International Journal of Engineering in Computer Science

**E-ISSN:** 2663-3590
**P-ISSN:** 2663-3582
www.computersciencejournals.com/ijecs
IJECS 2025; 7(2): 18-25
Received: 19-04-2025
Accepted: 23-05-2025

**Mezher H Mezher**
Department of Electronics and Communication, College of Engineering, University of Al-Qadisiyah, Iraq

**Tabarek Mazen Makki**
Scientific and Engineering Consulting Bureau, College of Engineering, University of Al-Qadisiyah, Iraq

**Corresponding Author:**
**Mezher H Mezher**
Department of Electronics and Communication, College of Engineering, University of Al-Qadisiyah, Iraq

# Advancements in fiber-optic communication: Addressing nonlinear challenges

**Mezher H Mezher and Tabarek Mazen Makki**

**DOI:** https://DOI.org/10.33545/26633582.2025.v7.i2a.194

**Abstract**
By using OPFs to transmit data in the form of light, fiber-optic communication has completely changed the way in-formation is transmitted. This technology's remarkable benefits, such as much lower attenuation, increased band-width capacity, and decreased crosstalk over extended distances, make it superior to conventional electrical trans-mission techniques. The deployment of Wavelength Division Multiplexing (WDM), which maximizes bandwidth usage by enabling several data channels to be carried simultaneously at various wavelengths, is one of the rapid breakthroughs in optical fiber (OPF) technology that are examined in this research. However, nonlinear event in-volved Self-Phase Modulation (S.P.M.), Four-Wave Mixing (FWM), and Stimulated Raman Scattering (S.R.S.) that are inherent in fiber optics frequently impair the performance of WDM systems. Signal distortion and energy loss may result from these causes. The study examines many digital modulation methods, such as Differential Phase Shift Keying (DPSK), Return-to-Zero (RZ), and Non-Return-to-Zero (NRZ), and evaluates how they affect system performance and efficiency at high bit-rates. The results point to a future path for optical communication system research and development, showing that DPSK provides improved sensitivity and lower bit error rates, while RZ modulation exhibits higher resilience to nonlinear effects.

**Keywords:** Fiber optic, WDM, S.P.M., FWM, S.R.S., DPSK, NRZ, and RZ

## 1. Introduction

The operation of convey the data and information from one place to another through an optical fiber (OPF) in the form of light called Fiber optic communication. This method of communication has not only played a crucial role in revolutionizing the field of telecommunications, but also has exercised a significant role in the sophistication of information due to its merits over electrical transmission [1]. In modern communication the copper wires have been replaced with fiber due to the advantages of OPF. One major advantage of fiber is its exceptionally low loss. Another merit is when fiber cables run together for long distances, the cross talk may vanish. Recently, bit rate fiber transmission took center stage to become an important part of state-of-the-art communications [2].

The rapid development in OPF communication technology has provided great transmission capacity and longer transmission distance to satisfy the growing demand of computer network. Also, modern technology in WDM permits very high-capacity networks. WDM provide an advantages of convey a significant number of data using different channels and varying wavelengths, which allows to invest all the bandwidth introduced by OPF [3].

High data rate OPFs in contemporary WDM systems have some adverse effects that decrease system performance by reacting negatively to the system's efficiency. The nonlinearity of the fiber is the WDM system's limiting factor. The main drawback of nonlinear impact is the poor performance of WDM optical networks, which results in output signal distortion and channel energy waste [4, 5].

In fiber optic systems, there are several digital modulations of different techniques. The variations are NRZ, RZ, and bi-phase. Consequently, various modulation schemes, such as Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK) are in use. In optical communication system, nonlinearity is a term that refers to the reliance of the system within the optical beam power, which is launched through the fiber cable. The effects of nonlinearity in OPFs have turned to be a vital field of academic research that bears great significance in OPF-based systems. Findings of previous

experiments have shown that the deployment of high-bitrate multi wavelength systems along with optical amplifiers cause principal impact of nonlinear like S.R.S., SBS, S.P.M, X.P.M. and FWM. The system designers should take into consideration the nonlinearity effects and their influence in deploying high-bit-rate (>10Gbit/s per channel) in multi wavelength systems. Both the positive and negative effects of nonlinearity on the system's performance were examined in the interest of make a decision whether that influence brings positive or negative outcomes [6, 1].
Nonlinearities of OPFs originated from the susceptibility of the third order (c3). Nonlinearity effects on the transmission length of the OPF. As the length of the OPF increases, the interaction between the light and the fiber material also increases, resulting in enhanced nonlinearity effects. However, nonlinearity effects will be reduced if power is decreased during the process of the transmission of light along the OPF. To overcome this R Z modulation format has become progressively common for the systems of Long-haul OPF transmission operates at bit rates of 10 GB/s and higher [7].
Despite the advantages of RZ format, it is frequently ignored and disregarded as the format requires greater bw than Non-N.R.Z format. Also, RZ format usually demands two cascaded MZ modulators. Recently, RZ showed that its performance was better especially in some areas with chromatic dispersion and fiber nonlinearities than the performance of NRZ [8, 9]
This is due to the possibility of soliton-like properties in the RZ pulse. Furthermore, compared to NRZ, RZ has demonstrated a higher tolerance to polarization-mode dispersion. R Z performance with various modulation schemes, including binary OOK and binary DPSK, is compared in some recent studies. The purpose of this comparison is to enhance long-distance transmission [10] [11].
The key to a future modulation approach that can maintain the signal over extended transmission distances with a low bet error rate is differential phase-shift keying (DPSK). Long-haul transmission systems that use this technique can perform better than those that rely on the traditional OOK format. Stated differently, it may result in the coexistence of several (pdftex.def) utilizing viewport instead of [12].
In this portion, the main problem, selected in the study should be discussed with the relevant earlier literature and the proposed method or solution. Proper references should be used in support to the content.

