The Applications of Digital Signal Processing Techniques for Enhancing the Performance of High Speed Optical Communication Systems

Sandy Montajab Hazzouri

Faculty of Informatics Engineering , Albaath University, Syria

Email: Samonhaco1994@gmail.com

Abstract

This paper presents Improving performance of 112 Gbit/s optical coherent communications systems using digital signal processing techniques to compensate linear impairments that are exposed to the signal during its propagation in optical fiber. In this paper, different multi-level modulation formats (DP-QPSK, DP 8PSK, DP- 16PSK and DP-16-QAM) were compared for the same data rate at different distances from the transmitter without amplification. the comparison was done by measuring bit error rate value. We used digital signal processing techniques for linear effects compensation. Where chromatic dispersion was compensated using a simple digital filter, and Polarization mod dispersion was realized by applying the constant-modulus algorithm (CMA). The phase and frequency mismatch between the transmitter and the local oscillator in the receiver was compensated using the modified Viterbi-Viterbi algorithm. We used the Optical simulator Opti-system , which was linked with MATLAB R2011 in order to implementation DSP algorithms and analyze obtained results.

Keywords: Communication system; mathematical model; optical; high-speed

1. Introduction:

During its propagation within the fiber, the optical signal suffers from several disadvantages, including losses resulting from the absorption of the fiber-forming material, scattering, and waveguide defects [10] [13]. Optical amplifiers can be used in order to compensate for these losses. Another drawback that significantly limits the width of the bandwidths used for transmitting optical signals is dispersion. We can distinguish two types of dispersion, the first: chromatic dispersion chromatic dispersion and the second: polarization mode polarization mode dispersion.

Dispersion the cause of chromatic dispersion is due to the fact that the fiber refractive index is dependent on the signal frequency, and the optical signal contains different frequencies transmitted at different speeds and reaches at different times to the receiver, while PMD is attributed to different polarizations of light traveling at different speeds, which leads to random propagation of light pulses. Scattering results in interference between the inter-symbol interference symbols due to the expansion of the pulses in such a way that one symbol overlaps the subsequent ones, and therefore an error occurs in the decision made by the receiver circuit.

Working with high speeds of signal transmission rates within optical systems has led to the need to monitor and compensate the signal correctly in order to minimize errors as much as possible. Chromatic dispersion can be compensated both in the light field and by modulators in the electronic field. Compensation within the optical field is usually carried out by using dispersion Compensation fiber DCF, or other optical compensators. Although these compensators are important to reduce system errors, they suffer from several disadvantages such as: large power loss, high cost, in addition to their large size[1]

Doi: https://doi.org/10.54216/GJMSA.080202
Received: April 05, 2023 Revised: July 02, 2023 Accepted: October 01, 2023

Previous studies have elucidated the idea of coherent detection used in the receiver with the presence of the use of signal processing techniques for DP-QPSK and DP-16-QAM modulation formulas, as well as the study of dispersion compensation using DSP using optical fiber for a data rate of 100 Gbit/s. [9] [8]

In this research, the compensation of linear effects such as color dispersion, polarization pattern dispersion and phase noise was studied using digital signal processing DSP digital signal processing techniques for several multi-level modulation formats that can be used with coherent detection for a data rate of 112 Gbit/s without using any amplifying elements, and we compared their performance based on measuring the bit error rate. DSP technology reduces the need for bulky, expensive, high-loss components and provides adaptive filtration methods with high functionality, easier applicability [10] .

2. the purpose of the research:

This research aims to improve the performance of coherent optical communication systems by compensating for scattering using digital signal processing. A system with a data transmission rate of up to 112 Gbit/s was tested using different modification formulas DP-QPSK) and DP-8PSKO DP-16PSKO DP-16-QAM) without using any amplifying elements, studying the performance of this system at different distances and analyzing the results derived from this study.

3. materials and methods of research:

This research begins with a reference study on coherent detection and DSP digital signal processing methods within the optical domain, as well as the study of multi-level modulation formulas that can be used in coherent optical communication systems. In the practical study, we relied on the optisystem program, a specialized program for simulating optical communication systems with high reliability and accredited by major telecommunications companies in the world, which was linked with the MATLAB R2011a program to implement DSP algorithms and analyze the results resulting from that study.

coherent detection: 3-1-

The signal can be detected within optical systems using two methods, namely: direct detection or coherent detection. Within the direct detection, the light intensity is converted into an electrical signal using the photodetector, and within this method, the entire phase information is lost, Figure (1) shows the concept of direct detection.

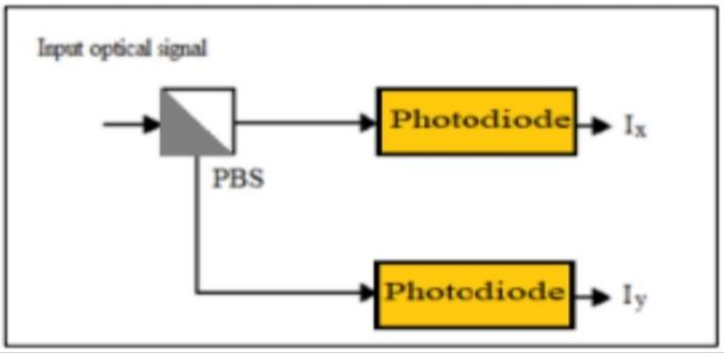

Figure 1: the concept of direct detection[7]

The second type: it is coherent detection, and it is considered the most advanced detection method because it enables the receiver to recover the full electric field, which contains both amplitude and phase information. This type is suitable for detection using any level of advanced digital modulation formats. Coherent detection requires precise polarization synchronization between the received signal and the local oscillator Local oscillator LO which acts as a phase reference [2]

Coherent detection appeared as early as 1979, but it was not used in commercial systems as it causes additional complexity because it tracks the phase and polarization of the incoming signal

