Research Article

Performance Evaluation of WDM Optical Fiber Communication System in the Presence of PMD

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Abstract

This paper investigates for rising optical fiber transmission strength, increasing bandwidth, and decreasing communication system weakness by using wavelength division multiplexing (WDM). WDM gives today's distention speed and communication traffic. Systems using WDM faces nonlinearities, which the most intensive nonlinear attack is, four wave mixing (FWM). FWM creates and increases crosstalk between WDM channels as a result slows down and impairs the performance of the communication system. This investigation uses orthogonal frequency division multiplexing (OFDM) for evaluating execution of WDM fiber system by repairing Polarization Mode Dispersion (PMD). We took results in the case of trying PMD-Emulator and without trying PMD-Emulator in the system design. We compared the results got in both cases. Furthermore, we compared the performance of the system with the investigations done using different ways, methods, and techniques for compensating PMD and FWM appears in WDM systems. As PMD-Emulator, helps enhancing the system design performance, and OFDM gives the feature of robustness and useful execution to the system. OFDM examined by appointing interfered orthogonal signal sets, for 16 channels; with equally spaced OFDM channels. Oure results showed that the optical fiber communication system using OFDM technique gives perfect removing FWM signal crosstalk, and accurate data transmission, comparing to other techniques used in other researches. We got a decreased FWM power to -77dBm, and the BER of -0.317. Furthermore, the system quality increased with applying PMD-Emulator and OFDM. In addition, using PMD-Emulator in the system design raised the results effectiveness. The program used in the present work is optisystem-15, and the results obtained in this study coincide with the theoretical and actual results obtained by the previous studies.

Keywords: WDM Improvement, PMD, OFDM, Nonlinearity, FWM.

1. Introduction

In systems operate on the bases of wavelength division multiplexing (WDM), nonlinear effects grown in significance, particularly at moderate powers and bitrates. In the WDM systems, at new frequencies FWM provide rise of new signals. These signals appear as crosstalk to the existing signals in the system (Alberto *et al.*, 2019), and (Petr *et al*, 2020). The effect of FWM is a great aspect for the future optical networks to consider (Alifdal *et al.*, 2017). As it decreases the performance of (WDM) optical networks, which damages the channel energy and the output signal (Petr *et al*, 2020). Moreover, to meet nowadays expansion demand for bandwidth, studying for overcoming ways of these transmission capacity limitations is continuous by the researchers (Salim, 2019). Furthermore, WDM is one of the solutions for expanding each fiber capacity to match the needing of enhanced mobile broadband (eMBB) within 5G network system

(Xiang Liu, 2019). In this paper, we connect an optical fiber communication system with (10 Gb/s) and modulating (16) channels using OFDM to evaluate the appearance of FWM, and (PMD) compensation in WDM systems.

In the latest years many researchers searched, studied, and published papers about this important issue. Researches are in different directions on it. Some of them are as following. In 2017 another group, worked on conservation matter set on controlling procedure of (FWM) make use of optical phase conjugation (OPC) elements, and using arrangements of OPCs that were non-identical in ultra-dense wavelength division multiplexing (WDM) system with coherent orthogonal frequency division multiplexing (OFDM) incorporation (Chawhan *et al.*, 2018). In 2018 researchers worked on the performance of (OCDMA/WDM), Simulation results showed bit-error-rate (BER)$\leq 10^{-9}$ for up to 25 Km distance at the bitrate of 1Gb/s optical communication networks (Ahmed *et al.*, 2018).. In 2019 investigation has been done on four-wave mixing noises suppression in QAM Coherent OFDM System They worked in polarization domain and showed improving the nonlinear tolerance of such system (Jianxin *et al,* 2019). They used the plan of phase-conjugated twin waves (PCTW) for decreasing the effect of FWM noise. In 2020 a group of researchers studied for upgrading FWM order in two-directed ultra DWDM-PON networking. They evenly located source of light and operated PMD emulator (Manzoor *et al,* 2020). In 2021 Fazal and his workmate worked for mitigation of FWM by operating DSP receiver. They could compensate FWM effect to attain a BER under 10^{-6} for reaching an optical fiber propagation far to 500 Km. (Fazal *et al*, 2021). Moreover, it will be continuous as overtime work on the internet, its various uses for fast, accurate, and pure communications needed and with a high possibility, the need increased.

