Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

M-Dimensional Modulation Techniques in Fiber Optics Communication Systems with Effect on Nonlinear Phase Noise (NPN): A review

Mahdi S.[1], Jassim K.[1], Ghufran Mahdi Hatem[2]

[1] University of Technology, Laser and Optoelectronics Engineering Department, Baghdad, Iraq
mahdisaheb.ms.ms@gmail.com
jassim.k.hmood@uotechnology.edu.iq
[2] University of Al-Furat Al-Awsat Technical, Communication Technical Engineering Department, Najaf, Iraq
coj.ghf@atu.edu.iq

Corresponding author: mahdisaheb.ms.ms@gmail.com

https://doi.org/10.46649/fjiece.v4.1.8a.25.3.2025

Abstract. *The degradation of signal quality in optical fiber communication (OFC) systems due to nonlinear phase noise (NPN) and the need for effective multi-dimensional modulation techniques to mitigate this issue is presented in this article. Optical communication technologies have seen significant advancements in recent decades, meeting the escalating demands for bandwidth, Nevertheless, the efficiency of these systems is compromised by fiber nonlinearity employing multiple dimensions' techniques a crucial role in (OFC) systems to address the degradation of signals, also overcoming the effects the nonlinear phase noise (NPN) that produce from send signal to far distance. This article explores the concept of Nonlinear impairment, including its Kerr effects, Polarization mode dispersion (PMD), Amplification spontaneous by noise emission, and Attenuation. It also highlights the importance of multi-dimensional modulation techniques to protect the signal sent in optical fiber. This paper explored the impact of different categories of M-dimensions techniques on the signal that is sent via optical fiber and Detect the effectiveness of nonlinear phase noise (NPN) like Digital backpropagation (DBP), mid-link optical phase conjugation (ML-OPC) and other techniques, also there is A different effective strategy recognized as phase conjugated twin waves (PCTWs) Which contribute significantly to nullify NPN. The paper concludes by providing an overview of the discussed topics and their significance in the field of optical fiber communication(OFC)*

Keywords: *nonlinear phase noise (NPN); optical fiber communication(OFC); Polarization mode dispersion (PMD); Digital backpropagation (DBP)*

1. INTRODUCTION

The coming out of narrowband optical fiber sources, such as a laser, and a tangible transmission of the optical medium, like a low fiber loss, catalyzer a growing fascination with the development of the fiber optic transmission structure. An advancement of controlled tests and practical trials were conducted to explain the possible benefits of light wave schemes in comparison to coaxial schemes. The initiatory commercial implementation of a light wave system occurred in 1980, functioning at a data rate of 45 Mb/s. Afterward, cables of optical fiber spanning the Atlantic and Pacific Oceans were deployed, functioning at a peak data rate of 280 Mb/s [1, 2]. Optical fiber communications have remarkably backing to the transformation of global information distribution while maintaining system performance safety [3-6]. The escalating information capacities in recent decades have led to an augmented demand for transmission methods that support optical signal-to-noise ratio (OSNR) and optimize the complete efficiency of optical systems [6]. Researchers are dedicated to stumble on novel approaches to check and reinforce the physical properties of optical light in order to make it extra efficient transmission of data. [7]

Modern society exhibits an authentic reliance on broadband optical fiber communication (OFC) solutions toward a range of applications" encompassing high-speed Internet connectivity, the Internet of Things (IoT), data services and mobile sound, broadcasting multimedia systems, extensive network data for network computing, remote storage and e.g.". This dependence is due to the unique capabilities of optical fibers that proved to effectively satisfy the high demands for data transmission rates, reliability, and energy efficiency, while there is no other medium that can do that [8]. The pursuit for outstanding performance continues unabated, leading the capacity of individual fibers to be significantly strengthened.

However, a major obstacle faced in optical fiber communication systems is the susceptibility to fiber nonlinearity, which forced limitations on the maximum achievable transmission distance, also constraining the overall capacity of the system [9-13]. To solve these constraints on data capacity and maximum transmission distance within optical fibers, a multi of physical parameters can be utilized.

Specifically, five principal physical dimensions" time, wavelength, polarization, spatial considerations (incorporating multi-core fibers, linear polarization approaches, orbital-angular momentum, and modes of the vector), and quadrature (amplitude and phase)" can be employed for multiplexing and modulation, therefore improve the capability of optical fiber connections, as shown in (figure.1). It is recognizable that the simultaneous use a multiple dimension, referred as "multi-dimension", expresses a fundamental attribute of future optical communication systems. [14]

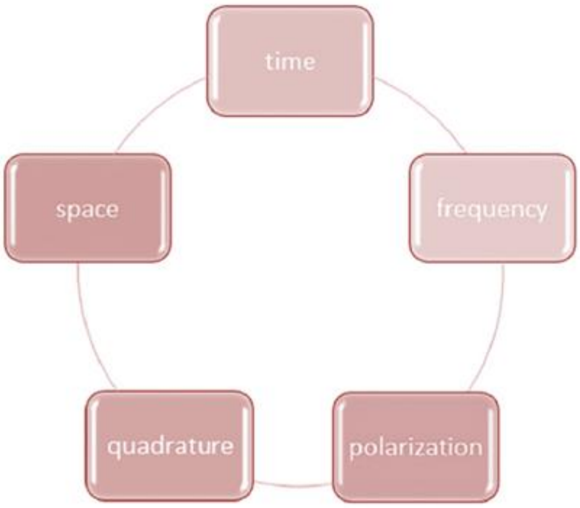


Fig. 1. Five physical parameters for capacity scaling in OFC system [14].

In the optical fiber connections field of long-distance, the Kerr nonlinearity effect appears as the major factor work to deteriorations that constrain the efficiency of optical communication frameworks. The primary guise of the Kerr nonlinearity effects is Self-Phase Modulation (SPM), wherever the field of an optical system faces a nonlinearity phase delay born as of itself. Conversely, Cross-Phase Modulation (XPM) involves the nonlinearity phase change of an optical system produced by the additional system with various wavelengths [15,16].

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

Continuing research attempts within the optical community focus on practical strategies to control escalating data volumes, with various suggestions already that will speak about it later. Several recent experimental achievements in capacity × distance in recent years, as illustrated in (Fig.2) [17].

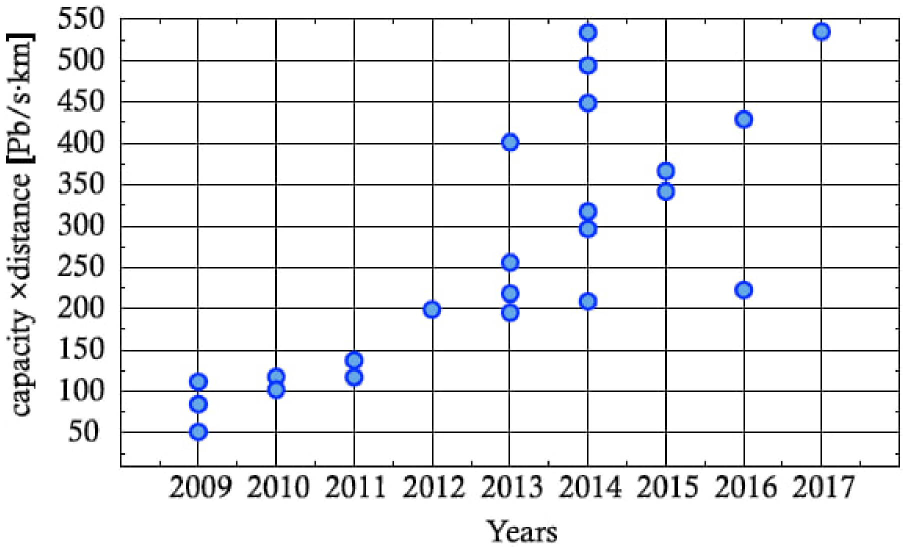


Figure 2. Recently years of demonstrated capacity x distance experimental record in OFC systems [17].

Also, intensive research on multi-core fibers has indicated that several signals can be spatial multiplexing by transmitting them over fibers or multiple cores. A recent development has displayed that spread phase-conjugated twin waves (PCTWs) within the single network are able to be subject to cancellation of the nonlinearity distortion and suppression phase noise. The principle of PCTWs will be explained by transmitted the wave alongside its phase-conjugated counterpart over dual orthogonal dimensions and then coherently Merge them at the receiver. [4,5,7,18]. This article reviews nonlinearity phase noise (NPN) in optical fibers communications (OFC) and multi-dimensional modulation techniques to mitigate it. It examines NPN's impact and highlights methods like Digital Backpropagation (DBP) and Phase-Conjugated Twin Waves (PCTWs) to enhance signal transmission efficiency.