The coherent digital receiver was able to reduce the limitations that hinder the performance of optical transmission systems, such as chromatic dispersion, PMD polarization pattern dispersion, and others using digital signal processing techniques by linear and adaptive digital filters resulting in a significant reduction in complexity[12] [5]

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Figure (2) shows the concept of coherent reception, which is used to decode the modulation of the modulated optical signal using one of the multi-level modulation formulas. The optical signal passes through the polarization beam splitter PBSAND is separated into two perpendicular polarized paths of optical signals, which then enter into two 90-degree 90o mixers to be mixed with the signal of the local oscillator

The light generated by the modulator is passed on balanced photodiode photodetectors to obtain continuous signals, these signals enter through the analog to digital converter ADC high-speed sample quantizer in order to convert them into digital signals, and the data is restored in the digital signal processor [16] [8]

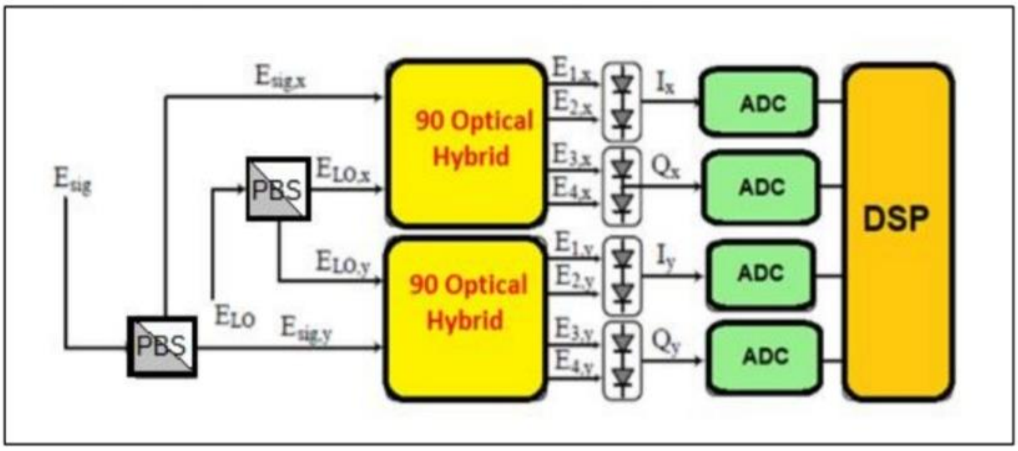

Figure 2: the concept of coherent reception [8]

data modulation in coherent optical communication systems: 3-2-

Within modern communication systems, information is stored and transmitted as digital data represented by selected symbols from a limited Alphabet. Digital data is modified by associating each value with a specific reference signal.

3-3-PSK phase shift adjustment:

Phase shift keying modulation stores information within the phase of the transmitted signal, and one of the most important advantages offered by this mode is the high tolerance of noise at the receiver and a greater tolerance of dispersion compared to On-off keying oak, but this tolerance decreases with increasing the level of modulation [10]

In the case of carrier modulation using more than one bit of the input signal we obtain a multi-level Phase Shift modulation M-PSK since M represents the number of levels .M=2m represents the number of bits used to encode each sample of the input signal.

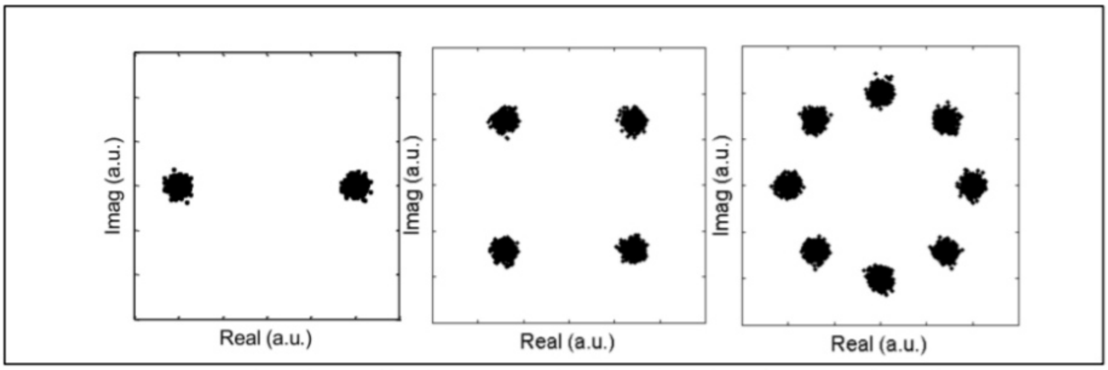

Figure 3: group diagram for BPSK (right), QPSK(Center), 8PSK (left) [6]

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3-2-2-orthogonal QAM amplitude modulation:

Orthogonal amplitude modulation Quadrature Amplitude Modulation is characterized by the possibility for the amplitude to take more than one value, as well as for the phase allowing to obtain the largest number of available levels or values. [6]

Considering the number of available capacitance values K and the number of available phase values KP, the number of available levels:

M = KA × KP

)This requires the number of Bits: N = Log2M = Log2 (KA × KP

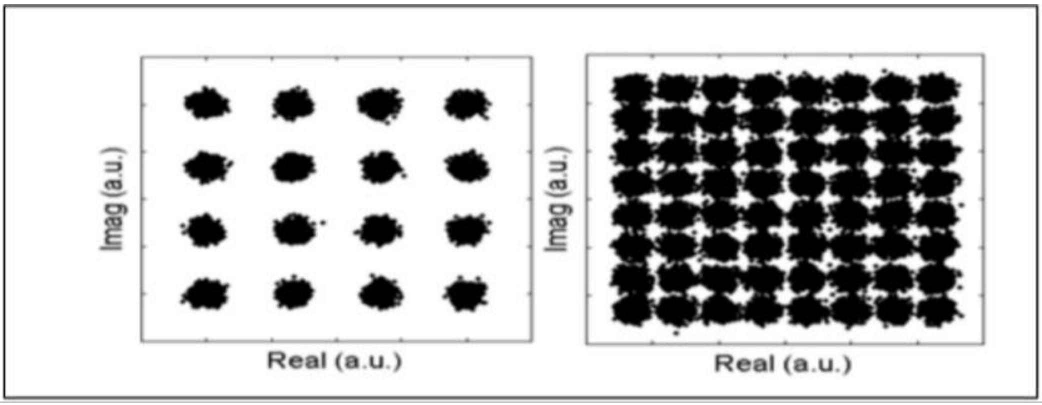

Figure 4: group diagram for 64QAM(right), 16QAM(left) [6]