2. Fiber Nonlinearity

The transmitted spectrum in optical WDM is linear as long as the fiber power is not large. Utilizing high input optical power in long haul connection for reducing the repeater numbers is some other great nonlinearity reference. These give rise to high production impairments. The basic nonlinear impairments in WDM fiber communication systems known as Kerr effects, which are self-phase modulation (SPM), cross phase modulation (XPM), and four wave mixing (FWM). Need to be reduced (Muhammad Irfan *et al,* 2020). SPM brings out new wavelength by widening the optical spectrum. It can be controlled by many techniques for restoring optical information such as operate spectral reparation filtering (Chung *et al,* 2018). Conversion of an optical pulse by another optical pulse expects to cross-phase modulation (XPM), that all the optical signal phases affected by one signal; and vice-versa (Alifdal *et al.*, 2017).

In fact FWM is interference just like ISI. Reaction of three wavelengths give rise to fourth wavelength. It causes phase shift in a WDM channel and lead for creation of new frequencies as shown in Fig 1 (Fazal *et al*, 2021).

The obstacle that is most worthy among the nonlinear type's wares by bringing down the execution of WDM optical networks. Creates possible distortion of the signal output and disperse channel energy is FWM. Which is the most powerful damage influence. When the index of refraction inside the fiber changes with the power level, the FWM turns up (Fazal *et al*, 2021).

In WDM, the occurrence of FWM counts on some factors. Among them; the power per channel, the channel spacing wavelength, the interact distance of transmission, effective area, and the optical fiber run features (Fazal *et al*, 2021). In FWM due to channel interference a heavy crosstalk is generated in the network (Alifdal *et al.*, 2017).

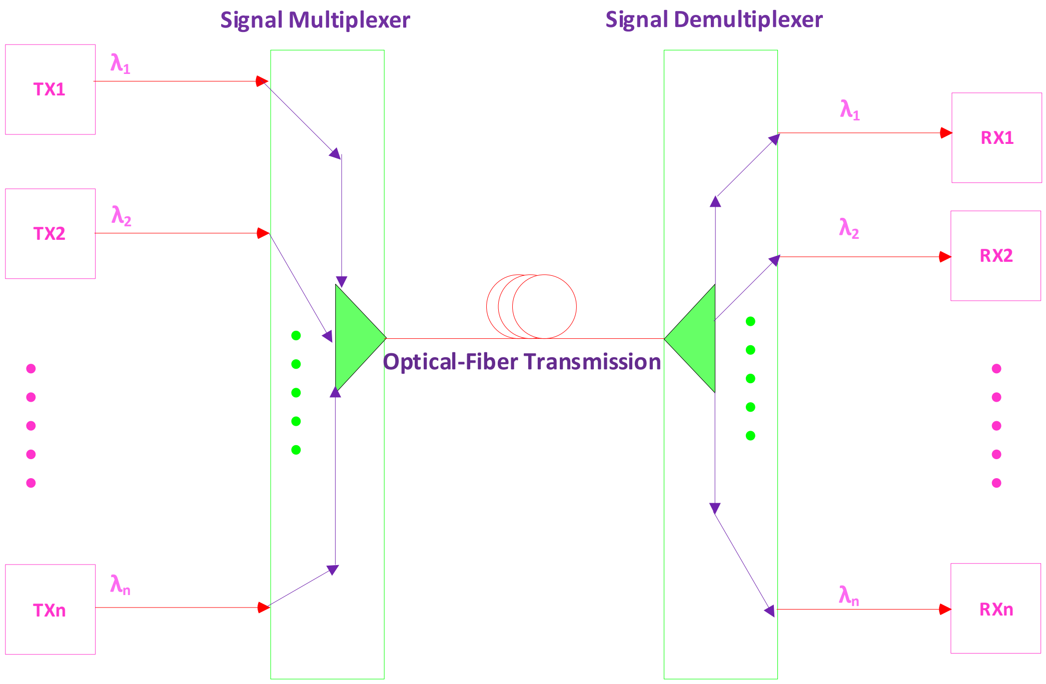


Figure 1. (WDM) Process Diagram.