2. LINEAR IMPAIRMENTS

The primary linear influences that affect the optical field and lead to Deterioration in the received signal are discussed as follows:

2.1. NONLINEAR IMPAIRMENT

The nonlinear phenomenon observed in optical fibers is generated from Differences in the refractive index corresponding to the optical intensity, such behaviour is a consequence of what is named "the Kerr effects" " As a result, the effect of nonlinear fibers in optical communication channels is immediately interconnected to the power level of optical. The Increased of optical power levels result in performance Deterioration of optical communications systems because of the effect of optical nonlinearity. Conversely, the launched power must become necessary to keep an acceptable signal-to-noise ratio (SNR) on the reception circuits. Nonlinear Disabilities in optical fibers are classified into three categories: SPM, XPM, and FWM. All of these SPM, XPM, and FWM - acts critical part in optical fiber system, particularly those

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

that utilize multi-level modulation schemes and transmit high bit data rates across multiple distances of optical system. [19]

There are also, random nonlinear Disabilities that can occur as a result of interactions between SPM, XPM, and FWM and Amplified Spontaneous Emission (ASE) noise within optical amplifiers.

2.1.1. SELF -PHASE MODULATION (SPM)

The Self Phase Modulation (SPM) phenomenon plays a prominent role in the change of the phase experienced by the optical wave while it travels via the optical fiber. when ignored of the effect of Cross-Phase Modulation (XPM) and Four-Wave Mixing (FWM), the Nonlinearity Schrodinger Equations (NLSE) may be resolved in a manner that takes on the specific structure as the following form [19, 20]:

$$E_x(\mathrm{z},\mathrm{t}) = E_x(0,t)\exp(-\frac{1}{2}\alpha z + i\,\varphi_{SPM}) \qquad (1)$$

Where Ex is the electric field allocated at distance z and time t, φ_{SPM} is the nonlinearity shift of phase induced by (SPM) as well as α is the attenuation given by[19, 21]:

$$\varphi_{SPM} = \frac{L_{eff}}{L_{NL}}\left|U(0,\mathrm{t})\right|^2 \qquad (2)$$

The length of the nonlinear L_{NL} and the fiber effective length Leff are defined by: [21]

$$L_{NL} = 1/\gamma P_0 \qquad (3)$$

$$L_{eff} = \left[1-\exp(-\alpha L)\right]/\alpha \qquad (4)$$

respectively, where P0 is the peak optical power.

2.1.2. CROSS PHASE MODULATION (XPM)

In the fiber optics communication systems field, XPM demonstrates when two signals with varying frequencies, polarization states, or directions cross through the fiber [20]. XPM can excite the alteration of the optical phase, impacted not only by SPM but also by the nonlinear phase of the Nearby signals. The resultant induced phase disparity among optical channels disposes an effect on both the mean power and the binary sequence. it can be represented as [21].

The two frequency carriers are ω 1 and ω 2 while ω 0refer to the frequency reference. The solution of NLSE can be resulted in the following[21]:

$$E(L) = \sqrt{P_j}\exp(i\,\varphi_{NL}) \qquad (5)$$

Pj is the power input and the nonlinearity shift in phase resulting from combined SPM and XPM is written as[21]:

$$\varphi_{NL} = \gamma L_{eff}\,(P_j + 2\sum_{m\neq j} P_m) \qquad (6)$$

2.1.3. FOUR-WAVE MIXING (FWM)

The FWM involves three frequencies of the nonlinear

The degeneracy factor is defined as $d_f = 2 - \delta_{ij}$ such that it is equal to 1 for i = j and 2 when i ≠ j. The phase mismatch is defined as:

$$\Delta\beta = \beta(\omega_3) + \beta(\omega_4) - \beta(\omega_1) - \beta(\omega_2) \qquad (8)$$

where $\beta(\omega)$ is the constant of propagation at frequency ω.

3. POLARIZATION MODE DISPERSION (PMD)

This is a temporal linear phenomenon that causes a widening of the input wave pulse due to fiber birefringence, which is considered the basic constraining element in high-speed optical fiber transmission. This phenomenon occurs from irregularities in the fiber core's structure, produced from manufacturing-induced thermal and mechanical strains leading to minute discrepancies in the refractive index for the two polarization states. Consequently, one polarization mode outpaces the other, producing a time delay in propagation known as differential group delay (DGD), typically calculated in picoseconds. In the case of the fiber with respect to the length (L), the average DGD is specifically outlined as: [24, 25]

$$\langle \Delta\tau \rangle = \left| \frac{L}{v_{gx}} - \frac{L}{v_{gy}} \right| \qquad (9)$$

Time delay is defined $t = L / v_g$

4. ATTENUATION

A phenomenon of attenuation stands out as the main cause of energy dissipation within optical fiber. The attenuation shows a direct correlation with the distance between repeaters in the communication network. if the attenuation still rises, there is a consequent reduction in repeater spacing, leading to a relative increase in overall system cost. This crucial parameter is established depending on the loss coefficient and is quantified from the mathematical relationship in units of decibels per kilometre (dB/km) as [26]:

$$\alpha(dB / \mathrm{km}) = -\frac{10}{L}\log_{10}\left(\frac{p_{out}}{p_{in}}\right) \qquad (10)$$

The Pout denotes the output power and Pin represents the input power, and The Parameter L represents the fiber length. A standard value for α in fiber of single-mode is 0.2dB/kilometre within traditional C-band cantered around 1550 nm. Typically, erbium-doped fiber amplifiers (EDFAs) are utilized to reward for fiber losses from attenuation [26].

5. AMPLIFIED SPONTANEOUS EMISSION NOISE (ASE)

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

In the field of long-distance optical communication networks, inline optical amplifiers (OAs) play a major role in reducing fiber loss and restoring the original signal. Erbium-doped fiber amplifiers (EDFAs) are utilized to offer a broad gain spectrum for the goal of aligning and enhancing numerous channels on the sometime. even so, it is essential to account for the amplified spontaneous emission noise (ASE) Outgoing from EDFAs. The ASE noise contributes to the signal and accelerates quickly throughout a chain of amplifiers. Towards the final amplifier within the connection, the cumulative ASE noise might obstruct signal amplification and affect the receiver Bit Error Rate (BER). This phenomenon is an outcome of the spontaneous emission of photons within the OA. The ASE noise may be characterized as an additive white Gaussian noise (AWGN) that affects together the imaginary and real units of the optical wave, thereby causing symmetrical symbol separation within the constellation diagram. The ASE noise power will be characterized as the following [27,28]:

$$p_{ASE} = 2\eta_{sp}(\mathrm{G}-1)\mathrm{h}\nu B \qquad (11)$$

Where P ASE represents the noise power of the ASE, With G being the amplifier gain, $\mathrm{h}\nu$ photon energy, B optical bandwidth and η_{sp} as spontaneous emission factor that is related to the noise figure (NF) of the amplifier[20]:

$$\eta_{sp} = \frac{NF.G}{2(\mathrm{G}-1)} \qquad (12)$$

The noise figure can be defined as the ratio between input SNR and output SNR[20]:

$$NF = \frac{SNR_{in}}{SNR_{out}} = \frac{P_{sig} / p_N}{G.P_{sig} / (p_{ASE} + P_N)} \qquad (13)$$

W

i

t

h

6. M-DIMENSSIONS MODULATION TECHNIQUES

p_N being the noise power added by an EDFA.

This examination discusses the latest advances in the field of the transmission of multidimensional signals and Confirming new approaches for investigating the dimensions of polarization to increase the capability or spectral efficiency of an individual fiber optics. Clear explanation on developments of M-dimensional wave transmission techniques were be offered.

6.1 A AO-OFDM RZ-mQAM Technique

A new and effective implementation of return-to-zero RZ-QAM-4 and RZ-QAM-16 modulation methods is introduced with the objective of improving the efficacy of an overall OFDM optical systems.

The performance assessment of the suggested overall OFDM optical system is conducted through numerical simulations, which employ a coupler created on fast Fourier transform and inverse fast Fourier transform architecture devoid of any nonlinearity benefit mechanisms. This system incorporates 29 subcarriers, both modulated at a rate of symbol of 25 G symbol/s. [27]

The performance metrics of the proposed systems are side by side with those of a traditional overall OFDM optical system utilizing QAM-4 and QAM-16 modulation formats. These findings indicate that the

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

suggested system performance of markedly surpasses that of the conventional counterparts, as the adverse impacts of fiber nonlinearities have been effectively relive. It has been noted that the power requirements to achieve minimal EVM escalate with the integration of RZ-QAM-4 and RZ-QAM-16 designs. Moreover, the requisite OSNR for attaining a BER=10 are minimized by approximately 1.9 dB and 5.8 dB when RZ-QAM-4 and RZ-QAM-16 are employed within overall OFDM optical systems, in comparison to the traditional OFDM systems utilizing QAM-4 and QAM-16. [27]

This Figure 3 (a) explain the relationship between EVM and transmission distance for RZ-QAM-4 and QAM-4 overall OFDM optical system. At the optimal power levels for each design modulation, the EVMs are measure over a distance of transmission of 550 km. It is clear that the EVM shows a linear increase with the expansion of fiber length. And moreover, the EVM related with the proposed system demonstrates superior performance. Similarly, the EVM at RZ-1QAM-16 is found to be minor than the QAM-16, as demonstrate in Figure 3 (b). In general, the phase noise is light that observed it be more effective with increased fiber length. [27]

