore or decode data issued.

Convolutional codes are codes with high interest for research. Introduced by Peter Elias in 1954 (Elias, 1954), the convolutional codes are among the most popular codes used in many applications: wireless communications, terrestrial and satellite communications. Their method of decoding the most popular is based on the Viterbi algorithm (Cain et Clark, 1981). The encoder generates a convolutional code with a memory effect as the code word depends on both the k blocks of incoming information, and also on m previous codes, stored in registers. The *Table 1* summarizes the characteristics of the convolutional encoder used in the transmission chain.

LDPC (Low Density Parity Check) codes, created by Gallager in 1960, are linear block codes for which the parity check matrix has a low density of bits "1", (Gallager, 1963). LDPC codes have attracted great interest in the community of researchers in coding, resulting in a greater understanding of different aspects of the code and the decoding process. The low inherent complexity of this decoder opens the way for its use in various high-speed applications such as optical communications.

TABLE 1: CONVOLUTIONAL ENCODER SETTINGS

Encoder type	Parameters				
	k	***n***	***r***	***constraint length***	***Generators***
Convolutional	1	2	1	7	[171 133]

LDPC codes have been well studied from a theoretical point of view since their rediscovery in 1995 (MacKay et Neal, 1996), and the problems with their hardware integration are beginning to be addressed. The choice of an LDPC code for Satellite Digital Video Broadcast (DVB-S2) makes the hot topic. The method of iterative decoding of LDPC codes requires long blocks of message and is based on the LLR (Log-Likelihood Ratio) algorithm. The *Table 2* summarizes the characteristics of the LDPC encoder used in the transmission chain.

TABLE 2: LDPC ENCODER SETTINGS

Encoder type	**Parameters**		
	k	***n***	***r***
LDPC	32400	64800	32400

BCH codes were introduced in 1959 by A. Hocquenghem and in 1960 by R. C. Bose and D. K. Ray-Chaudhuri. These codes are based on the Hamming metric. They are considered as very powerful cyclic codes for correcting a series of random errors.

BCH correcting codes are part of cyclic linear codes described by the roots of a polynomial with coefficients in a finite Galois (Galois field). The mathematical foundations of this concept are shown in (Adams, 2008). With a BCH code (n, k, d) built on the field GF (q), a message composed of k information bits is encoded into a code word of n bits, d is the minimum distance of the code. The characteristics of the encoder used are summarized in the *Table 3*:

TABLE 3: BCH ENCODER SETTINGS

Encoder type	**Parameters**				
	k	$n = 2^m - 1$	$r = n-k \leq m*t$	***t***	$d_{\min} \geq 2*t+1$
BCH	4	7	3	1	3

RS codes are a subfamily of BCH codes also based on finite Galois field. They use a coding technique which is applied to symbols. This feature makes them particularly powerful to correct errors in bursts. An RS (n, k, t, d) code is a BCH (n, k, t, d) code, not binary, and built on a GF(q) field. The characteristics of the encoder used are summarized in the *Table 4*:

TABLE 4: RS ENCODER SETTINGS

Encoder type	**Parameters**				
	k	$n = q - 1$	$r = n-k = 2*t$	***t***	$d_{\min} = 2*t+1$
RS	3	7	4	2	5

V. MQAM OPTICAL CHAIN SIMULATION

The mQAM optical transmission Chain is simulated in a cosimulation environment with softwares VPITransmissionMaker 8.7 of VPIphotonics GmbH (Kaminow I. and Li T., 2002), (Piprek J., 2005) and Matlab R2010a of MathWorks. Cosimulation with Matlab allowed adding specific treatments to channel coding because the used error-correcting codes are not available in VPITransmissionMaker. VPITransmissionMaker is an integrated design environment where a simulation consists on interacting with components of the library as well as those created to exchange signals and make calculations and measures. VPITransmissionMaker uses a hierarchical organization of objects whose star, galaxy and the universe. A galaxy contains two or more stars interconnected and the universe is the simulation scheme represented as follows:

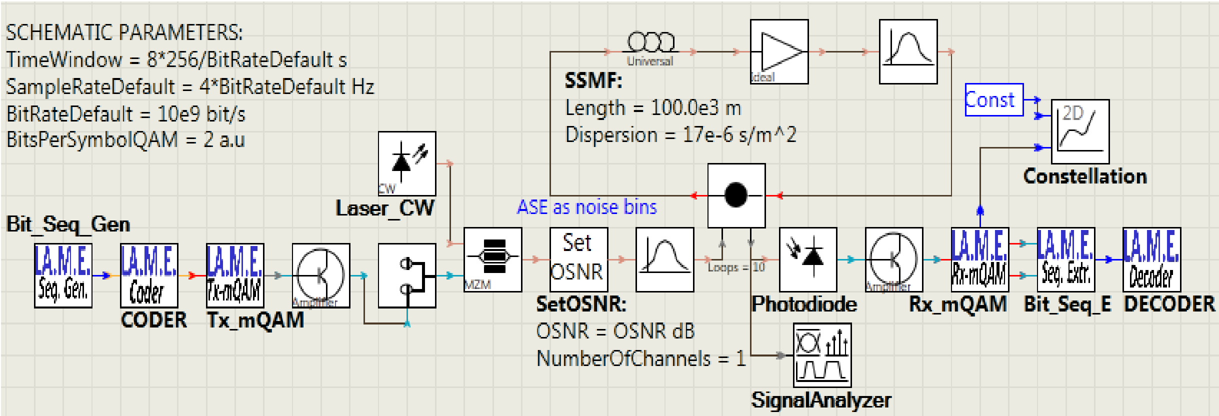


Figure 2: Scheme of the simulation in VPITransmissionMaker 8.7

New galaxies, LAME_Seq.Gen., LAME_Coder, LAME_Seq.Extr. and LAME_Decoder were created with cosimulation to achieve the generation of a random binary sequence, coding and the decoding process of the binary sequence . The LAME_Seq.Extr galaxy estimate the received bit sequence in order to proceed to the channel decoding by the LAME_Decoder galaxy. The simulation model "OFDM for Long-Haul Transmission" available VPITransmissionMaker was used and modified by adding components AmpSysEl and SetOSNR that model respectively an electric amplifier and fixing the optical signal to noise ratio. Galaxies LAME_Tx-mQAM and LAME_Rx-mQAM are electrical mQAM transmitters and receivers modified from reference galaxies Tx_El_mQAM and Rx_El_mQAM_BER. The example of the galaxy LAME_Tx-mQAM is illustrated as follows:

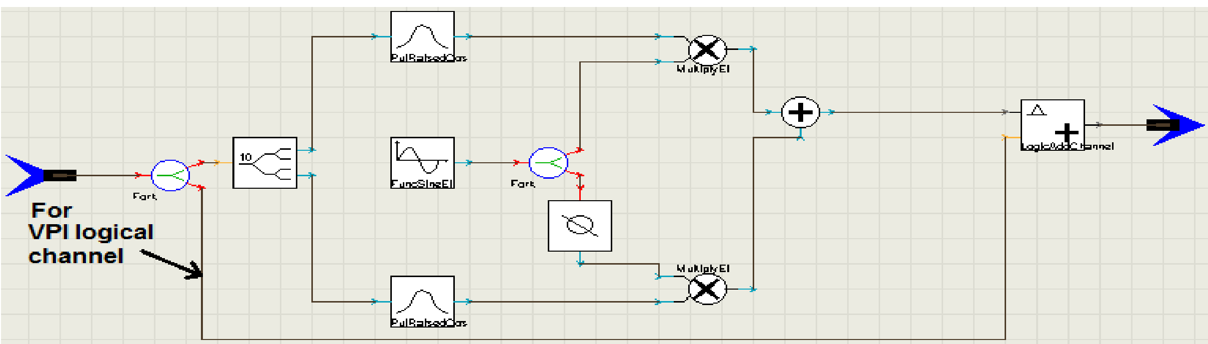


Figure 3: Architecture of the galaxy LAME_Tx-mQAM

In this architecture, we have, from the galaxy Tx_El_mQAM, deleted PRBS module whose function is carried out by Matlab treatment of the galaxy LAME_ Seq.Gen., And kept the transmission link of binary data for the logical channel of VPI, in order to compare the estimation of the BER of the transmission channel by two different approaches: one through the module BER_El-mQAM of VPI, and the other by the Matlab treatment in module LAME_Decoder. In case of 16QAM modulation, we receive the following constellation:

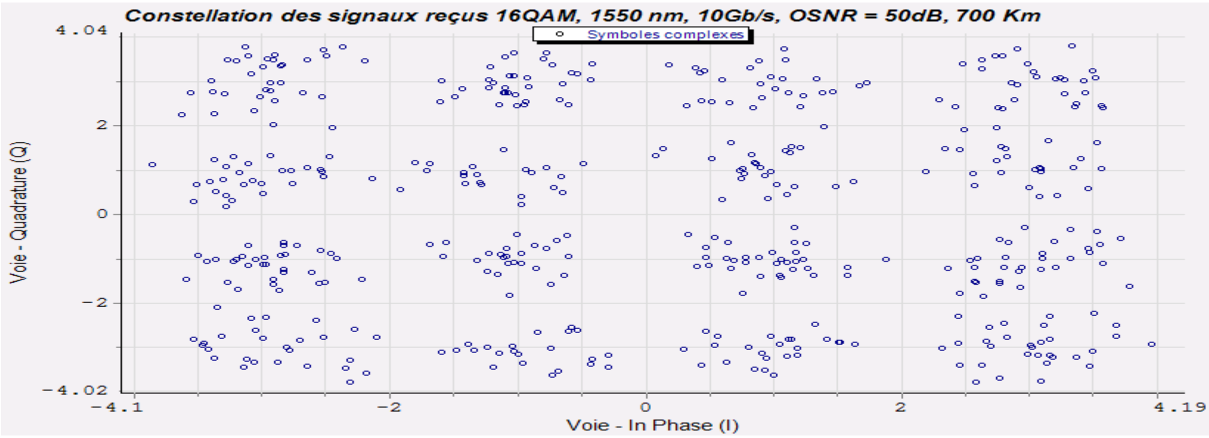
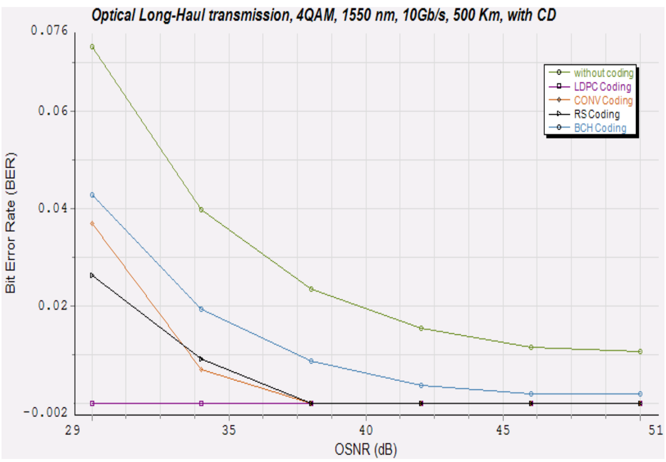