3-3-digital signal processing with the help of coherent detection:

Signal transmission at high rates over long distances is one of the most important goals of optical network designers, therefore DSP digital signal processing is used from the receiver to eliminate the need for dynamic polarization control and also to effectively compensate for chromatic dispersion LONCD, polarization pattern dispersationpmd, phase noise PN and nonlinear effects in the electronic field.

The dynamic nature of some limitations such as PMD requires that the compensator be adaptive, but this adaptation is not easily achieved in the light field due to the low flexibility of the components.

Adaptation is important in order to track down variable PMD States and can be easily implemented depending on digital signal processing techniques using adaptive algorithms such as the constant modulus Algorithm CMA [3]

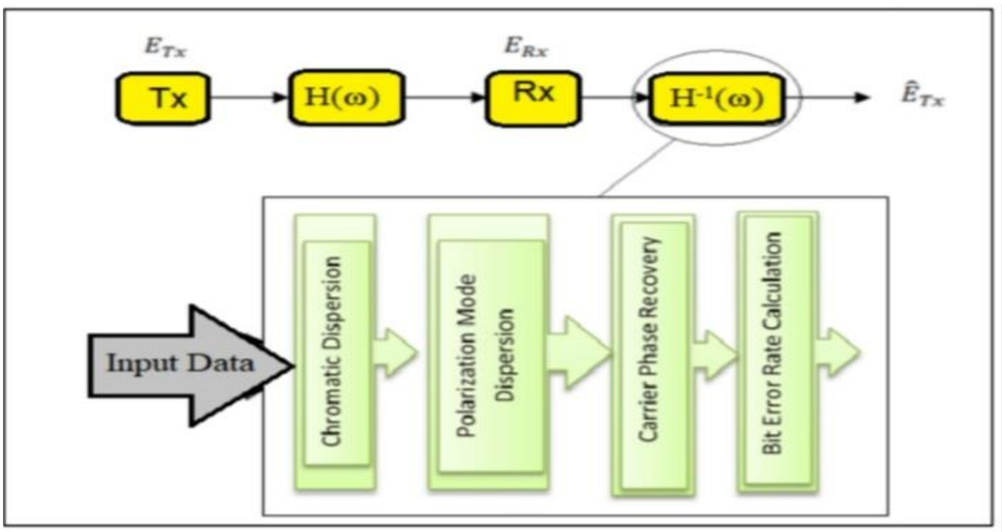

Figure 5: transmission system with DSP component [11]

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The optical transmission system can be represented as shown in Figure (5) where ETXIS the transmitted signal, H (ω) is the channel transmission follower and ERX is the received signal. The goal of DSP is to implement H-1(ω) which can be interpreted as a combination of linear effects affecting the signal during propagation, and an estimate of ERX which represents the processed signal. In order to compensate for all these effects, the samples of the received electrical signal are separated by a series of algorithms with the aim of reducing the ber bit error rate, which is the main evaluation criterion of the quality of the digital communication system [11]

3-4-channel impedance compensation:

The four signals enter the DSP component and are transmitted to the digital domain for processing, after that the color dispersion is compensated using a simple digital filter, then the adapted PMD is compensated by applying the CMA algorithm and the phase and frequency mismatch between the transmitter and the local oscillator LO is compensated using the modified Viterbi - Viterbi phase estimation algorithm.

3-4-1-color dispersion compensation:

Color dispersion is one of the main factors causing the decline in the performance of optical communication systems. Neglecting nonlinear effects, an optical fiber can be treated as a filter with the following transmission continuation [14]

$$G(z,\omega) = exp(-j\frac{D\lambda^2 z}{4\pi c}\,\omega^2) \qquad (1)$$

Where:

z: transmission distance,: ω angular frequency,: J imaginary unit,: λ channel wavelength,: C speed of light, D = Do + S x (λ – λo): fiber dispersion coefficient for wavelengths,: dispersion slope,: λo reference wavelength [9]

Since the amount of optical fiber dispersion is basically a constant value, a Firth constant filter can be used to compensate for CD color dispersion.

3-4-2-dispersion compensation of the polarization pattern PMD:

This type of dispersion occurs as a result of the non-ideal cylindrical fabrication of the fiber cores and this produces different patterns with polar compounds perpendicular to the basic fiber pattern. If there are two poles of the basic pattern at the input, there will be a difference in the distance between them, because the propagation speed of each pole is different from the other and polar dispersion results.