If we have three waves with frequencies f_i, f_j, and f_k, over an optical fiber cooperating. They produce nonlinearity by interacting with each other and getting out nine new waves at frequencies of equation 1, and Fig 2 (Manzoor *et al,* 2020):

$$f_{ijk} = f_i \pm f_j \pm f_k \qquad (1)$$

The number of new waves produced by the FWM symbolled as M. In general shown in the formula of equation (2) for N number of input wavelengths: (Alifdal *et al.*, 2017), and (Manzoor *et al,* 2020):

$$M = \frac{N^2(N-1)}{2} \qquad (2)$$

Where: N = number of channels multiplexed.

At frequency fijk the power of the new produced optical wave is (Alifdal *et al.*, 2017):

$$P_{ijk} = \eta \frac{1024\pi^6}{\eta^4\lambda^2c^2}\left(\frac{DX_{1111}L_{eff}}{A_{eff}}\right)^2 P_iP_jP_k e^{-\alpha L} \qquad (3)$$

Where:

Pi, pj, pk = Insert powers, α = loss coefficient of Fiber, n = index of refraction of Core, X_{1111} = Nonlinear susceptibility (third order), λ = inner wavelength, c = Vacuum velocity of Light (= 3×108 m/s), L_{eff} = Fiber effective length. It given by

$$L_{eff} = \frac{(1-e^{-\alpha L})}{\alpha} \qquad (4)$$

A_{eff} = effective area of Core, D = decadence factor (D = 3 for i = j, D = 6 for i ≠j

FWM efficiency, it is given by (η).

$$\eta = \frac{\alpha^2}{\alpha^2+\Delta\beta^2}\left[1 + \frac{4e^{-\alpha L}sin^2(\Delta\beta L/2)}{[1-e^{-\alpha L}]^2}\right] \quad (5)$$

This efficiency depends on the channel spacing through the phase mismatch (Alifdal *et al.*, 2017):

$$\Delta\beta = \frac{2\pi\lambda^2}{c}|f_i - f_k|\left[D_c + \frac{dD}{d\lambda}\left(\frac{\lambda^2}{2c}\right)\left(|f_i - f_k| + |f_j - f_k|\right)\right] \quad (6)$$

Dc is the chromatic dispersion coefficient and $\frac{dD}{d\lambda}$ is its slop.

For N number of WDM system channels, the total power produced in the result of FWM at the frequency fm expressed as (Alifdal *et al.*, 2017):

$$P_{tot}(f_m) = \sum f_k = f_i + f_j - f_m \sum f_j \sum f_i P_{ijk} \quad (7)$$

The schematic of Figure-2 illustrates the FWM frequencies, the subscripts i, j, and k pick out 1, 2, and 3. It clears three various signal frequencies f1, f2, and f3, and nine new frequencies fijk.

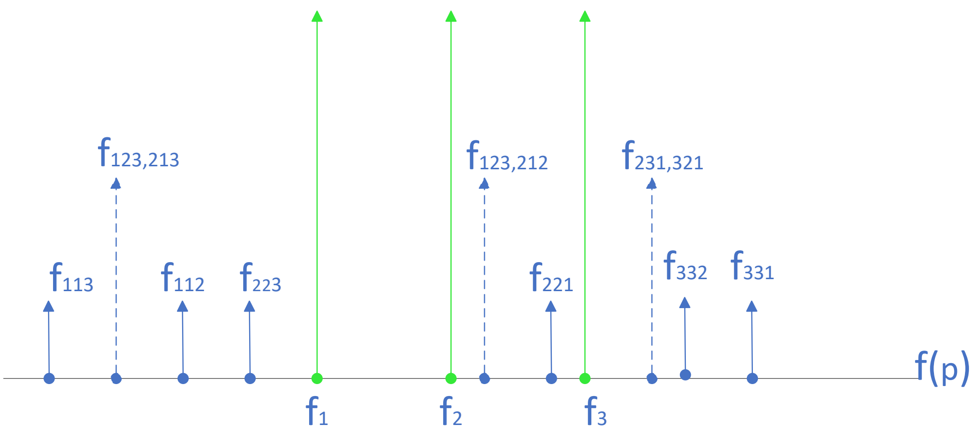
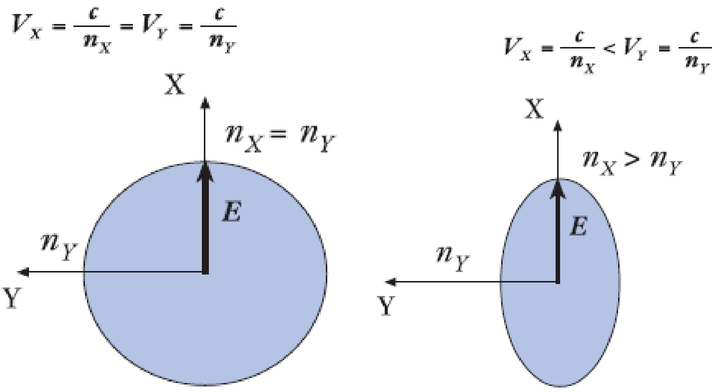