## 2. Fiber Optic Communication System
### 2.1 Components of OPF system
Modern OPF communication system could be classified into different components with variations in functions and technological implementations. This section describes the key elements of a communication system using fiber optics [13].

#### 2.1.1 Transmitter
A light source is the transmitter's main part. Information signals are converted from their electrical form into light via the light source. These days, fiber-optic communication system a light source known as Laser Diode (LDs) is used extensively in fiber-optic communication system. Meanwhile, the miniature semiconductor devices efficiently convert all the electrical signals into light. These devices demand connection of power supply and modulation circuitry. Therefore, the light source and semi-conductor devices make up one integrated package [13] [14].

#### 2.1.2 OPF
An OPF operates as the transmission media. Light is sent from a transmitter to a receiver via this transparent, flexible filament. In a fiber-optic communication system, the OPF transmits the signal of optical information from the transmitter end to the reception end. As with any communication link, the optical-fiber provides the link between a transmitter and a receiver. In the case of fiber-optic communication, fiber conducts light while copper wire and coaxial conduct an electrical signal. Generally, fibers are made from silica, a type of glass or from plastic, but is less commonly used nowadays. The thickness of an optical-fiber is as fine as a strand of the human hair. In order to keep the very delicate optical-fiber from the hostile environment and mechanical damage, it is usually enclosed in a certain structure. Therefore, the bare optical-fiber is coated for protection and encapsulated in many layers that constitute the fiber-optic cable [13] [14] [15].

#### 2.1.3 Receiver
The photo detector is the fundamental component of an optical receiver. Reconverting an optical information signal back into an electrical signal is the job of a photo detector. In the current fiber-optic communication system, a semiconductor called a photodiode (PD) serves as the photo detector. This little gadget is frequently updated together with its electrical components to create a cohesive package that provides signal amplification and power-supply connections [13] [14].

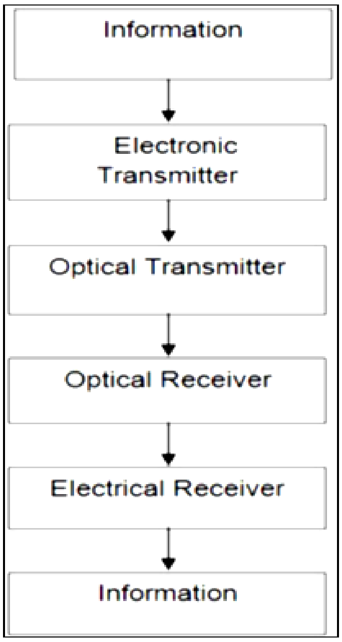


**Fig.1:** Communication System of Fiber-Optic

#### 2.1.4 Types of OPF
A thin glass strand is called optical-fiber. But it is harder than steel, inch for inch. The idea of optical-fiber was merely a scientist's fantasy thirty years ago. But now that this amazing technology is a reality, it is changing how information is sent and received globally. MLF and SMF are the two varieties of optical-fiber [16].

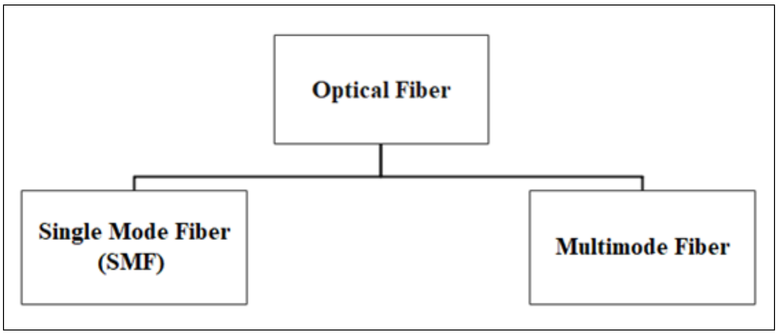


**Fig 2:** Types of optical-fiber.

### 2.1.5 Single Mode Fiber (SMF)

It is an optical-fiber with a few losses which is commonly used for long haul. This type of fiber is distinguished by a small core radius varying between 1-16 µm. The differential refractive index between the core and the cladding is about 0.6%. This type of fibers only used with lasers because of its narrow Numerical Aperture (NA). Also, Single Mode Fiber (SMF) has a small core diameter that keeps the light beam move in a single pathway, or single mode, down the center of the fiber core. The signal in single mode fibers travels faster than in multi-mode fiber because the signal does not reflect off the cladding in the small diameter core. Single mode fiber is typically favored for telecommunications because of the huge amount of traffic that it can carry [17] [18].