The dispersion produced by PMD changes rapidly compared to the constant-value color dispersion, so an adaptive equalizer must be used to compensate for PMD. So that the adaptive equalizer can dynamically change according to the characteristics of the channel to adjust the coefficients of the digital filter. Polarization-dependent effects that affect the transmitted signal can be expressed by the Jones matrix shown by the relation [9]

$$J = \begin{pmatrix} \cos\theta e^{j\frac{\pi}{2}} & -\sin\theta e^{-j\frac{\pi}{2}} \\ \sin\theta e^{j\frac{\pi}{2}} & \cos\theta e^{-j\frac{\pi}{2}} \end{pmatrix} \qquad (2)$$

To compensate for the polarization rotation and PMD, a block box of 4 FIR filters designed based on the inverse of the Jones Matrix organized in a butterfly structure can be used [12]. The inverse of the Jones matrix is given by the relation:

$$J^{-1} = \begin{pmatrix} h_{xx} & h_{xy} \\ h_{yx} & h_{yy} \end{pmatrix} \qquad (3)$$

hyy ،h_{yx} ،h_{xy} ،h_{xx} :Such as the four digital filters used to balance the polarization angle and phase delay. The FIR filter is selected with three weights, the initial values are

$h_{xx} = (\ldots 010 \ldots)$
$h_{yx} = (\ldots 000 \ldots)$
$h_{xy} = (\ldots 000 \ldots)$
$h_{yy} = (\ldots 010 \ldots)$

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When finding the inverse of the MatrixJ^{-1}, You can use the constant coefficient algorithm CMA to compensate .PMD Figure (6) shows the box diagram of the CMA algorithm [4]

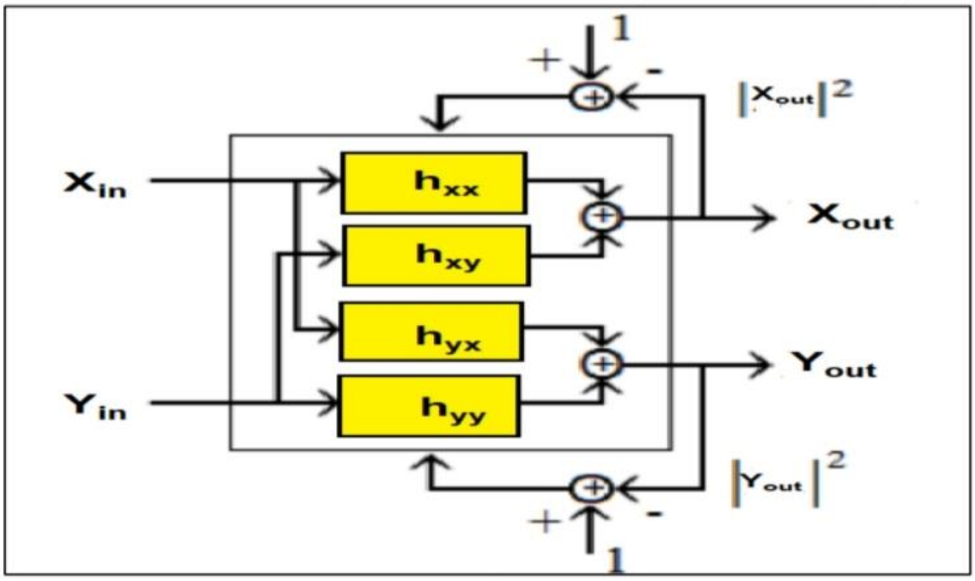

Figure 6: the box diagram of the CMA algorithm. [4]

CMA is a type of blind modified algorithm used to update the coefficients of the FIR filter weights, in order to minimize the value of the output dependent error. The $X_{in}$and Y_{in} inputs are consideredpolarized biased signals. And the output signals are two orthogonally polarized X_{out} signals . $Y_{out}$are represented by the relations:

$$X_{out} = h_{xx} \otimes X_{in} + h_{xy} \otimes Y_{in} \quad (4)$$
$$Y_{out} = h_{yx} \otimes X_{in} + h_{yy} \otimes Y_{in} \quad (5)$$

$\otimes$Represent folding processes in the time domain. And we call the filter the final Impulse response FIR butterfly filter.

3-4-3-carrier phase estimation CPE Carrier Phase Estimation

The phase lock circuit can be replaced by phase estimation in the digital field by .DSPAT this stage, the Phase Shift and frequency are compensated between the local oscillator and the received signal. And the most widespread way to achieve this end is an algorithm .[15] Viterbi–Viterbi the scheme of the algorithm is shown in Figure (7)

The QPSK signal can be present dreceived by equation (6)

$$E(t) = A\exp\{j[\theta s(t) + \theta c(t)]\} \quad (6)$$

Where:

θc: carrier adjustment phase information.

θs: phase difference.

The power m algorithm is the most widely used algorithm for phase estimation for the QPSK modulation formula and we use this algorithm to estimate the phase of the QPSK signal in the Digital Domain.

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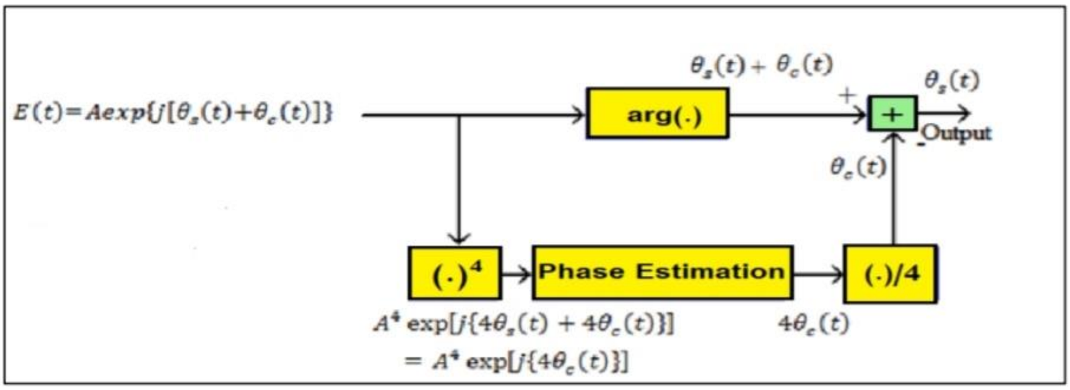

Figure 7: the box diagram of the Viterbi–Viterbi algorithm. [6]

4. results and discussion:

4-1-simulation model

Figure (8) shows the general scheme of the considered model, which represents a coherent optical communication system at a rate of 112 Gbit/s using various multi-level modulation formats and based on digital signal processing technology.