Figure 2. Sketch of the three input waves and the nine unwanted created waves in FWM sum.

3. PMD Theory

Fiber index of refraction determines the speed of propagated optical pulses in an optical fiber for X and Y polarized light; the refractive indices are symbolized as n_x and n_y respectively. For graphically explaining light refractive indices, with a particular polarization it is familiar to draw an index of refraction ellipse. The ellipse index of refraction becomes a circle with a fiber of completely symmetric index of refraction outline, as shown in Fig 3,



(a) Completely symmetrical fiber description when the speed of light does not depend on its polarization.

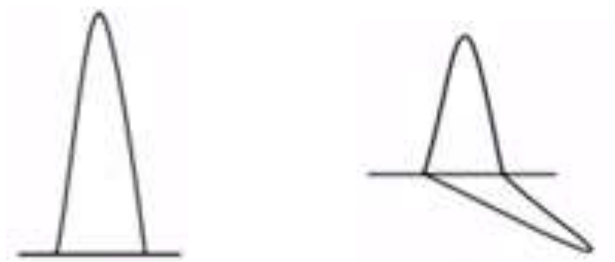
(b) Description of fiber birefringence because Y-polarized light propagates faster than X-polarized lig

Figure 3. (Dubovan *et al,* 2020).

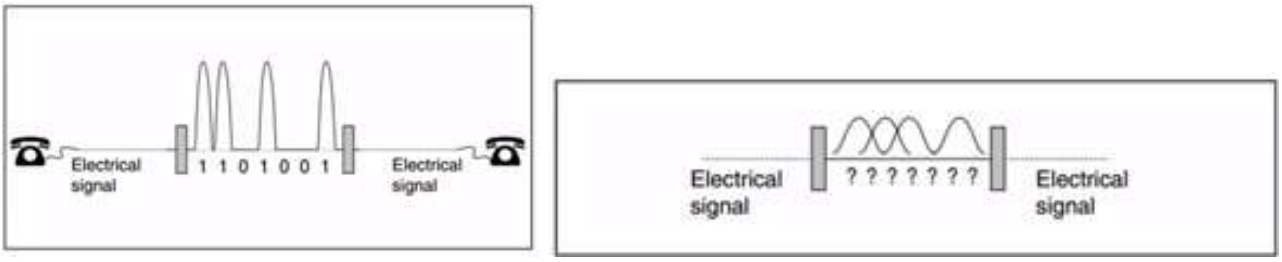
The two orthogonally polarized modes go along the fiber in unlike group velocities. Consequently time propagation delay occurring between them, that affects the optical fibers' polarization features.
The appearance of the time delay showed differential group delay (DGD) and its symbol $\Delta\tau$ equation 8, and Fig 4. (Jozef Dubovan *et al,* 2020).

$$\Delta\tau = D_{PMD}\sqrt{L} \quad (8)$$

$$\Delta\tau = D_{PMD}\sqrt{L} < 0.1T \quad (9)$$



The standard pulse **Two orthogonal polarization modes**



Pulses in 10 Gb/s are closer PMD-affected pulses in a 10 Gb/s system overlap

Figure 4. The transmitted pulses status PMD and DGD

4. OFDM THEORY

Next generation optical fiber networks call for switching strength, spectral efficiency, segmentation, and wanted capacity; to generate these a powerful modulation format is needed. Since large bitrates along optical transmission link is requested (Arpan Garg, and Nitin Mittal, 2020). OFDM is one of the newest versions of telecommunication and wireless communication system modulation technique (David *et al,* 2020). It has been quite suggested for presenting this strong modulation shape, as it uses digital signal processing (DSP) technique efficiently.