### 2.1.6 Multimode Fiber

Multi-mode step index fibers were the first type of fiber design but it was too slow for most uses, due to dispersion due to the multi path lengths of the dissimilar modes. Its big core diameter, is larger than the Numerical Aperture (NA), with a core radius ranging from 25 to 60 µm. These fibers are used as short links between building or campus networks [19]. Multimode graded index fibers core manufacturing from different glass composite used in different guide length of modes. Thus, Multimode offer very high band width compare to fiber step index up to about 2GHz. This type of fiber has a core radius that ranges from 10-35 µm [19] [20].

### 2.2 Nonlinear effects of OPF

Even though the signal power is relatively modes, nonlinear effects in optical-fiber s arise when the optical intensity of a propagating signal is strong.

A tiny optical-fiber cross section is responsible for the high intensity, which is enough to produce noticeable nonlinearity effects. Furthermore, because optically amplified systems have a long interval between regenerations, the effects of nonlinearity may compound over extended distances. Depending on where they come from, nonlinearity influences can be divided into two groups: optical Kerr impact and stimulated scatterings. The intensity dependence of an optical-fiber's refractive index results in a phase constant that varies with optical intensity, which causes the optical Kerr effect. In contrast, stimulated scattering happens when a scattering results in an attenuation constant that is intensity dependent. S.R.S. and SBS are two examples of stimulated scattering phenomena that can happen in an optical-fiber. FWM, X.P.M., and S.P.M might result from the intensity relented of refractive index. The fact that stimulated scattering is linked to threshold powers at which its effects become notable is another way that it differs from the effects of nonlinear refractive index [21, 22, 23].

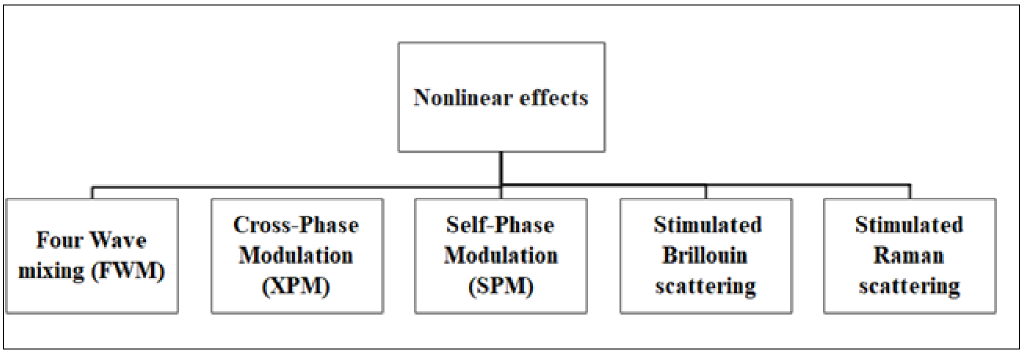


**Fig 3:** Classification of nonlinear effects.

### 2.2.1 Four Wave mixing (FWM)

For the case of several wavelengths co propagate in the exact fiber and meet the phase matching criterion, a nonlinear process known as FWM takes place. When two or more frequencies interact in FWM, a variety of new frequencies are produced. For instance, when three frequencies $(\omega_i, \omega_j, \omega_k)$ co-propagate in the fiber, the generation of new frequencies $(\omega_{i\,jk})$ is represented by [24]

$$\omega_{i\,jk} = \omega_i + \omega_j - \omega_k \tag{1}$$

If two of three of these frequencies are similar only two new wavelengths are created in the fiber. This is illustrated in Figure 2. Partially degenerate four-wave mixing (PDFWM) is another name for this situation [25]. In this case, when $\omega_i = \omega_j$, the additional frequencies generated are $\omega_{112}$ *and* $\omega_{221}$. This is shown in Figure 4.

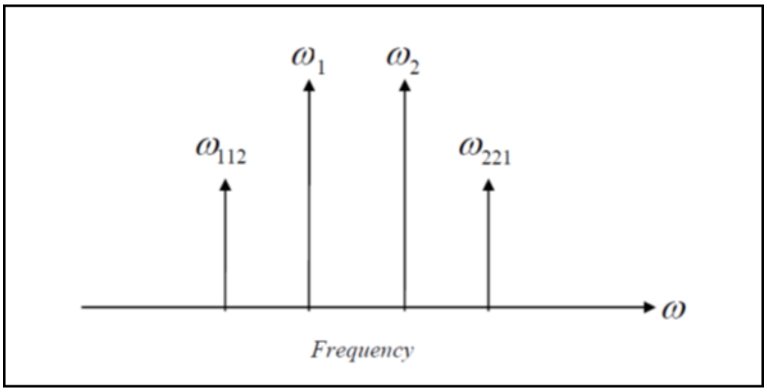


**Fig 4:** Additional frequencies generated through FWM.

According to equation 2, nine new frequencies would be produced if three distinct frequencies were sent into a fiber. Nondegenerate four-wave mixing is another name for this phenomenon. Put otherwise, a fiber with N co-propagating wavelengths might use FWM to produce M extra frequencies. The relationship between these two variables can be shown as:

$$M = \frac{1}{2}\left(N^3 - N^2\right) \quad (2)$$

Happening the FWM requires the phase matching condition, which refers the capacity of FWM be contingent on dispersion and channel spacing. Dispersion prevents the velocity match, which in turn destroys the condition of phase appropriate. So that, rise local waste fiber and larger channel spacing are helpful in a WDM system [12, 26, 27].

### 2.2.2 Self-Phase Modulation (S.P.M.), Cross-Phase Modulation (X.P.M.)

S.P.M. as well as X.P.M. are the significant nonlinear influence that result from the intensity be contingent on the refractive index. S.P.M. is represent by the self-inducing phase shift that an optical field undergoes when traveling through optical-fibers. At different wavelengths, a co-propagating filed is due to the nonlinear phase shift of the fiber field this refer to X.P.M. In a fiber, co-propagation happens simultaneously when two optical fields at frequency $\omega_1 and\ \omega_2$ polarize along the x axis. This is shown in the equation below:

$$E = \frac{1}{2} X\left[E_1 \exp(-j\overline{\omega}_1 t) + E_2 \exp(-j\overline{\omega}_2 t) + c.c.\right] \quad (3)$$

The field at w1 and the nonlinear phase shift caused by S.P.M. and X.P.M. can be written as follows:

$$\emptyset_{NL} = n_2 k_{\circ} L\left(|E_1|^2 + 2|E_2|^2\right) \quad (4)$$

**Where**

N2 is the coefficient of the nonlinear index,

$k_{\circ} = 2\pi/\lambda$, and L fiber length.

The equation 2.4 content from two part, first one refers to SPM and second refers to X.P.M.-induced nonlinear phase shift, the previous formula show SPM is a half of face shift nonlinear phase shift. From this equation it can be said that for equally intense optical fields, the contribution of X.P.M. to is twice as high compared with that of S.P.M.[12, 26, 27].

### 2.2.3 Stimulated-Raman-scattering (S.B.S.) also the Stimulated-Brillouin-scattering (S.R.S.)

It causes both S.R.S. as well as SBS, where the optical field partially transports its energy to the nonlinear medium. S.R.S. and SBS vary primarily in that whilst acoustic phonons engage in SBS, optical phonons participate in S.R.S. A photon of the pump is blocked to produce a photon at the downshifted Stokes frequency and a phonon with the proper energy and momentum to save the energy and momentum in a straightforward quantum-mechanical illustration that applies to both S.R.S. and SBS. Of course, if a photon with the proper energy and momentum is available, it can also produce a higher-energy photon at the anti-Stokes frequency. Even while S.R.S. and SBS share a lot of similarities, they vary fundamentally. In optical-fiber s, S.R.S. controded the forward direction while SBS only happens in the reverse direction. For S.R.S., the initial development of the Stokes wave can be represented simply by the following equation:

$$\frac{dI_s}{dz} = gRI_p I_s \quad (5)$$

Knowing that

Is, IP and gr are the Stokes, pump intensities and the Raman-gain coefficient, respectively.

The same formula applies to SBS when the Brillouingain coefficient is used in place of (gR). The broad gB Raman gain spectrum reaches up to about 30 THz. The maximal gain of (gR) happens at the Stokes shift of approximately 13 THz and is approximately $10^{-3}$ m/w at one mm of pump wavelength. The Brillouin-gain spectrum, on the other hand, has a bandwidth of roughly 10 MHz and is incredibly narrow. Around 0.006 m/w is the peak value of gB, which happens at the Stokes shift of roughly 10 GHz. When the pump intensity surpasses a particular threshold, a notable conversion of pump energy of Stokes takes place for both S.R.S. and SBS. SBS is often detectable at a pump power of 10mW, whereas S.R.S. is typically detectable at a pump power of 1mW. The Stokes shift for S.R.S. is very significant (up to 13 THz). In actuality, this figure is more than the shift for the entire bandwidth of the conventional C-band simulated WDM system. When compared to the bandwidth of the optical spectrum of the transmitted signal in a high-speed lightwave system, SBS's small spectrum bandwidth is insignificant. Therefore, it is essential to take into account the nonlinear degradation effects of fibers while they are being transmitted [12, 26, 27].