We modulated the signal using multi-level modulation formulas, we divided the system into five main parts: the transmitter, the transmission link which is single-mode optical fiber SMF, the coherent receiver, the Digital Signal Processing Unit, the modulation and detection decoder, and the bitلدا-ror Rate BER counter to estimate the bit error rate.

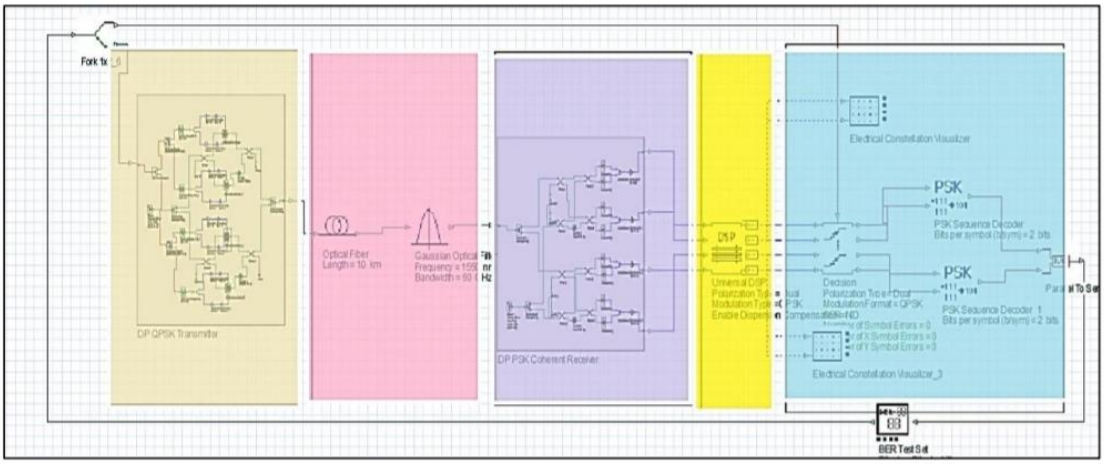

Figure 8: the general scheme of the considered model

4-1-1-DP-QPSK optical transmitter:

The dual-polarization Quadrature phase shift keying DP-QPSK optical transmitter divides a continuous light beam by a polarization beam splitter PBS polarization beam splitter into two orthogonal light beams of equal power. Then the two resulting beams are fed to the IQ modulator to be adjusted and at the output of the modulator we get two orthogonal polarized modulated signals that are combined into a uniform beam through the polarization Beam combiner PBC polarization beam collector Figure (9) shows the mechanism of action.

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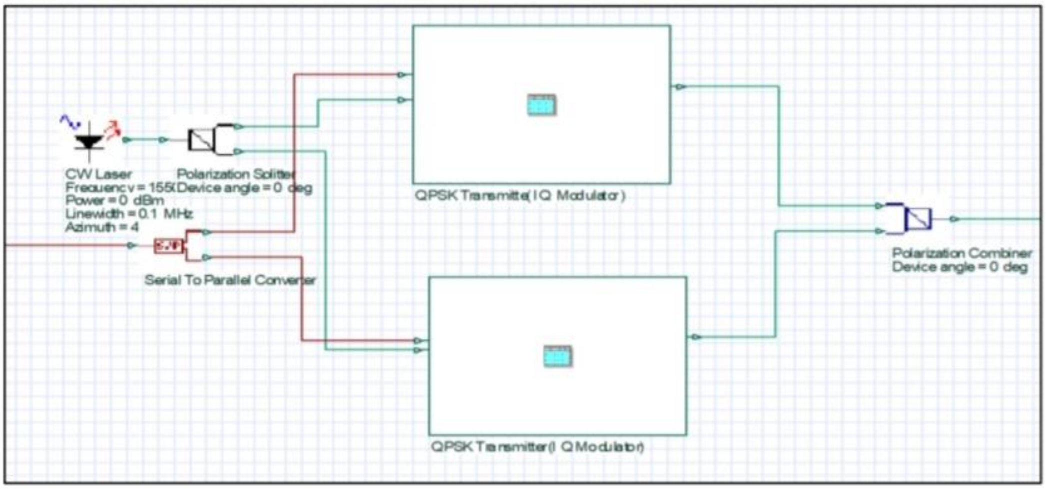

Figure 9: DP-QPSK optical transmitter

Table (1) shows the parameters of the CW laser used in the simulation, where the frequency value of 1550 nm was selected in accordance with the lowest damping of wave propagation within the fiber, as well as the energy value of 0 dBm was determined to prevent the appearance of nonlinear effects, and the laser line width of 0.1 MHz was chosen in order to study the effect of light scattering.

Table 1: CW laser parameters

The limiter	1550 nmc
Frequency	1550 nm
Energy	0 dBm
Line width	0.1 MHz

Figure (19) shows the QPSK modifier that starts with the PSK string generator, generating two parallel m-ary code strings of binary signals depending on the PSK phase shift modulation, using 2 bits to represent each code. After that, the signals pass through an M-ary pulse generator to generate multi-level pulses according to the input-ary signal matrix, then each signal is modulated by the Mach-Zehnder modulator and the two signals are combined together to form a QPSK signal.