OFDM modulates many carriers with individual modulated subcarriers. The orthogonality structure of the carriers decrease crosstalk, interference, and channel scattering (Arpan *et al,* 2020). Many wireless employments use OFDM, such as, 3G, 4G, WLAN standards, and Digital Video Broadcasting (DVB). It characterized as flexibility and large spectral efficiency (Davinder *et al,* 2019). OFDM system is cleared in the block diagram of Fig -5. The OFDM signal represented as eq. 10 (David *et al,* 2020):

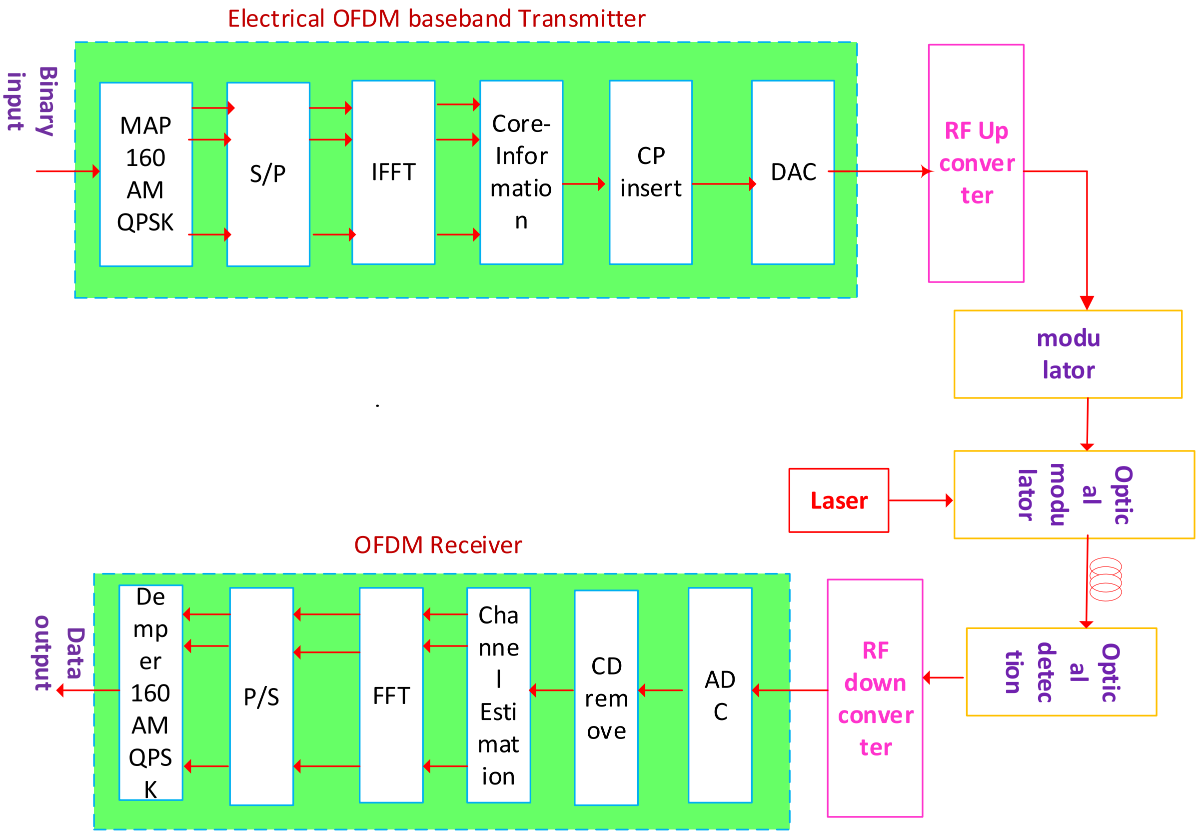


Figure 5. Proposed Structure diagram of OFDM system

$$g(t) = \sum_{\eta=-\infty}^{\infty} a_n(t)\cos\left(2\pi nt/_T\right) - b_n(t)\sin\left(2\pi nt/_T\right) \quad (10)$$