Figure 4: 16QAM received constellation, 1550nm, 10Gbps, OSNR = 50dB

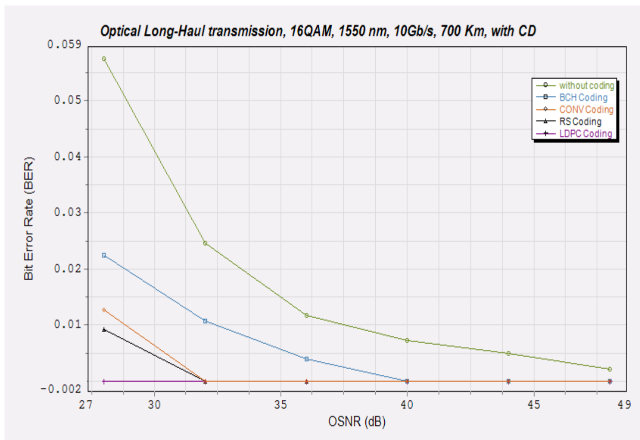
The results allow comparing the bit error rate (BER) of the mQAM transmission chain transmitted without channel coding and with channel coding, depending on the OSNR. Similarly we compare the bit error rate of different encoders based on the distance of the optical link.

A. BER as a function of the OSNR with 4QAM, 16QAM, 64QAM et256QAM modulations.

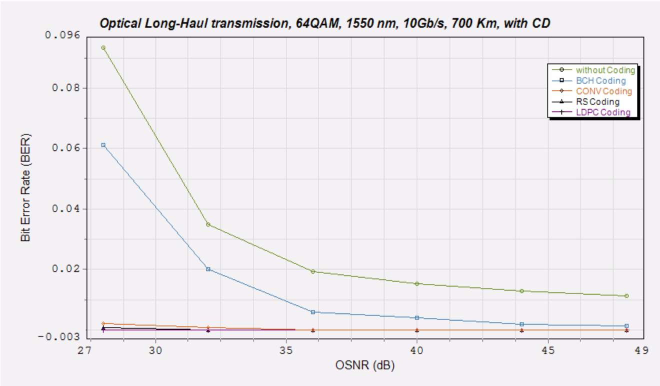
The curves of the BER of the used error codes with 4QAM, 16QAM, 64QAM and 256QAM modulations show improvement by encoding in reducing the BER compared to the curve of BER without coding. The following diagrams show the effectiveness of error correcting codes in their ability to reduce the bit error rate compared to the transmission without encoding.



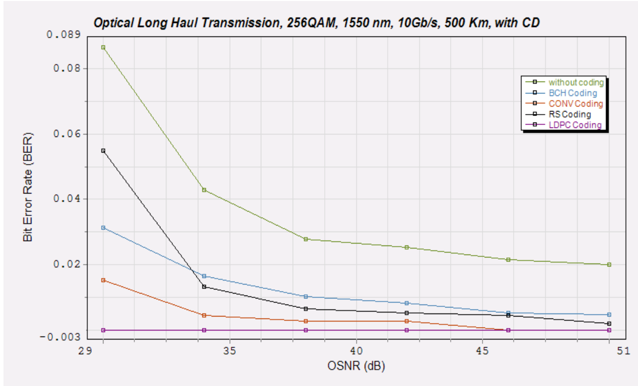
a)



b)



c).

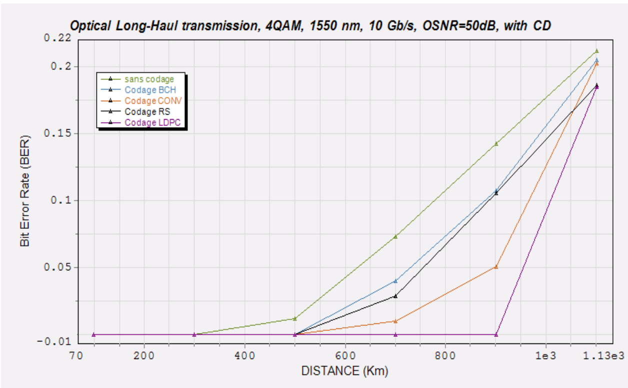


d)

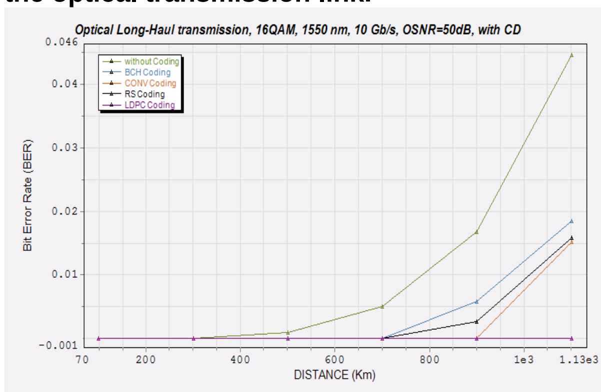
Figure 5: BER of error correcting codes based on OSNR: a) 4QAM modulation; b) 16QAM modulation; c) 64QAM modulation; d) 256QAM modulation.