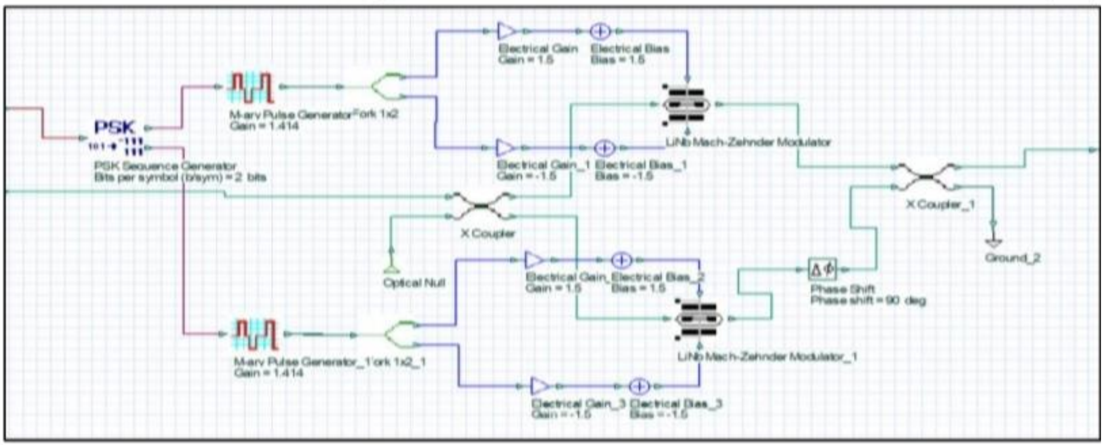

Figure 10: QPSK rate

Doi: https://doi.org/10.54216/GJMSA.080202
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4-1-2-optical communication channel:

The signal is transmitted in the optical fiber channel and is a single-mode SMF fiber, which has a span that varies from 10 to 100km. Table (2) shows the simulation parameters of the optical fiber channel. In this model, the attenuation of the SMF fiber is not compensated using Theخمbium Doped Fiber Amplifier EDFA amplifier .

Table 2: optical fiber parameters.

The limiter	Value
Length [km]	Variant
Constant attenuation∝	0.2 Db/km
Dispersion coefficient D	16.75 ps/(nm.km)
Regression coefficient S	0.075 ps/(km.nm2)
PMD coefficient	0.004 ps/√km

3-1-4-DP-QPSK photodetector receiver

The coherent photoreceptor includes a local laser oscillator lop-polarized at 45 degrees associated with a polarization beam splitter. The modulation of the received signal is decoded using two QPSK receiversdeparated polarization. Figure (11) represents a coherent photoreceptor

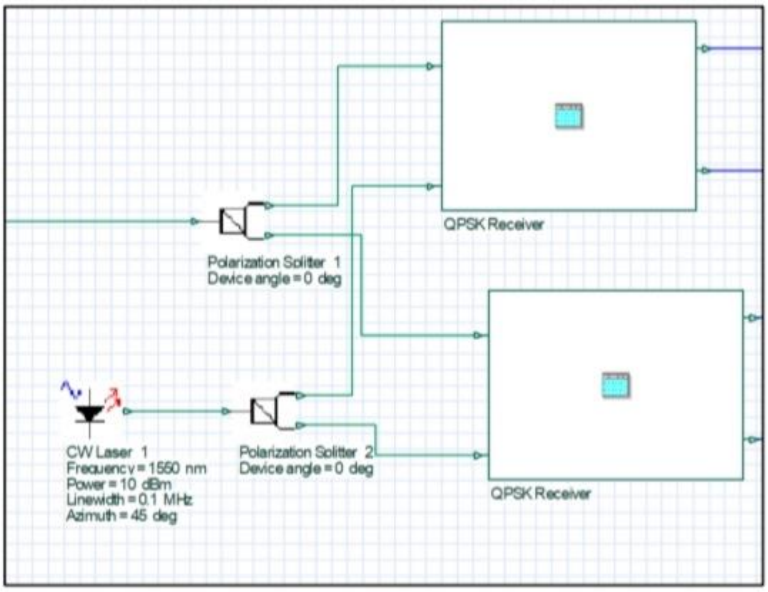

Figure 11: DP-QPSK optical coherent receiver

4-1-4-digital signal processing component:

The signals coming out of the optical coherent DP-QPSK receiver are fed to the DSP component in order to compensate for transmission impedances in the Digital Domain, this helps in recovering the incoming signal after coherent detection as explained earlier.

4-1-5-detector and decoder:

The signal reaches the decision component where it processes the in-phase I and quadrature Q sections of the received electrical signal coming from the DSP phase, normalizes the electrical demands of each I and Q channel to its m - PSK network and gives a decision on each receiving code based on the measured threshold settings. The decoder then decodes the two parallel m-ary code strings into binary signals. Which, in turn, is sent to the Berl test groupto detect errors as shown in Figure (12)

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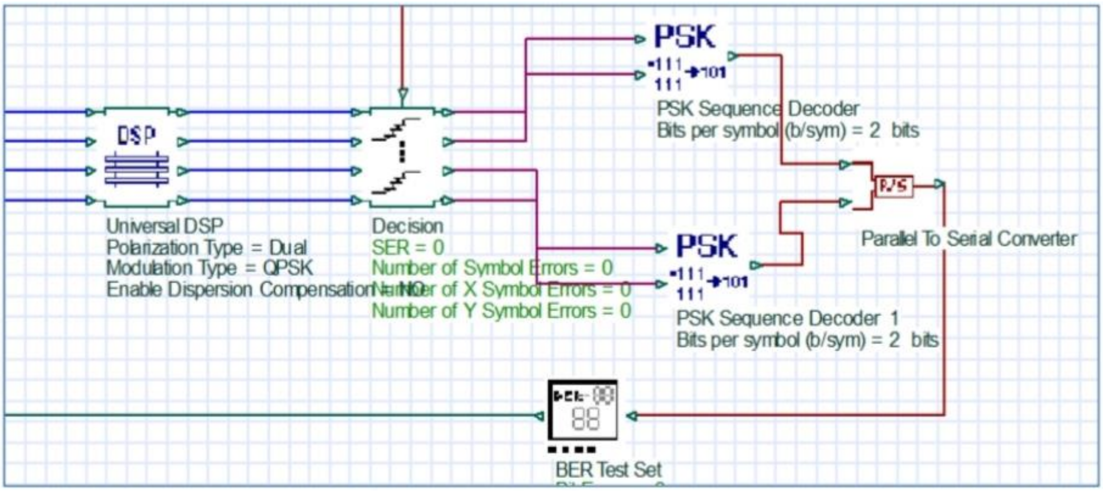

Figure 12: detection and decoding after DPS

4-2-better modulation formula suitable for coherent detection:

The model was tested for different values of the optical fiber length and using different multi-level modulation formulas to modulate the transmitted optical signal. Assuming that the length of the bit string generated by the random Bit Generator is 65536 bits, Table (3) shows the appropriate code rate for each of the modification formulas used.