### 2.3 Modulation Format

Data can be impressed onto an optical carrier wave for transmission across an optical-fiber using an optical modulation format. A high-capacity transport infrastructure made up of fiber-optic communication systems enables the use of established internet applications and universal broadband data services. Optimally routed networks with high spectrum efficiency are the result of the goal for both greater per-fiber transport capabilities and, at the same time, reduced costs per end-toned transferred information bit. Other technologies, like as optical modulation formats, have emerged as essential components of capacity design. The process of imprinting digital data onto an optical carrier is known as modulation. Coding is also used in modulation to either stop errors from being transmitted or fix transmission problems that have already happened. Recently, fiber nonlinearity has a negative effect on WDM system, whereby this behavior is reflected on the receiver sensitivity of the system. Many techniques have been proposed to reduce this phenomenon and to enhance the bit error rate. Figure 5 shows. Therefore, modulation format is an important key feature to overcome the nonlinear effect in the optical link. The modulation format can be classified into different types [11, 12, 28].

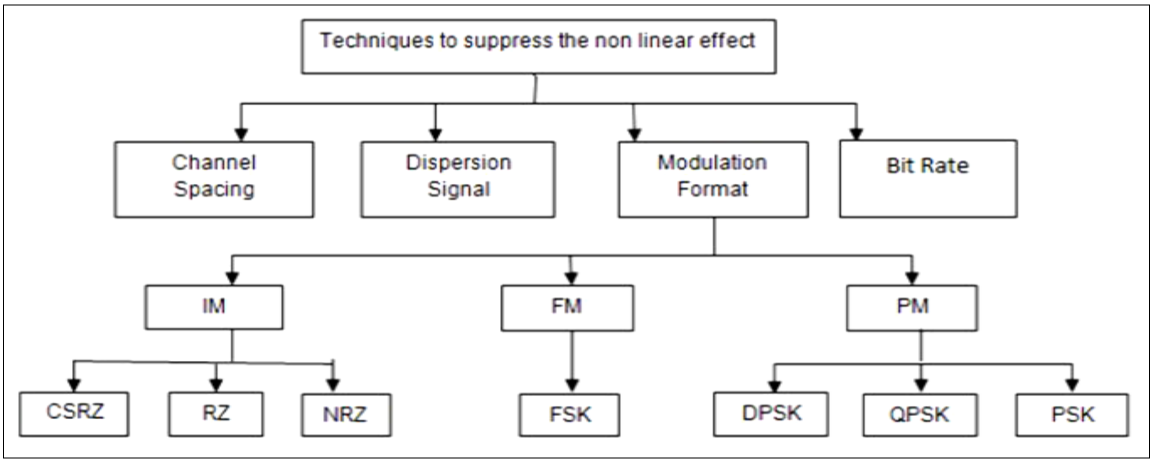


**Fig 5:** Classification of Modulation Formats

The first type is differential modulation technique which deals with the input signal phase while the second type of modulation format is intensity modulation whereby the attribute key is the intensity of the input signal[12, 26, 27].

### 2.4 Non return to zero on off Keying (NRZ OOK)

The NRZ is predominant modulation in fiber-optical communication systems. The most commonly used data waveform is NRZ, which has an on/off modulation amplitude. The NRZ format is used for data transmission using fiber optics at lower data speeds of 10 Gb/s. The NRZ optical fiber modulations was used for a number of purposes. One of the reasons is that, in contrast to return-to-zero modulation, the small electrical bandwidth take place in NRZ modulation due to transmitter and receiver operations. The other reason is that, in contrast to phase shift keying, it is less susceptible to laser phase noise. Lastly, the transmitter and receiver configuration is the most straightforward. The NRZ modulation format might not be the ideal option for upcoming high-capacity optical networking systems given the latest advancements in the field of optical communication. However, due to its historical supremacy and simplicity, it has been widely used; NRZ would be an excellent reference for comparison when an external intensity modulator is utilized for modulating an electrical signal [29, 30].

An electrical signal can be converted to an optical signal (OS) at the same data rate using either a Mach-Zehnder or an electro-absorption intensity modulator. An NRZ OS is detected at the receiver using a photodiode, which converts the signal's optical strength into an electrical current. Direct detection from one side is the word used to describe this technique. For WDM systems, the NRZ modulation format is more suitable. NRZ is more negatively impacted than RZ by nonlinearity, the main source of degradation. When compared to other modulation schemes, the NRZ modulated OS often has the most condensed spectrum. This does not imply, however, that NRZ is more resilient to FWM and X.P.M. in DWDM systems. It has been demonstrated that NRZ OS are less resistant to the GVD-and Self Phase Modulation effect during transmission than their RZ counterparts because of their strong carrier component in the optical spectrum [11, 25, 27, 28, 31].

#### 2.4.1 Return to zero on off Keying (RZ OOK)

Two bandwidth ultra-long-haul of 10Gb/s and long-haul of 40Gb/s that suffring long time due to power of peak is high, low bit rate error and SNR signal to noise ratio the characteristics of non-return-to zero (NRZ) modulation therefore use the Return to Zero (RZ) become common solution[32]. The RZ had many specifications such as dispersion mode of polarization, immune to nonminority from opt optical fiber due to DWDM interaction channel and modulation of cross phase. The shape of the OSs of RZ is carved by the use of a clock signal with the same data-rate as electrical signal. It is created by an external intensity modulator; after a synchronized pulse train with the same data-rate as the electrical signal that modulates the OS by cascading another intensity modulator. Also, waveforms of RZ can be created first followed by modulation onto an optical carrier. if we campers between optical pulse between NRZ and RZ we found that RZ have dou 50% duty-cycle, duty cycle and optical power average remain same at the constant, while optical amplifier take pace to rise in power and run in the saturation mode, resulting in a gain that scales with average input power [33].