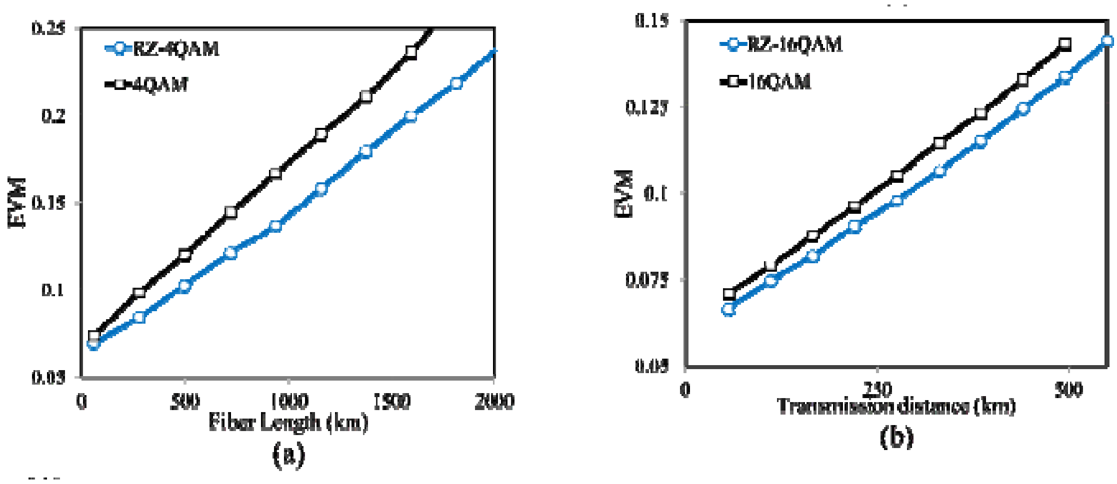


Fig.3. EVM against length of fiber at: a) RZ-QAM-4 versus QAM-4 b) RZ-QAM-16 versus QAM-16 [27]

In optical Orthogonal Frequency Division Multiplexing with transmissions, of OFDM , the phase noise was intricately associated with the amount of subcarriers, as the interface occurrence between subcarriers, like Cross-Phase Modulation (XPM) and Four Wave Mixing (FWM), are depending upon their quantity. as a result, created a conducted a numerical scrutinization across varying numbers of subcarriers. Figure 4 illustrates the correlation between Bit Error Rate (BER) and transmission distance for configurations that using 9 and 29 subcarriers. For each specified distance that transmit a signal, the related subcarrier power that minimizes the Error Vector Magnitude (EVM) is utilized. As showing in Figure 4 (a), the Return-to-Zero (RZ) 4QAM modulation format exhibits Improve performance over the standard 4QAM format via transmission distances for both specified numbers of subcarriers. as will, the performance of the this system experiences a remarkable enhancement when using 9 subcarriers, which demonstrating a 62% improvement then the 4QAM OFDM system. [27].

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

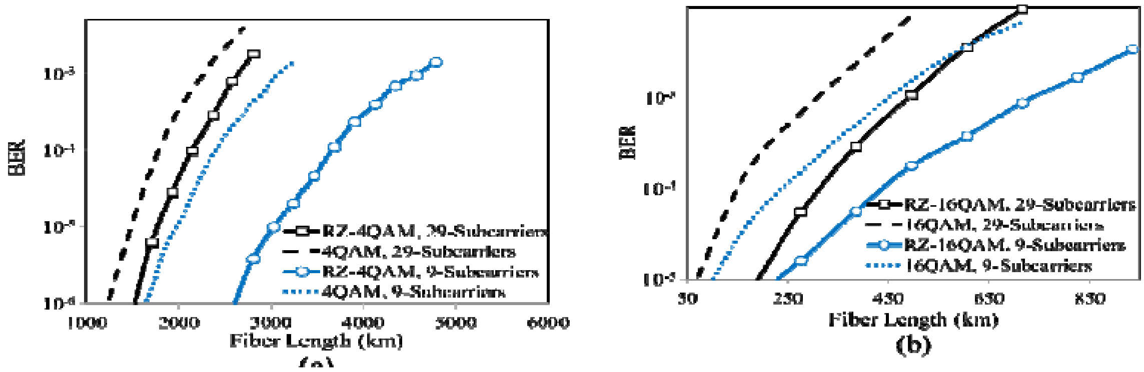


Fig. 4. BER against distance of transmission at a rate of symbol of 25GSymbol/s with: a) QAM-4 and RZ-QAM-4 b) QAM-16 and RZ-QAM-16 [27]

In 16QAM the higher-order modulation formats, important to increased OSNR to effectively mitigate the effects of phase noise. as a consequence, the distance of transmission is markedly diminished when using either the QAM-16 or RZ-QAM-16 designs within overall OFDM optical signals, as depicted in Figure 4 (b) [27].

6.2 TI-4QAM MDM system Technique

This paper has been formulated for efficacious technology to diminish the overlap among fiber modes and to decrease nonlinear-phase-noise (NPN) in multi-mode-division multiplexing (m-MDM) systems. This approach depending upon the reduction of nonlinear interactions among the transmitted fiber modulation by reformulating the magnitudes of m-QAM modulation, followed by temporal overlapping among the more closely overlap approaches, specifically the degeneration approaches. An amazing improvement in the whole optical systems performance have been achieved through the carrying out of the time interleaved four-level quadrature amplitude modulation (TI-4QAM) MDM system. The effectiveness of this system has been rated by developing an analytical modulo to quantify the nonlinear phase noise (NPN) induced by many optical related losses. The analytical and numerical result relate to this system have indicated that the optimal delay time agree with to 0.5 of duration of the symbol, resulting in a significant reduction of NPN attributable to each cross-phase modulation (XPM)and self-phase modulation (SPM) [28].

Additionally, the suggestion of this technique are examined through numerical scrutinizations assessing the performance of both 2-mode and 5-mode transmission system. all of mode transmits a sinusoidal cover 4QAM signal at a rate of 20 G symbol/s. In the condition of the five-mode TI-4QAM MDM systems, the nonlinear phase noise is minimized by approximately 72%, 75.5%, and 73% for the LP01, LP11a, and LP21a modes, respectively, while the reach of transmission is expanded by more than 270% for many excitation modes in comparison to the conventional 4QAM MDM system. A modified analysis between the analytical and numerical findings is conducted by assessing the vector magnitude of error (EVM) and error rate of symbol(SER) or Bit error rate(BER) in relation to mode power and distance. as well, the influence of the time interleaving technique on the nonlinear phase noise is forecasted by graphically representing the variance of (NPN) against power mode for both QAM-4 and TIQAM-4 MDM) system, wherein the "LP01, LP11a, and LP21a channels" , which denote the degenerated fiber modes.[28]

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

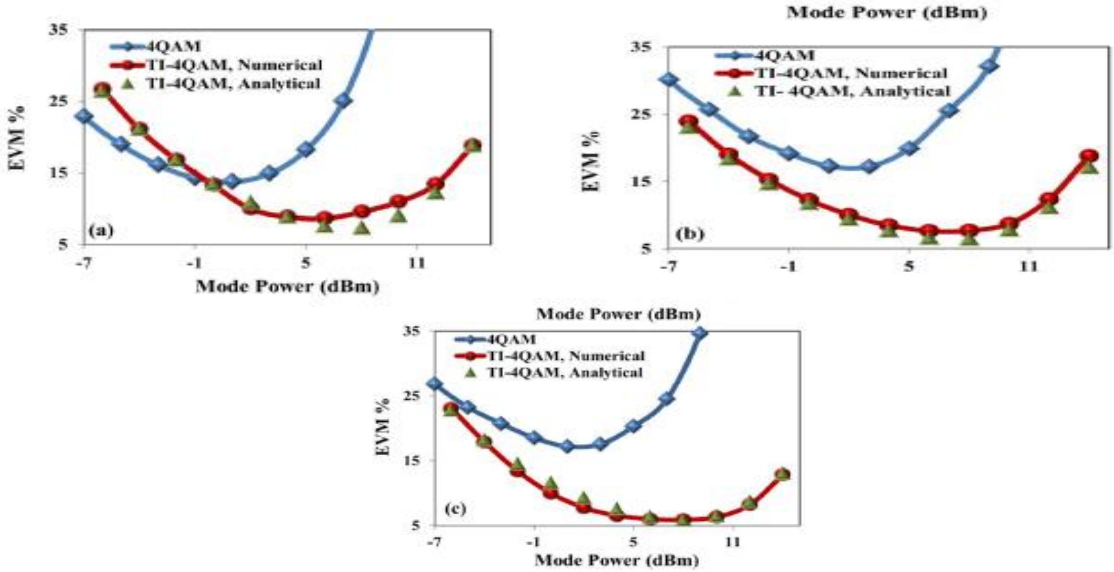


Fig.5. Error Vector Magnitude against power of mode for (a)LP01,(b)LP11a,(c)LP21a. .[28]