Table 3: the appropriate code rate for each of the modification formulas used

Modification formula	Data rate	Code rate
DP-QPSK	112 Gbit/s	28e+009 Symbols/s
DP-8PSK	112 Gbit/s	18.6e+009 Symbols/s
DP-16PSK	112 Gbit/s	14e+009 Symbols/s
DP-16QAM	112 Gbit/s	14e+009 Symbols/s

Figure 13 shows the bit error rate at different distances for the modulation formulas used

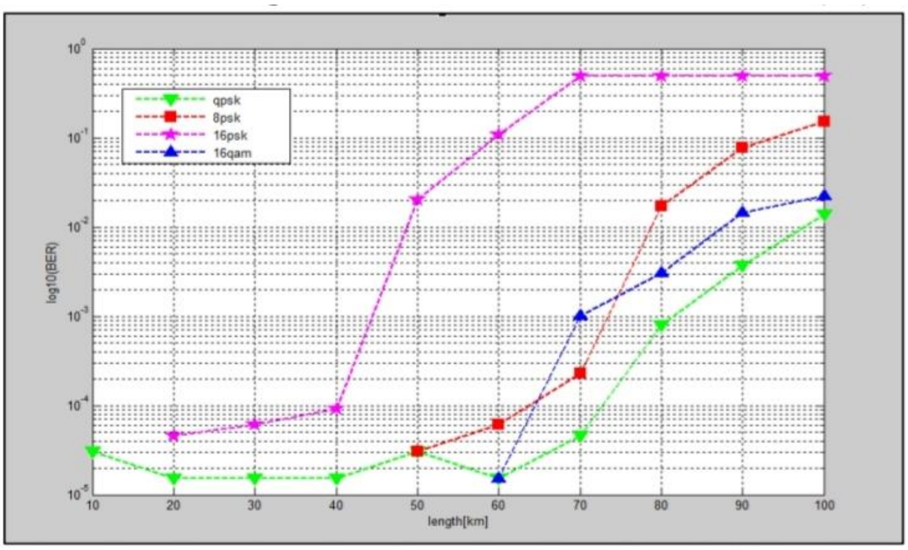

Figure 13: bit error rate for different multi-level adjustment formulas

We conclude from this scheme that the modified system using the DP-QPSK modification formula achieves the best bcompared with other systems and is able to reach a distance of 80 km with high transmission quality. Comparing the ratio of the received optical signal to noise Optical signal to noise ratio OSNR with the

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transmission distance shown in Figure (14), we also find that the DP-QPSK modulation formula provides a High received signal quality compared to other systems.

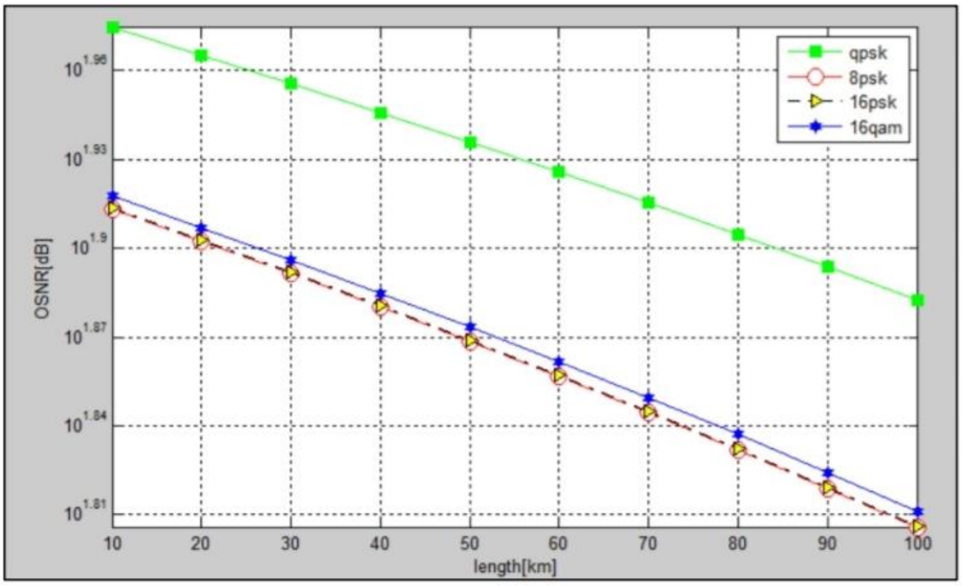

Figure 14: the ratio of the received optical signal to the noise.

-4-3compensation of linear transmission impedances using DSP in a coherent 112 Gbit/s optical system using the DP-QPSK modulation formula

From the previous study it was shown that DP-QPSK is the most convenient modulation formula for use with coherent detection technology. We analyzed the performance of the digital processing unit used to compensate for scattering in a coherent optical system at a rate of 112 Gbit/s.it will use the DP-QPSK modulation formula assuming that the length of the bit string generated by the random Bit Generator is 65536 bits.

In the DSP unit the linear impedances to which the signal is subjected during its passage in the optical fiber are compensated. The color dispersion was compensated by using a simple digital filter, the polarization pattern dispersion was compensated by applying the constant coefficient CMA algorithm, while the phase and frequency mismatch between the transmitter and the receiver used oscillator is compensated by using the modified Viterbi–Viterbi phase estimation algorithm. The system schema selectors are set as follows:

Table 3: parameters representing the parameters of the system used.