There is some relationship had been used, like the photodiode was a square law detector, while the photo-current had proportional relationship to optical power then optical power receiver became proportional relationship to square photo-current and optical power. Thus, resulting the electrical pulse of NR double of NRZ. Some more of the RZ that require more complexity of transmitters structure. The combination MZ modulator at 50% duty-cycle data rate produces a RZ pulse with duty-cycle of 33% that located between minimums and maximums transmission. Thus behave show good tolerance to nonlinear optical effects camper to NRZ due to data pattern regular in OS while the RZ pulse show large spectrum due to have narrow pulse. This feature makes the spectrum of pulse shaping of RZ less efficient in a WDM system [34, 35].

#### 2.4.2 Differential Phase Shift Keying (DPSK)

The Differential binary phase shift keying (DPSK) modulation used to encode the binary information that can be change between bit 0 and bit1 where 0 represent absence the phase change while 1 encode the phase change, that represent DPSK and OOK can be executed in RZ and NRZ format.[36, 37, 38]. The phase of a narrow-lined width laser source in the optical field is then between 0 and p using the preceded data sequence. This means one is free to use either a straight-line Phase Modulation (PM) or an MZM to achieve the optical phase modulation [39, 40, 41].

The insertion of a pulse carver can help to convert the NRZ-DPSK signal to RZ-DPSK, respectively. The absence of a 0-bit rail in the eye diagrams, is characteristic of phase-modulated formats. The intensity that dips between the two bits in the NRZ-DPSK eye represents the residual intensity modulation of the MZM caused by the finite NRZ drive signal bandwidth. Since DPSK cannot be received directly by the use of square law detection, one inserts Delay-Interferometer is (DI) inserted in the optical path at the receiver to convert the differential phase modulation into intensity modulation. In addition to that, the length difference of the (DI) has to be fine-tuned with sub wavelength accuracy (i.e. on the order of 10 nm and matches with less than 0.1 fs, in the 1550-nm wavelength range) for the purpose of controlling interferences at the DI output [42, 43, 44].

In a direct-detection DPSK receiver, the DI allows two adjacent bits interfere with each other on its output ports. Such interference can lead to the presence of power at a DI output port if the two adjacent bits interfere constructively or otherwise with each other. As a result, in a bit stream that is DPSK encoded, the bits that come before it serve as the phase reference for the current bit's demodulation. In a practical DPSK known as a balanced receiver, this phase reference can be provided by a local laser inside the receiver in order to beat the received signal in the case of coherent detection. This results in both constructive and destructive interferences. This receiver makes advantage of both the constructive and destructive MZI ports. Therefore, the primary benefit of DPSK is its 3-dB sensitivity, which allows for balanced detection [45].

### 2.5 Related Works

It is necessary to study and investigate the efficient modulation formats for high bit [31]. Fiber-optic communication's advanced modulation algorithms make up the high-capacity transport backbone that makes developed Internet applications and global broadband data services possible [12]. Optically routed networks with high spectrum efficiency have been created due to the need for both reduced prices per end-to-end transmitted information bit and better per-fiber transport capabilities. In this study, two channels with data rate of 10 Gb/s were used for the purpose of comparing the results with of intensity modulation and phase modulation format of Quantum Limited DPSK Receivers with Optical Mach-Zehnder Interferometer Demodulation [46, 47]. The study for the advancement in performance is on the 10 Gb/s to large the network of system, requires some essential components such as high speed electronic, optical and opto electronic components, a novel modulation format as well as, resilience in impairments and transmission [48, 49]. The design and application of such large networks is an expensive and costly project. These networks are also time-consuming exercise because of sophisticated and intricate design procedures.

## 3. Conclusion

Fiber-optic communication technology has established itself as a fundamental component of contemporary telecommunications, enabling unprecedented data transmission speeds and capacities. The transition from traditional copper wiring to optical-fiber has been driven by the need for efficient communication systems capable of handling the exponential growth of data traffic. Despite the advantages, the challenge of nonlinear effects remains a significant concern, particularly in high-speed WDM systems. This paper highlights the importance of understanding these nonlinearities and their implications for system design. The analysis of modulation formats reveals that both RZ and DPSK offer viable solutions to mitigate the adverse effects of nonlinearity. RZ modulation demonstrates improved performance in environments with chromatic dispersion, while DPSK's differential encoding reduces susceptibility to noise, enhancing overall system robustness. This indicates that careful selection of modulation techniques is crucial for optimizing performance in fiber-optic networks. Looking forward, continued research into advanced modulation strategies and the development of adaptive techniques to counteract nonlinear distortions will be essential. The findings underscore the need for ongoing innovation in fiber-optic technology to meet the demands of future high-capacity communication networks, ensuring that they remain reliable and efficient in an increasingly data-driven world.