To explain the impact of the time interleaving technique on decreasing nonlinear mode interactions, the error vector magnitude against of power mode for 5- modes transmission is presented in Fig.5. The calculation outcomes were derived from a few-mode fiber (FMF) with a length of 700 km. The interleaving of modes resulted in a significant improvement being observed. This phenomenon can be assign to the substantial reduction in the communication time among modes and the phase matching conditions, particularly among the degenerate modes. the Fig. 5 show a correlation between the analytical predictions and the numerical findings. [28]

At the last of suggests system, the impact of the suggested system on distance of the transmission is showed in Fig. 6 The symbol error rate (SER) in correlation to the transmission distance is evaluated at optimal power for 5-modes of transmission. The findings refer a remarkable increasing in distance of transmission when utilize the suggested techniques, as contrasted with four-level quadrature amplitude modulation (4QAM) mode division multiplexing (MDM) transmission. when a SER of 0.1 micro, the distance of the transmission of the LP-01 channel is increase from 1150 km for QAM-4 to 4300 km for time-interleaved 4QAM, reflecting the increasing exceeding 270%. in similar method, a notable extension in transmission and reach is evident for both the LP11a and LP21a channels. [28]

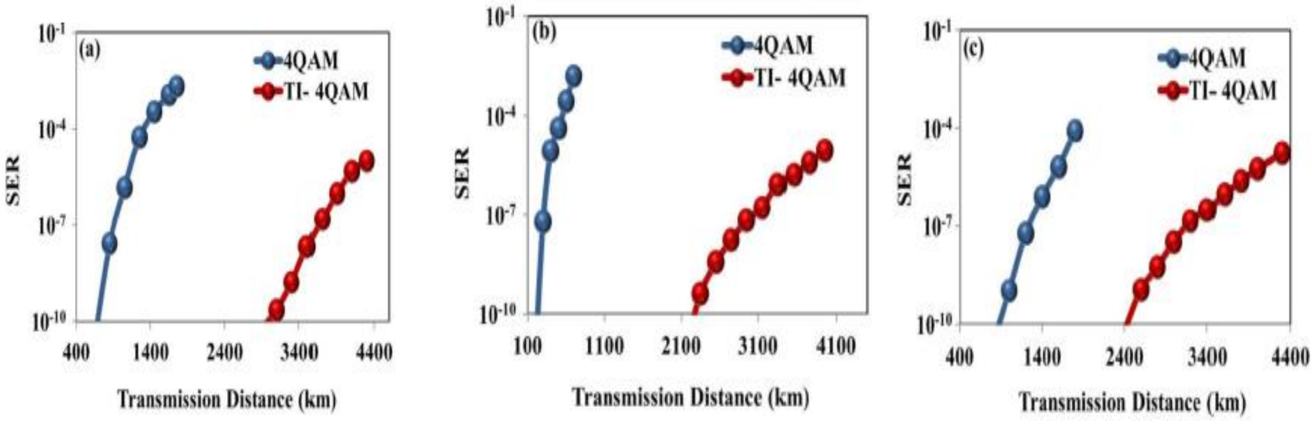


Fig. 6. Bit rate error against distance of transmission for (a)LP-01,(b)LP-11a,(c)LP-21a. [28].

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

6.3. POLMUX-RZ-16QAM TECHNIQUE

The 16QAM signal is generated and modulated using POLMUX-RZ techniques at 224 Gbit/sec. Furthermore, we reported the transmission of 11 224 Gbit/sec of POL-MUX-RZ-QAM-16 above 670 kilometres of SSMF within a space channel about 50 GHz as well as spectral efficiency of 4.2 bit/sec/Hz, the power launched for the 11 224 Gbit/sec POLMUX RZ-QAM-16 channel is different between 2 and 7 dBm, while the BER is considered for the 1550.5-nm channels at each of the calculated powers launch. These powers deferent in measurement have been carried out afterward distances of transmission of 385 and 670 km. For each types, the best power launched is start to be about 3 dBm. [29]

6.4 PPM-RZ-MQAM UDWDM TECHNIQUE

M-QAM and RZ are combined with PPM in the ultra-high density wavelength division multiplexing (UDWDM) framework to decrease an effect of nonlinear phase noise (NPN) and optimize the transmitted signal ratio. A 4-dimensional UDWDM signal (phase, amplitudes, wavelengths and time) is transmitted, which has superior sensitive compared to traditional systems. It is first modulated using mQAM and then encoded using RZ and PPM as shown in Figure 7. The results show the impact of the suggested technology on the system, where the spectral efficiency and signal quality are improved. [30].

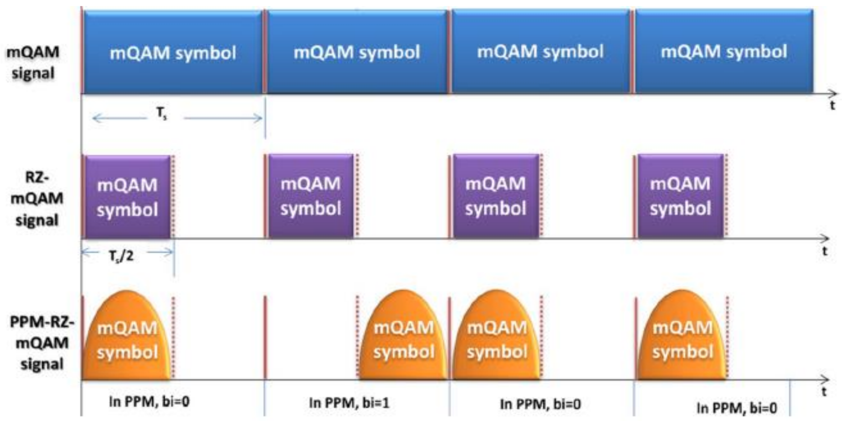


Fig. 7: Basic of Modulate the Signal Throw PPM-RZ-mQAM. [30]

In Figure 8, the signal to noise ratio (SNR) of both PPM-RZ-QAM-4 and PPM-RZ-QAM-16 systems is plotted relative to the transmission power within the channel at a transmission distance of up to 1200 km. After performing the SNR analysis, the results of mQAM and PPM RZ-mQAM UDWDM at 16QAM and 4QAM are compared to prove the effectiveness of the proposed technique. We note that the PPM-RZ-4QAM UDWDM system offers greater performance of NR compared with the conventional system and is also capable of transmitting data over long distances without losses. Also, for the PPM-RZ-16QAM system, higher SNR values are achieved compared to 16QAM channels. [30].

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

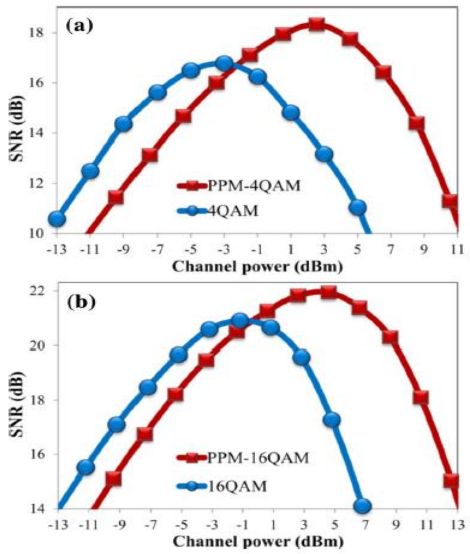


Fig. 8. Effect of SNR on \UDWDM system within:
a) PPM-RZ QAM-4 and QAM-4.
b) PPM-RZ QAM-16 and QAM-16. [30]

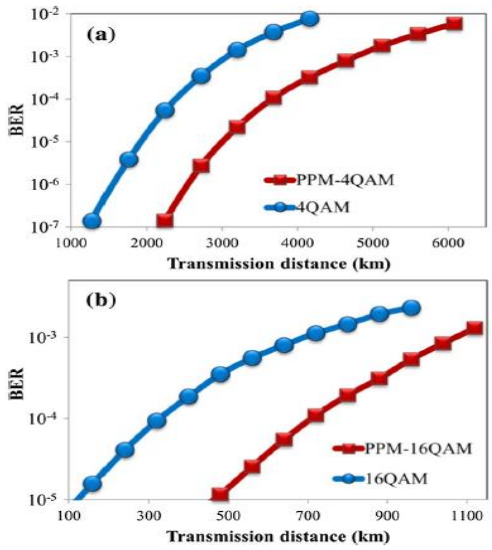


Fig.9.BER to the distances of transmission for : a) PPM-RZ-QAM-4 and QAM-4.
b) PPM-RZ-QAM- 16 and QAM-16. [30]

The variation in BER agonist transmission distance for PPM-RZ QAM-4, QAM-4, PPM-RZ QAM-16, and QAM-16 channels is plotted in Figure 9. The distance of transmission is improved by 55% when using PPM-RZ QAM-4 compared to 4QAM UDWDM at a BER of 1 × 10–3. Also, in PPM-RZ-16QAM, the transmission distance is increased significantly compared to 16QAM at the same BER. [30]

7. PRINCIPLE OF PCTWS TECHNIQUE

In past years, the technique of PCTW has been employed in two mutually orthogonally dimensions to nullify NPN [31]. The symmetrically dispersion map is a critical requirement for achieving optimal efficiency of the PCTWs technically different forms of orthogonal domains have been used for the application of the PCTWs technique. In the beginning, the PCTWs procedure was executed using orthogonal polarization states. However, the PMD plays a real challenge to the effectiveness of PCTWs. [31-34]

Furthermore, the transmission of PCTWs via adjacent time slots has proven to be effective in decreasing nonlinear distortions [35]. Additionally, scrutinization of the PCTWs method in the frequency domain has been conducted by directing the waves through neighbouring channels [32], [36]. it is Also, important to note that the PCTWs technique is unable to eliminate the stochastic component of nonlinear distortion, which occurs from the interaction of nonlinear effects with amplifier noise [37].