The limiter	value
Propagation distance	80 km
Code rate	28E009 Symbols/s
Dispersion coefficient D	16.75 ps/(nm.km)
Regression coefficient S	0.075 ps/(km.nm2)
PMD coefficient	0.004 ps/√km
Wave length	1550 nm
Number of symbols	Chain length/4
The number of samples in the code	2

The rank of the FIR filter, used in order to compensate for color dispersion, is .191, while the rank of the FIR filter in order to compensate for the dispersion of the polarization pattern is 13, with the step size of the CMA algorithm equal to0.003.

Figure (15) shows the diagram of the electrical group before and after compensation of each phase of linear impedances

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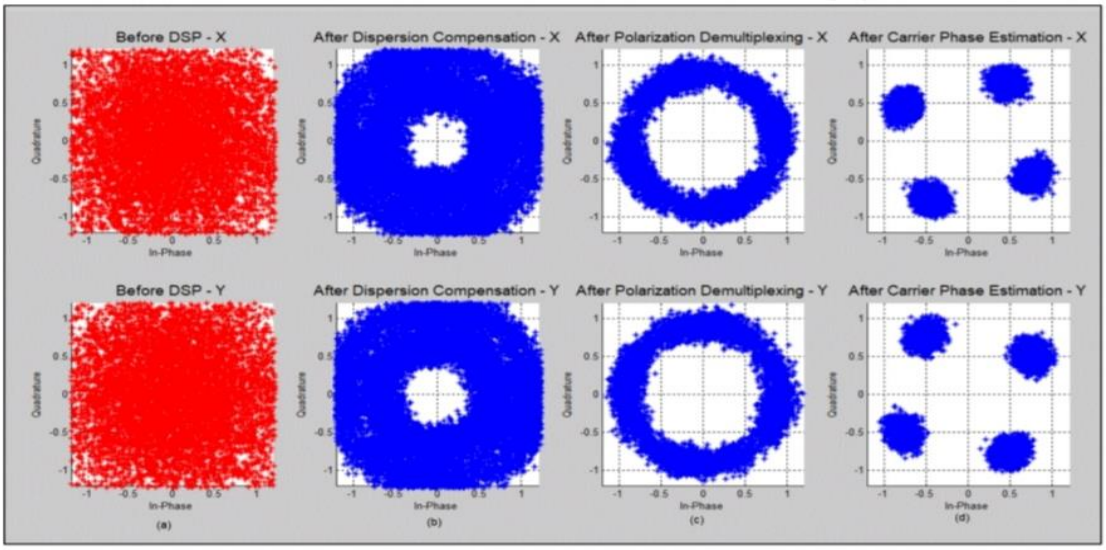

Figure 15: Group diagram (a) group diagram before using.DSP (b) group diagram after color dispersion compensation. (c) Group scheme after dispersion compensation pattern

Polarization. (d) group diagram after carrier phase estimation

The results from Figure (15-a) indicate that the distribution of the phase of the signal, or its length, is decentralized. In addition, there is high dispersion and phase noise. Thus, we cannot extract the signal information directly. Figure (15-b) shows the scheme of the set after color dispersion compensation, where the sampling point becomes unevenly distributed on the perimeter of the circular ring, as well as the density of sampling points is large due to the phase difference of the sampling point for each sample. As Figure (15-c) shows, the overall distribution becomes more concentrated, but the presence of a large Phase Noise will lead to the distribution of points around the center in the group diagram. Whereas in Figure (15-d) the distribution of each point is more concentrated and further from the boundary, and the noise is significantly reduced.

5. conclusions and recommendations:

During this research, we compared different multi-level dipole modulation formulas (DP-QPSK, DP-8PSK, DP-16PSK, DP-16-QAM) and selected the optimal formula for coherent optical communication systems based on determining the bit error rate and the maximum propagation distance that the signal can travel with high quality, and we can summarize our conclusions as follows:

∗The DP-QPSK modulation formula is the best modulation formula that can be used with coherent optical communication systems as it achieves the best value of the bit error rate and the farthest possible distance of about 80 km without using any amplifying elements along the optical link path.

∗Digital signal processing helps to compensate linear impedances such as chromatic dispersion, polarization pattern dispersion and phase noise well without the need to use rectifiers with large cost and high loss.

∗Linear impedance compensation using DSP in coherent optical system achieved transmission at high rates up to 112 Gbit / s

∗Digital signal processing techniques can be used to compensate for the nonlinear effects that the signal may experience when propagated within the fiber.

∗The performance of a coherent optical communication system can be studied using the DP-QPSK modulation formula for different transmission rates and compare their performance.

References

[1] Devra, S; Kaur, G. 2011, *Dispersion Compensation using Raised Cosine Filter in optical fibers*. International Journal of Information and Electronics Engineering. Vol. 1, No. 1, 47.

Doi: https://doi.org/10.54216/GJMSA.080202
Received: April 05, 2023 Revised: July 02, 2023 Accepted: October 01, 2023

[2] Ip, E. 2009, *Coherent detection and digital signal processing for fiber optic communications*. Stanford University, California, 55-56.
[3] Sewter, J. 2005, *Electronic equalization of polarization-mode dispersion in 40- GB/S optical systems.* Electrical and Computer Engineering, University of Toronto. MSc. Thesis, 489.
[4] Kikuchi, K. 2008, *Polarization-demultiplexing algorithm in the digital coherent receiver*. In IEEE/LEOS Summer Topical Meetings, IEEE,101-102.
[5] Kikuchi, K.2016, *Fundamentals of coherent optical fiber communications.* Journal of Lightwave Technology, Vol. 34, No. 1, 157-179.
[6] Millar, D. S. 2011. *Digital signal processing for coherent optical fibre communications* . University College London UCL. Ph.D Thesis, 29-30.
[7] Mussolin, M. 2010, *Digital Signal Processing Algorithms for High-Speed Coherent Transmission in Optical Fibers*. M Sc. Thesis, Telecommunications Engineering, Padova University, Italy

Doi: https://doi.org/10.54216/GJMSA.080202
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