## 4. References

1. Elsherif M, Salih AE, Muñoz MG, Alam F, AlQattan B, Antonysamy DS, *et al*. OPF sensors: working principle, applications, and limitations. Adv Photonics Res. 2022;3(11):2100371. DOI:10.1002/adpr.202100371
2. Gangwar A, Sharma B. OPF: the new era of high speed communication (technology, advantages and future aspects). Int J Eng Res. 2012;4(2):19-23.
3. Hayee MI, Willner AE. NRZ versus RZ in 10-40-Gb/s dispersion-managed WDM transmission systems. IEEE

Photonics Technol Lett. 1999;11(8):991-993. DOI:10.1109/68.775323
4. Kaur G, Singh ML, Patterh MS. Effect of fibre nonlinearities in a WDM transmission system. Optik. 2010;121(10):889-896. DOI:10.1016/j.ijleo.2008.09.035
5. Wehmann CF, Fernandes LM, Sobrinho CS, Lima JLS, Da Silva MG, De Almeida EF, *et al*. Analysis of the four wave mixing effect (FWM) in a dispersion decreasing fiber (DDF) for a WDM system. Opt Fiber Technol. 2005;11(3):306-318. DOI:10.1016/j.yofte.2005.01.003
6. Begum SJ, Thamhina K. Fiber optical communication systems, modulation techniques and its applications. 2022;71(2):430-434.
7. Sahara A, Inui T, Komukai T, Kubota H, Nakazawa M. 40-Gb/s RZ transmission over a transoceanic distance in a dispersion managed standard fiber using a modified inline synchronous modulation method. J Lightwave Technol. 2000;18(10):1364-1373. DOI:10.1109/50.887187
8. Breuer D, Petermann K. Comparison of NRZ- and RZ-modulation format for 40-Gb/s TDM standard-fiber systems. IEEE Photonics Technol Lett. 1997;9(3):398-400. DOI:10.1109/68.556086
9. Sunnerud H, Karlsson M, Andrekson PA. RZ data. n.d.;10-12.
10. Mizuochi T, Ishida K, Kobayashi T, Abe J, Kinjo K, Motoshima K, *et al*. A comparative study of DPSK and OOK WDM transmission over transoceanic distances and their performance degradations due to nonlinear phase noise. J Lightwave Technol. 2003;21(9):1933-1943. DOI:10.1109/JLT.2003.816849
11. Xu C, Liu X, Mollenauer LF, Wei X. Comparison of return-to-zero differential phase-shift keying and ON-OFF keying in long-haul dispersion managed transmission. IEEE Photonics Technol Lett. 2003;15(4):617-619. DOI:10.1109/LPT.2003.809317
12. Winzer PJ, Essiambre RJ. Advanced optical modulation formats. Opt Telecommun VB: Syst Netw. DOI:10.1016/B978-0-12-374172-1.00002-3
13. Ummah MS. Digital and analog fiber optic communications for CATV and FTTx applications. Sustainability. 2019;11.
14. Sharma P, Arora RK, Pardeshi S, Singh M. Fibre optic communications: an overview. Cert J. 2008;3(5):474-479.
15. Al Ibraheemi MMA, Radhy ZH, Anayi FJ, Al Ibraheemi H. Memorized approach for implementation of space vector pulse width modulation. Period Eng Nat Sci. 2019;7(4):1892-1903. DOI:10.21533/pen.v7i4.955
16. Koike Y, Koike K. OPFs. Polym Sci: Compr Ref. DOI:10.1016/B978-0-444-53349-4.00209-0
17. Girsang L, Napitupulu A, Simorangkir I, Dahlan D, Eng SM. Indepth study of single mode optical fibre. 1991;1:2-7.
18. Yuan FG. Structural health monitoring/management (SHM) in aerospace structures. Struct Health Monit/Manag Aerosp Struct. DOI:10.1016/C2022-0-00499-2
19. Salih AR. Design of step-index multimode OPF. J Phys Conf Ser. 2021;1879(3):032074. DOI:10.1088/1742-6596/1879/3/032074
20. Sillard P, Molin D. OPFs. Springer Ser Opt Sci. 2016;161. DOI:10.1007/978-3-319-42367-8 2
21. Al Ibraheemi MMA, Anayi FJ, Radhy ZH, Neamah MW. Parameters estimation of non-saturated permanent magnet synchronous machines by aid of statistical analysis. Al-Qadisiyah J Eng Sci. 2023;16(2):127-132. DOI:10.30772/qjes.v16i2.877
22. In P. Nonlinear effects in OPFs: origin, management and applications. Prog Electromagn Res. 2007;249-275.
23. González-Herráez M, Sylvestre T. Nonlinear effects in OPFs. Adv Fiber Opt. 2011;145-170. DOI:10.1201/9781315370521-9
24. Thiel C. Four-wave mixing and its applications. 2011;1-19.
25. Wang H, Suter D. Double-sideband carrier suppressed RZ and NRZ modulation formats for ultra-high capacity 40 Gb/s optical communications systems. 2003.
26. Billington R. A report on four-wave mixing in optical fibre and its metrological applications. NPL Rep COEM. 1999;24:7-9.
27. Pavanasam C, Science C. Vestigial side band demultiplexing for high spectral efficiency WDM systems. 2000.
28. Winzer PJ, Pfennigbauer M, Strasser MM, Leeb WR. Optimum filter bandwidths for optically preamplified NRZ receivers. J Lightwave Technol. 2001;19(9):1263-1273. DOI:10.1109/50.948273
29. Mishina K, Kitagawa S, Maruta A. All-optical modulation format conversion from on-off-keying to multiple-level phase-shift-keying based on nonlinearity in OPF. Opt Express. 2007;15(13):8444. DOI:10.1364/oe.15.008444
30. Moghaddasi M, Rahman SBA. Comparison between NRZ and RZ OOK modulation format in chromatic dispersion compensation in both electrical and optical compensator. ISBEIA 2011 - 2011 IEEE Symp Bus Eng Ind Appl. 2011;494-497. DOI:10.1109/ISBEIA.2011.6088865
31. Haris M. Advanced modulation formats for high-bit-rate optical networks. 2008.
32. Hassan Abbas R, Fattah AY. 33% RZ-DPSK 10 Gb/s WDM transmission. Eng Technol J. 2011;29(11):2282-2297. DOI:10.30684/etj.29.11.16
33. Ip E, Kahn JM. Power spectra of return-to-zero optical signals. J Lightwave Technol. 2006;24(3):1610-1618. DOI:10.1109/JLT.2005.863328
34. Malhotra JS, Kumar M. Performance analysis of NRZ, RZ, CRZ and CSRZ data formats in 10 Gb/s optical soliton transmission link under the impact of chirp and TOD. Optik. 2010;121(9):800-807. DOI:10.1016/j.ijleo.2008.08.010
35. Yao S, Fu S, Wang H, Tang M, Shum P, Liu D. Performance comparison for NRZ, RZ, and CSRZ modulation formats in RS-DBS Nyquist WDM system. J Opt Commun Netw. 2014;6(4):355-361. DOI:10.1364/JOCN.6.000355
36. Humblet PA, Azizoglu M. On the bit error rate of lightwave systems with optical amplifiers. J Lightwave Technol. 1991;9(11):1576-1582. DOI:10.1109/50.97649
37. Gnauck AH, Winzer PJ. Optical phase-shift-keyed transmission. J Lightwave Technol. 2005;23(1):115-130.
38. Ummah MS. Data communication principles.