7.1. AO-OFDM- PCTWS TECHNIQUES

A technique for mitigating out-of-phase noise (NPN) in orthogonal frequency division multiplexing (AO-OFDM) systems uses envelope modulation derived from phase-coupled twin waves (PCTWs). Under the proposed technology, each sub wave, along with its homogeneous phase-coupled counterpart, is initially modulated using m-array quadrature amplitude modulation (mQAM) scheme with modulated through a return-to-zero (RZ) coding format. Subsequently, multiple subwaves are transmitted to produce dual AO-OFDM waves, which are transmitted over 2-analog optical fiber channels. Upon reception, each waveform is detected independently, and the dual sub waves are then combined to facilitate NPN suppression. Figure 10 shows an analytical model to describe NPN and the effect of the proposed systems on its reduction and justification of the system effectiveness, where the numerical results indicate a significant reduction in NPN at a transmission distance of up to 600 km [38].

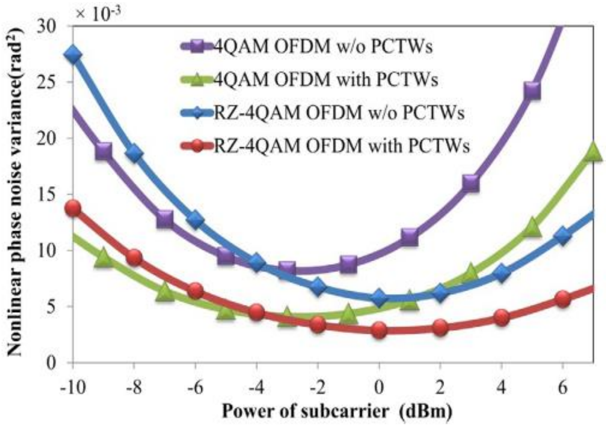


Fig.10. Shows (NPN) Versus Power For RZ-4QAM OFDM and 4QAM OFDM Technologies, Both With And Without PCTW [38].

In Figure 11, the SNR ratios of the transmission power of the subwaves is shown at a transmission distance of up to 600 km. The results indicate that the SNR improves significantly when using PCTWs technology by 3.6 dB with 4QAM only and 5.7 dB with RZ-4QAM. As a result, the signal can be transmitted with high quality and power level [38].

.

.

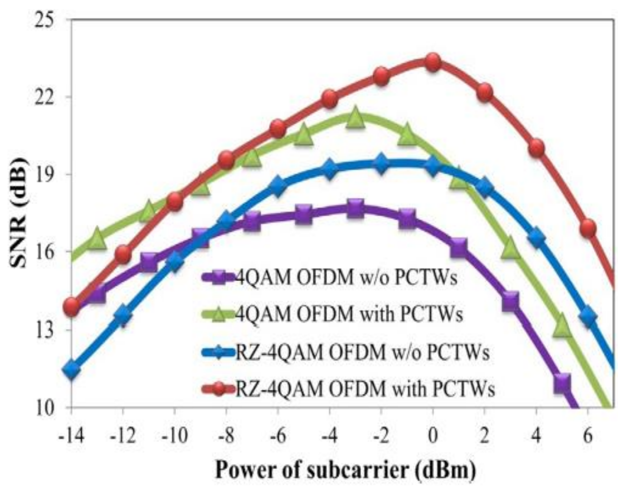


Fig.11. SNR Ratios of The Transmissions Power Of AO-OFDM system [38].

In the proposed technique, we notice an upsurge in the transmissions distance versus the conventional system, reaching 5000 km. Figure 12 illustrations BER against the transmission distances length, at the best power for all systems, where the transmission distance extends by 66.7% at QAM-4 AO-OFDM PCTWs and 150% at RZ-QAM-4 AO-OFDM PCTWs [38].

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

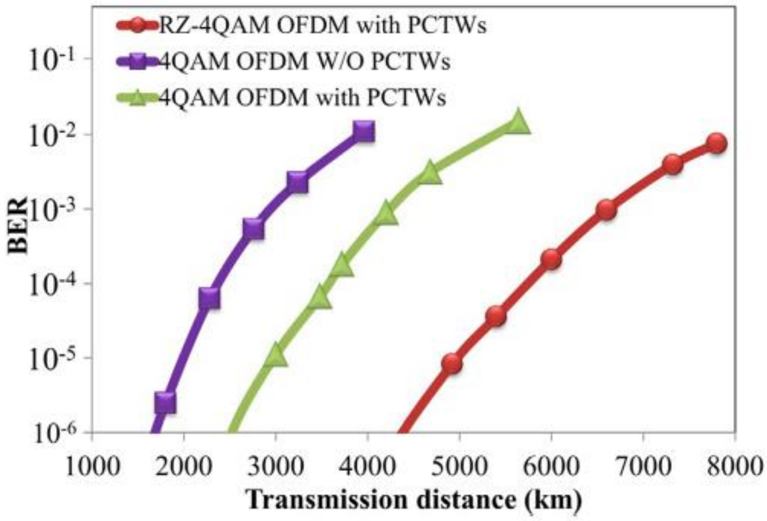
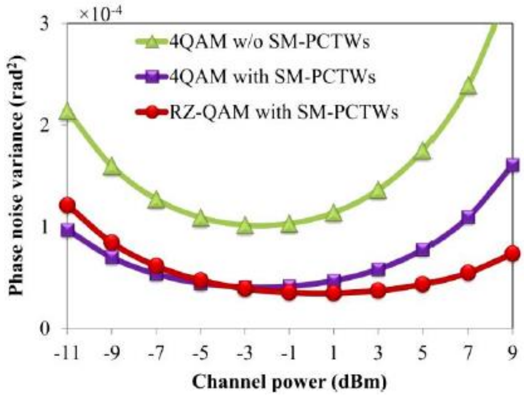


Fig. 12. maximum transmission distance in AO-OFDM technique with/out using PCTWs[38]

To increase the performance of fiber optics communications system, a spatial division multiplexing (SDM) system was proposed using PCTWs technology with the use of return-to-zero (RZ) coding. Where the two signals are modulated and transmitted by a laser source, in the reception part the signals are collected coherently to reduce the effects of non-linear noise (NPN). The effect of PCTWs technology and the effectiveness of RZ code on improving the signal ratio within the SDM system was examined and analyzed, where the results were displayed digitally using the VPI program for the SDM system using or not using PCTWs and RZ code to reveal the effectiveness of these techniques [39].

The signals are transmitted at a ratio of 20 Gsymbol/sec, we notice the clear effect when using PCTWs and RZ code compared to the original (4QAM) system, where Figure 13 shows the NPN rate for each of the techniques used in the (SDM) systems at a distance of transmission of 1800 km, where the lowest NPN rate is when using PCTWs technology with RZ code in the 4QAM-SDM system. These results prove the capability of the proposed system to transmit optical signals and reduce phase noise at high power levels [39].



`Fig. 13. The NPN Rate For Each Of The Techniques Used In The *4QAM System[39]*

In Figure 14, the SNR is designed against the power at a transmission distance of 1800 km. The results show that the SNR improves with increasing power ratio when using the proposed techniques associated to the basic 4QAM systems by around 6.5 dB, with the maximum SNR value reaching 25 dB when using (PCTWs RZ-4QAM) [39].

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

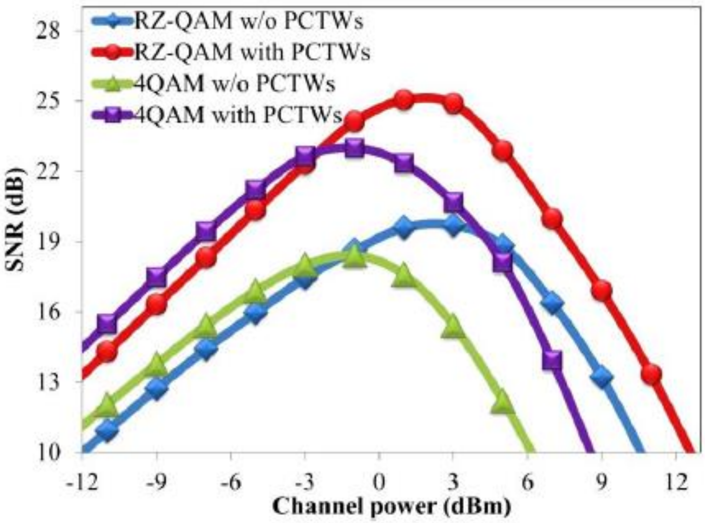


Fig. 14. Effect of PCTWs and RZ code Technique on 4QAM System [39]

Figure 15 illustrations the BER against transmission distances for RZ-4QAM and 4QAM technologies, both with and without PCTW. We see that the distance of transmission increases from 4500 km in the 4QAM scheme to 9000 km in the SM PCTWs RZ-4QAM system, where the transmission distance increases by 77.8% [39].