We find that the different curves of BER of coders have a similar appearance when the modulation changes. The results demonstrate both the effectiveness of the channel coding to combat the effects of imperfections in the optical transmission channel. LDPC codes are particularly effective because they allow having almost zero BER under the conditions defined for testing.

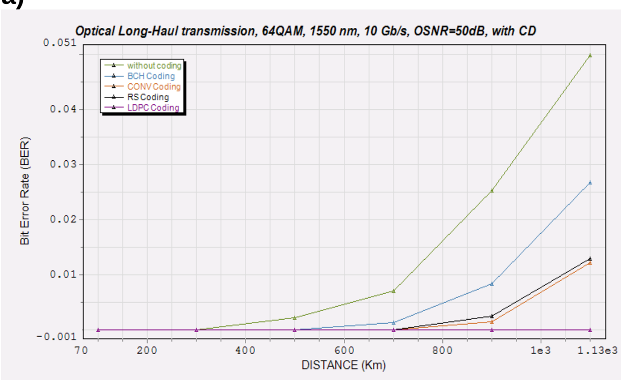
B. BER as a function of the distance of the optical transmission link.



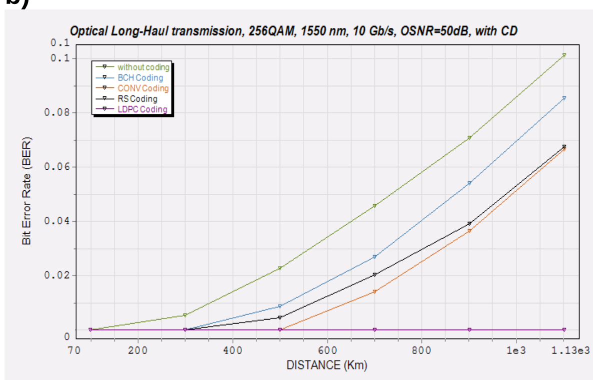
a)



b)



c).



d)

Figure 6: BER of error correcting codes based on the distance: a) 4QAM modulation; b) 16QAM modulation; c) 64QAM modulation; d) 256QAM modulation.

Simulation results of BER curves as a function of distance are shown in the figures above that show the effect of distance on the BER as a function of modulation 4QAM, 16QAM and 64QAM. The greater the distance increases, the more we increase the transmission errors. Coding can therefore increase the maximum transmission distance for a given modulation. This also confirms the coding efficiency in reducing the effects of the imperfections of the optical channel.

VI. CONCLUSION

The simulations show that the error-correcting codes used are effective in reducing the BER and correcting transmission errors of the optical channel and combat imperfections arising from the use of optical fiber, optical amplifiers, and other components of the transmission chain. The simulation of the bit error rate as a function of the distance shows that with a suitable channel coding, we can maximize the maximum distance of transmission.

In the case of the simulated BER as a function of OSNR, the results show the superiority of LDPC codes compared with other error-correcting codes studied and thus allows them as an ideal channel coding solution suitable for optical transmission channels. This proves that they can be considered as a new generation of advanced encoding solutions for high-bandwidth applications in photonic networks.

On the other hand, to improve the effectiveness of error correcting codes, such solutions as the interleaving of the binary information and the concatenation of codes allows increasing significantly the efficiency of the encoders whose performance can approach the Shannon's theoretical limit. It should be a compromise between the complexity of the architecture to implement and the efficient channel coding technique used.

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