Sustainability. 2019;11.
39. Kabal P, Pasupathy S. Partial-response signaling. IEEE Trans Commun. 1975;23(9):921-934. DOI:10.1109/TCOM.1975.1092918
40. Chikama T, Watanabe S, Naito T, Onaka H, Kiyonaga T, Onoda Y, *et al*. Modulation and demodulation techniques in optical heterodyne PSK transmission systems. J Lightwave Technol. 1990;8(3):309-322. DOI:10.1109/50.50728
41. Winzer PJ, Kim H. Degradations in balanced DPSK receivers. IEEE Photonics Technol Lett. 2003;15(9):1282-1284. DOI:10.1109/LPT.2003.816112
42. Kim H, Winzer PJ. Nonlinear phase noise in phase-coded transmission. Conf Opt Fiber Commun Tech Dig Ser. 2005;4:453-455. DOI:10.1109/ofc.2005.192984
43. Penninckx D, Bissessur H, Brindel P, Gohin E, Bakhti F. Optical differential phase shift keying (DPSK) direct detection considered as a duobinary signal. Eur Conf Opt Commun ECOC. 2001;3:456-457. DOI:10.1109/ecoc.2001.989713
44. May G, Solheim A, Conradi J. Extended 10 Gb/s fiber transmission distance at 1538 nm using a duobinary receiver. IEEE Photonics Technol Lett. 1994;6(5):648-650. DOI:10.1109/68.285568
45. Sinsky JH, Adamiecki A, Duelk M. High-speed electrical backplane transmission using duobinary signaling Jeffrey. IEEE MTT-S Int Microw Symp Dig. 2004;1(1):109-112. DOI:10.1109/mwsym.2004.1335814
46. Zhang X, Qu Z, Wang L. Calculation of bit error ratio for optically pre-amplified DPSK receivers using optical Mach-Zehnder interferometer demodulation and balanced detection. Photonics North 2006. 2006;6343:63430O. DOI:10.1117/12.707686
47. Zhang X. Quantum limited DPSK receivers with optical Mach-Zehnder interferometer demodulation. n.d.;1-5.
48. Zhang S. Advanced optical modulation formats in high-speed lightwave system. 2004;85.
49. García-Pérez A, Andrade-Lucio JA, Ibarra-Manzano OG, Alvarado-Méndez E, Trejo-Duran M, Gutiérrez-Martín H. Efficient modulation formats for high bit-rate fiber transmission. Acta Univ. 2006;16(2):17-26. DOI:10.15174/au.2006.184