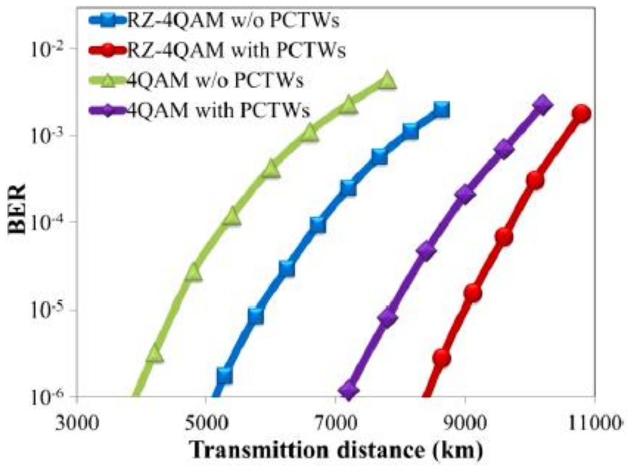


Fig. 15. Shows BER Against Transmission Distances for RZ-QAM-4 and QAM-4 Technologies, Both With And Without PCTW [39]

The PCTW method proposed to combat the effects of nonlinearity fiber distortions in the wavelength division multiplexing - space division multiplexing (WDM-SDM) system is studied and analysed and simulated digitally using the program VPI. The proposed system consists of 16 signal transmission channels, each signal is modulated by (4QAM) and sends different wavelengths to generate a WDM signal at the same time and transmit it with its phase conjugate through two similar optical fiber links. In the future, they are collected in a coherent manner. The results of using this proposed technique indicate an improvement in the performance of structure and an upsurge in the transmission distance.

Also, the nonlinearity of the fiber was significantly reduced during the use of the PCTWs technique to reach 68.6% compared to the conventional WDM system [40].

Figure 16 shows the relationship between NPN and transmission power at a transmission distance of 1800 km, where it initially decreases relative to the power and then rises with the rise of the power. This is becouse the generation of nonlinear phase noise, which arises Self-phase modulation (SPM) and ASE noise at high power levels [40].

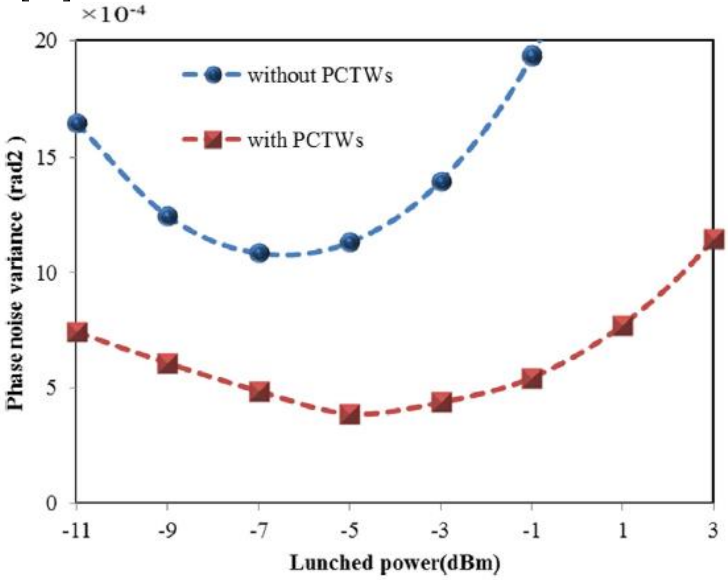


Fig. 16. Effect of PCTWs technique on the NPN in 4QAM-WDM-SDM.[40]

Figure 17 shows SNR of the received signal versus power of channels to identify the effects of PCTWs on the system. At a distance of transmission of 1800 km, there is a noticeable increase of up to 3 dBm after which it drops sharply. The SNR of PCTWs is about 20.2 dBm compared to the conventional system [40].

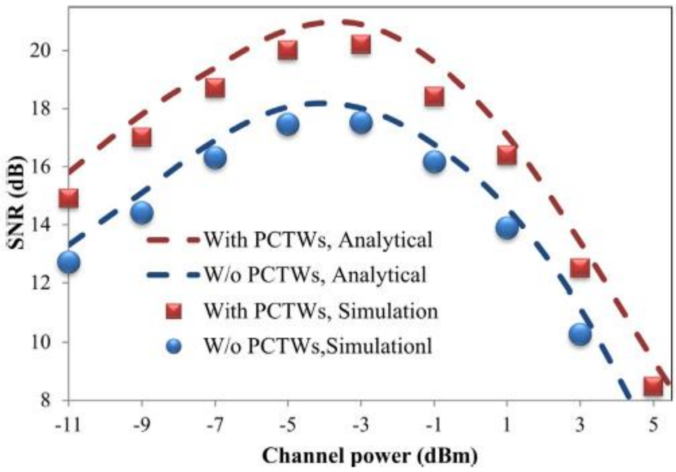


Fig. 17. Effect of PCTWs technique on the SNR in 4QAM-WDM-SDM.[40]

In Figure 18, the BER is shown relative to the distance of the transmission of system. Overall, the indicated system shows an improved ability to increase the transmission distance by 39.4%. At the BER level of 10^{-5}, the transmission distance of the system using PCTWs technology reaches 5520 km compared to the original system which reaches 3960 km [40].

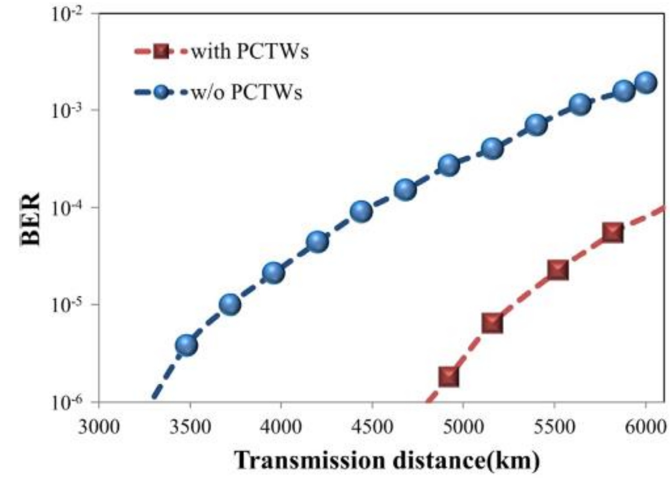


Fig. 18. The Relative of BER and transmission distance of the systems in QAM-4-WDM-SDM with PCTWs .[40]

8. PHASE CONJUGATED TWIN WAVES TECHNIQUE EFFICIENCY ON SPATIAL-DIVISION (SD) AND FREQUENCY-DIVISION (FD)

As shown in figure 19, The effectiveness of phase-coupled double wave (PCTWs) technology to reduce fiber nonlinearity within a single system-channel has been thoroughly studied in both frequency- and spatial-multiplexing transmission frameworks. In the spatial-division systems, the quadrature phase-shift keying (QPSK) signals with their coupled phase counterpart are modulated by a unique source of laser and at that time transmitted instantaneously over 2-analog fiber optic connections. At the receiver, the 2-signals are coherently combined to reduce nonlinearity distortion of phase. In the frequency-division systems, the signals with their phase-coupled counterpart are transmitted through two separate laser sources at a frequency rate of 100 GHz and then transmitted together over an identical fiber link. To effectively remove nonlinear distortions, the 2-signals are coherently cover up at the reception end. To demonstrate the feasibility of the effects of PCTW technology on system efficiency, analytical results using the VPI program are presented. The results show a major development in the performance metrics for both systems. [41]

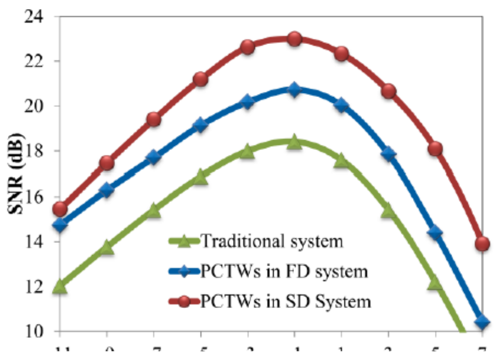


Fig. 19. SNR ratio against power in SD and FD schemes with PCTW method [41]

Figure .20 displays the relationship between signal to noise ratio (SNR) with channel laser power to see the effect of PCTWs methodology on the integrity of the signal received in frequency-multiplexed and

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

spatial-multiplexed system. Also, these results are compared with the signal to noise ratio of the conventional systems. The data show that PCTWs technique in spatial division (SD) configuration shows 4.5 dB greater efficiency than frequency division (FD) scheme by only 2.5 dB and compared to the conventional Quadrature Phase Shift Keying (QPSK) system [41].

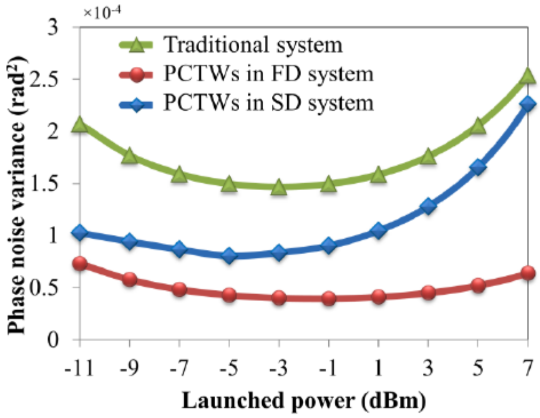


Fig. 20. Show the effect of (NPN) in SD and FD system with PCTWs technique [41]

The efficiency of reducing the nonlinear phase noise (NPN) to know the effectiveness of (PCTWs) is illustrated by Figure 21. It shows the difference between the nonlinear phase noise (NPN) with respect to the launch power of the Quadrature Phase Shift Keying (QPSK) signal within both the Single Domain (SD) and Frequency Domain (FD) systems, with the implementation of the PCTWs technique, at a fiber length of 1800 km for both systems. It is observed that the phase noise differences initially decrease with the increase of the laser power in the channel, from the figure it is observed that the efficiency of using the PCTWs technique on the frequency division (FD) system is observed where the nonlinear phase noise decreases compared to the spatial division (SD) system in PCTWs technique , the phase noise differences show a 72% reduction for the SD system and a 56% reduction for the FD system, compared with the normal QPSK systems [41].

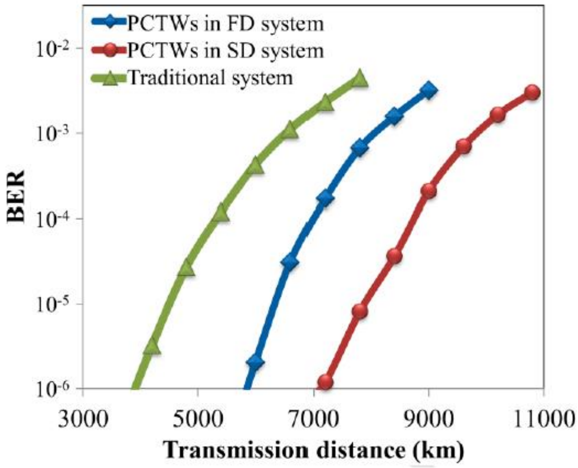


Fig. 21. the bit error rate (BER) is represented as a function of transmission distance. [41]

relative to the transmission distance on frequency division keying (FD) and spatial division keying (SD) systems as shown in Figure 22. The absolute power is continuously set at -1 dBm in both systems. A clear effect of PCTWs technology on the proposed systems is observed compared to the conventional Quadrature Phase Shift Keying (QPSK) system over different transmission distances. Where at a BER of 10-5, in the

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

conventional QPSK system the transmission distance reaches 4500 km, while in the frequency division keying (FD) system with PCTWs technology the transmission distance increases from 10 to 6500 km, indicating a 44.5% improvement in transmission distance. In the spatial division keying (SD) system with PCTWs technology the transmission distance increases to 8000 km for the spatial division keying (SD) system, indicating a 77.8% improvement [41].

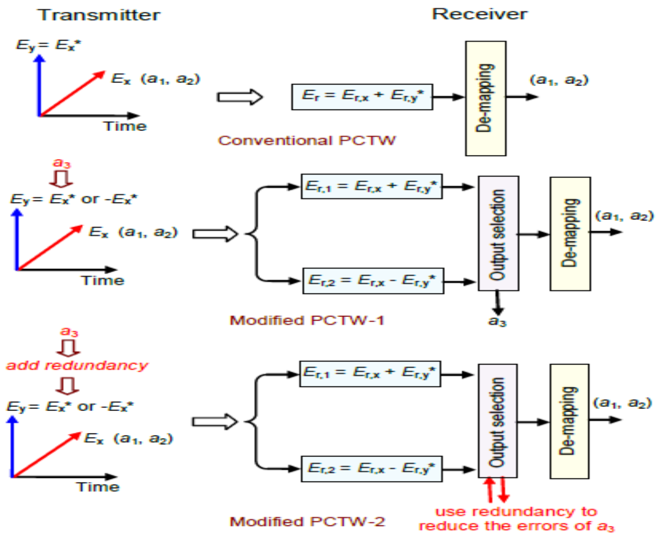


Fig. 22. Principle of traditional modifications (M-PCTW1 and M-PCTW2) [42].

9. PCTW- PCTW-1- PCTW-2 TECHNIQUES

In this paper, the traditional PCTW technique is modified to improve the standard error from 50% to 70% while maintaining its performance. This paper explains the method of modifying the PCTW technique by addition 2-bits with redundancy in the Ey encoding to increase the standard error to approach 100% using the QPSK signal. [42]

Figure .22 shows the working principles of the traditional PCTW technique and the suggested modifications (M-PCTW1 and M-PCTW2). The traditional PCTW signal consists of x and y polarized and phase-coupled ($E_y = E_x^*$). In the future, distortions resulting from the non-linearity of the fiber for these two polarizations are generated ($E_{r,y} = -E_{r,x}^*$) and are removed by $E_r = E_{r,x} + E_{r,y}^*$. This method is effective to a certain level. In the proposed M-PCTW-1 modification, an additional bit a3=1 is added when $E_y = E_x^*$ is transmitted and a_3=-1 when $E_y = -E_x^*$ is transmitted, at the receiver the signal is divided into two halves and decoded using $E_{r,1} = E_{r,x} + E_{r,y*}$ and $E_{r,2} = E_{r,x} - E_{r,y}^*$, respectively. This M-PCTW1 modification contributes to an improvement of the standard error by 25% compared to the conventional PCTW technique and the original QPSK signal, however, this method still has some major problems where when decoding it generates an error in bit a_3 and also increases the error a_1 a_2. [42].

Al-Furat Journal of Innovations in Electronics and Computer
Engineering (FJIECE)
ISSN -2708-3985

To avoid this problem, in M-PCTW-2 technique a redundancy is added in bit a3 by using error correction code, pseudo random bit sequence (PRBS) is used to generate binary bits on PDM QPSK signal. This process is repeated three times with different patterns and (BER) is calculated to find Q factor. Figure .23, shows the signal power and its effect on Q factor of QPSK signal using traditional PCTW technique and suggested techniques M-PCTW1 and M-PCTW2, the improvement in Q factor can be observed [42].

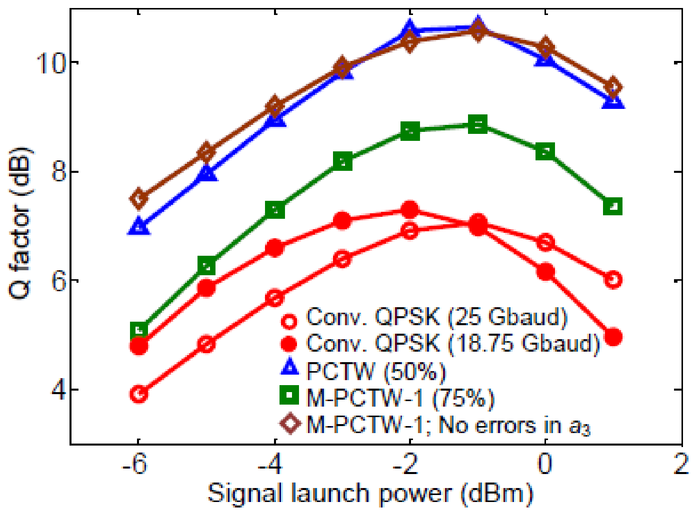


Fig. 23. The signal power and its effect on Q factor of QPSK signal using traditional PCTW technique and suggested techniques M-PCTW-1 and M-PCTW-2[42].

10. CONCLUSIONS

This article underlines the critical challenges modelled by nonlinear phase noise (NPN) in fiber optics communications and highlights the role of multi-dimensional modulation techniques to reduce these impacts. The explored approaches, including Digital Backpropagation (DBP), Mid-link Optical Phase Conjugation (ML-OPC), and Phase-Conjugated Twin Wave (PCTW), offer effective strategies to improve signal quality and system performance, ensuring the continued optimizing and efficiency of optical communication technologies.

Al-Furat Journal of Innovations in Electronics and Computer Engineering (FJIECE)
ISSN -2708-3985

REFERENCES

1. J. K. Fischer, S. Alreesh, R. Elschner, F. Frey, M. Nölle, C. Schmidt-Langhorst, and C. Schubert, “Bandwidth-Variable Transceivers based on Four-Dimensional Modulation Formats,” J. Lightw. Technol., vol. 32, pp. 2886–2895, Aug. 2014.
2. S. Alreesh, J. K. Fischer, M. Nölle, and C. Schubert, “Joint-Polarization Carrier Phase Estimation for PS-QPSK Signals,” IEEE Photon. Technol. Lett., vol. 24, no. 15, pp. 1282– 1284, Aug 2012.
3. S. Le, M. McCarthy, S. Turitsyn, I. Phillips, D. Lavery, T. Xu, et al., "Optical and digital phase conjugation techniques for fiber nonlinearity compensation," in Opto-Electronics and Communications Conference (OECC), 2015, 2015, pp. 1-3.
4. X. Liu, A. Chraplyvy, P. Winzer, R. Tkach, and S. Chandrasekhar, "Phase-conjugated twin waves for communication beyond the Kerr nonlinearity limit," Nature Photonics, vol. 7, pp. 560-568, 2013.
5. Y. Yu, W. Wang, P. D. Townsend, and J. Zhao, "Modified phase-conjugate twin wave schemes for spectral efficiency enhancement," in Optical Communication (ECOC), 2015 European Conference on, 2015, pp. 1-3.
6. L. B. Du, M. M. Morshed, and A. J. Lowery, "Fiber nonlinearity compensation for OFDM super channels using optical phase conjugation," Optics express, vol. 20, pp. 19921-19927, 2012.
7. T. Yoshida, T. Sugihara, K. Ishida, and T. Mizuochi, "Spectrally-efficient dual phase-conjugate twin waves with orthogonally multiplexed quadrature pulse-shaped signals," in Optical Fiber Communication Conference, 2014, p. M3C. 6.
8. E. Agrell et al., “Roadmap of optical communications”, Journal of Optics, vol.18, 2016, doi:10.1088/2040-8978/18/6/063002
9. X. Liu, S. Chandrasekhar, P. Winzer, R. Tkach, and A. Chraplyvy, Journal of Lightwave Technology, vol. 32, pp. 766-775, 2014.
10. S. Le, M. McCarthy, S. Turitsyn, I. Phillips, D. Lavery, T. Xu, et al., in Opto-Electronics and Communications Conference (OECC), 2015, 2015, pp. 1-3.
11. T. Yoshida, T. Sugihara, K. Ishida, and T. Mizuochi, in Optical Fiber Communication Conference, 2014, p. M3C. 6.
12. Y. Yu, W. Wang, P. D. Townsend, and J. Zhao, in Optical Communication (ECOC), 2015 European Conference on, 2015, pp. 1-3.
13. X. Liu, A. Chraplyvy, P. Winzer, R. Tkach, and S. Chandrasekhar, Nature Photonics, vol. 7, pp. 560 568, 2013.
14. X.Yi, L.Yan, Y.Pan, L.Jiang, Z.Chen, W.Pan, B.Luo," Transmission of multi-dimensional signals for next generation optical communication systems" 2017 Elsevier , Optics Communications ( ) –
15. X. Liu, S. Chandrasekhar, P. Winzer, R. Tkach, A. Chraplyvy, J. Lightwave Technol. 32 (2014) 766–775.
16. O. Vassilieva, I. Kim, T. Ikeuchi, J. Lightwave Technol. 37 (2018) 50–60.
17. A. Napoli, M. Bohn, D. Rafique, A. Stavdas, N. Sambo, L. Poti, M. Nölle, J. K. Fischer, E. Riccardi, A. Pagano, A. D. Giglio, M. S. Moreolo, J. M. Fabrega, E. Hugues-Salas, G. Zervas, D. Simeonidou, P. Layec, A. D’Errico, T. Rahman, and J. P. F. P. Giménez, “Next generation elastic optical networks: The vision of the European research project IDEALIST,” IEEE Commun. Mag., vol. 53, pp. 152–162, Feb. 2015.
18. Z. Zheng, X. Lv, F. Zhang, D. Wang, E. Sun, Y. Zhu, et al., "Fiber nonlinearity mitigation in 32-Gbaud 16QAM Nyquist-WDM systems," Journal of Lightwave Technology, vol. 34, pp. 2182-2187, 2016

19. NADERI, S.S., Analysis and mitigation of the nonlinear impairments in fiber-optic communication systems. 2013.
20. Behrens, C., Mitigation of nonlinear impairments for advanced optical modulation formats. 2012, UCL (University College London).
21. Agrawal, G.P., Nonlinear fiber optics. 2007: Academic press.
22. Neokosmidis, I., et al., New techniques for the suppression of the four-wave mixing-induced distortion in nonzero dispersion fiber WDM systems. Journal of lightwave technology, 2005. 23(3): p. 1137.
23. Agrawal, G.P., Fiber-optic communication systems. Vol. 222. 2012: John Wiley & Sons.
24. Nelson, L. and R. Jopson, Introduction to polarization mode dispersion in optical systems, in Polarization Mode Dispersion. 2004, Springer. p. 1-33.
25. Agrawal, G.P., Lightwave technology: telecommunication systems. 2005: John Wiley & Sons.
26. Ghatak, A. and K. Thyagarajan, *An introduction to fiber optics*. 1998: Cambridge university press.
27. J. K. HMOOD, K. A. NOORDIN , H. AHMAD , S. W. HARUN, " Performance improvement of all-optical OFDM systems based on combining RZ coding with m-array QAM ", OURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS ,Vol. 17, No. 1-2, January – February 2015, p. 33 - 38
28. E.K.Hamed , J.K. Hmood,M.A. Munshid " Minimizing modes interaction based on time interleaving method in mode division multiplexing systems", Optics Communications 501 (2021) 127392
29. M.S.Alfiad, M. Kuschnerov" 11 224-Gb/s POLMUX-RZ-16QAM Transmission Over 670 km of SSMFWith 50-GHz Channel Spacing", IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 22, NO. 15, AUGUST 1, 2010
30. A.S. Abdulzahrah , J.K. Hmood, " Proposal of PPM-RZ-mQAM scheme for suppressing nonlinear phase noise in high spectral ultra-DWDM system", Optical and Quantum Electronics (2022) 54:45 https://doi.org/10.1007/s11082-021-03418-5
31. X. Liu, A. Chraplyvy, P. Winzer, R. Tkach, and S. Chandrasekhar, "Phase-conjugated twin waves for communication beyond the Kerr nonlinearity limit," Nature Photonics, vol. 7, p. 560, 2013.
32. X. Liu, S. Chandrasekhar, P. Winzer, R. Tkach, and A. Chraplyvy, "Fiber-nonlinearity-tolerant superchannel transmission via nonlinear noise squeezing and generalized phase-conjugated twin waves," Journal of Lightwave Technology, vol. 32, pp. 766-775, 2014.
33. S. T. Le, M. E. McCarthy, N. Mac Suibhne, A. D. Ellis, and S. K. Turitsyn, "Phase-conjugated pilots for fibre nonlinearity compensation in CO-OFDM transmission," Journal of Lightwave Technology, vol. 33, pp. 1308-1314, 2015.
34. X. Liu, H. Hu, S. Chandrasekhar, R. Jopson, A. Gnauck and M. Dinu., "Generation of 1.024-Tb/s Nyquist-WDM phase-conjugated twin vector waves by a polarization-insensitive optical parametric amplifier for fiber-nonlinearity-tolerant transmission," Optics Express, vol. 22, pp. 6478-6485, 2014.
35. S. Le, M. McCarthy, S. Turitsyn, I. Phillips, D. Lavery and T. Xu,"Optical and digital phase conjugation techniques for fiber nonlinearity compensation," in 2015 Opto-Electronics and Communications Conference (OECC), pp. 1-3, 2015.
36. J. K. Hmood and S. S. Radhi, "Influence of physical dimensions on efficiency of phase-conjugated twin waves technique in coherent optical communication systems," Optics Communications, vol. 428, pp. 113-119, 2018.
37. A. Ellis, S. Le, M. McCarthy, and S. Turitsyn, "The impact of parametric noise amplification on long haul transmission throughput," in 2015 17th International Conference on Transparent Optical Networks (ICTON), pp. 1-4, 2015.

38. J.K. Hmood, S.S.Husain, S.W. Harun, "Efficiency enhancement of phase-conjugated twin waves technique by shaping envelopes of subcarriers in all-optical OFDM systems", Optics Communications 472 (2020) 125864
39. S.S.Husain , J.K. Hmood, " Nonlinear Distortion Cancellation in Spatial Division Multiplexing System Based on RZ-Coded PCTWs Technique ", DOI: https://doi.org/10.33103/uot.ijccce.20.2.6
40. S.S.Radhi, J.K. Hmood, S.W. Harun, " Performance analysis of WDM-SDM system with employing Phase-Conjugated twin waves technique", Materials Today: Proceedings 42 (2021) 2490–2496
41. J.K. Hmood, S.S. Radhi, "Influence of physical dimensions on efficiency of phase-conjugated twin waves technique in coherent optical communication systems", Optics Communications (2018), https://doi.org/10.1016/j.optcom.2018.07.051
42. Y. Yu ,W.i Wang, P. D. Townsend, J. Zhao," Modified Phase-Conjugate Twin Wave Schemes for Spectral Efficiency Enhancement", Ecoc 2015 - ID: 0429.