The orthogonality represented as eq. 11 when, moves to zero on a certain time (Arpan *et al*, 2020):

$$\frac{2}{T}\int_t^{t-T}\cos\left(2\pi nt/_T\right)\times\cos\left(2\pi mt/_T\right)dt = \begin{cases}0\ (n\neq m)\\ 1\ (n=m)\end{cases} \quad (11)$$

$$\frac{2}{T}\int_t^{t-T}\sin\left(2\pi nt/_T\right)\times\sin\left(2\pi mt/_T\right)dt = \begin{cases}0\ (n\neq m)\\ 1\ (n=m)\end{cases} \quad (12)$$

Demodulation:

$$a_n(t_o) = \frac{2}{T}\int_t^{t-T} g(t)\cos\left(2\pi nt/_T\right)dt \quad (13)$$

$$b_n(t_o) = \frac{2}{T}\int_t^{t-T} g(t)sin\left(2\pi nt/_T\right)dt \quad (14)$$

Where $T = \frac{1}{Nf_s}$ the symbol period fs is Nyquist filter of frequency.

g(t) is analog signal and is taken from gn insertion (Arpan *et al*, 2020).

$$g(t) = \sum_n g(nT)\emptyset_n(t) \quad (15)$$

$\Phi_n(t)$ are time interleaved optical Nyquist pulses and is given by:

$$\emptyset_n(t) = r(t-nT) \quad (16)$$

Any OFDM subcarrier has a sinc, $\left(\frac{\sin x}{x}\right)$ spectrum in the frequency domain as shown in Fig-6.

The measurement of spectral efficiency is Bps/Hz such as $C = B\times\log\left(1+\frac{S}{N}\right)$. Comprise to noise extra data is transmitted (Davinder *et al*, 2019).

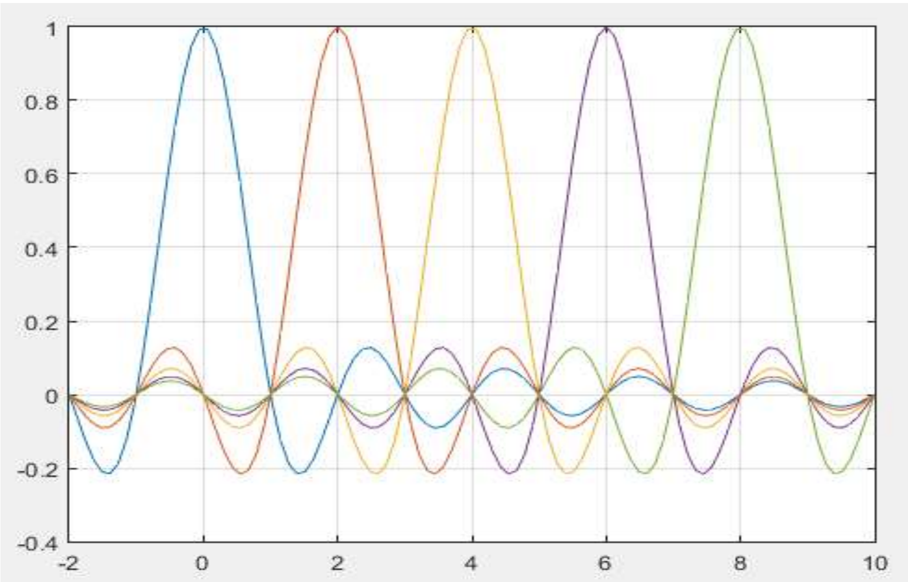


Figure 6. Orthogonal OFDM spectrum

5. Modelling System Analysis

Through certain length of fiber link having SMF 5 Km for 1 Km DCF which has a given PMD, polarization dependent loss (PDL), and chromatic dispersion (CD), a system of (N = 16) channels of OFDM signals as shown in Figure-7 is designed. Starting from frequency of first channel 193.1 THz to the frequency 194.6 THz of the 16^{th} channel has transmitted. In the experimental setup, considering a model of receiver has OFDM/ Demodulator that consists of LP Cosine Roll off Filters, with two Mach-Zehnder Modulators. The signal output from the receiver OFDM model go through QAM Sequence Decoder, NRZ Pulse Generator, and 3R Regenerator. Optisystem-15 has used for the simulation and the parameters given in the data table-1where applied for the simulation.

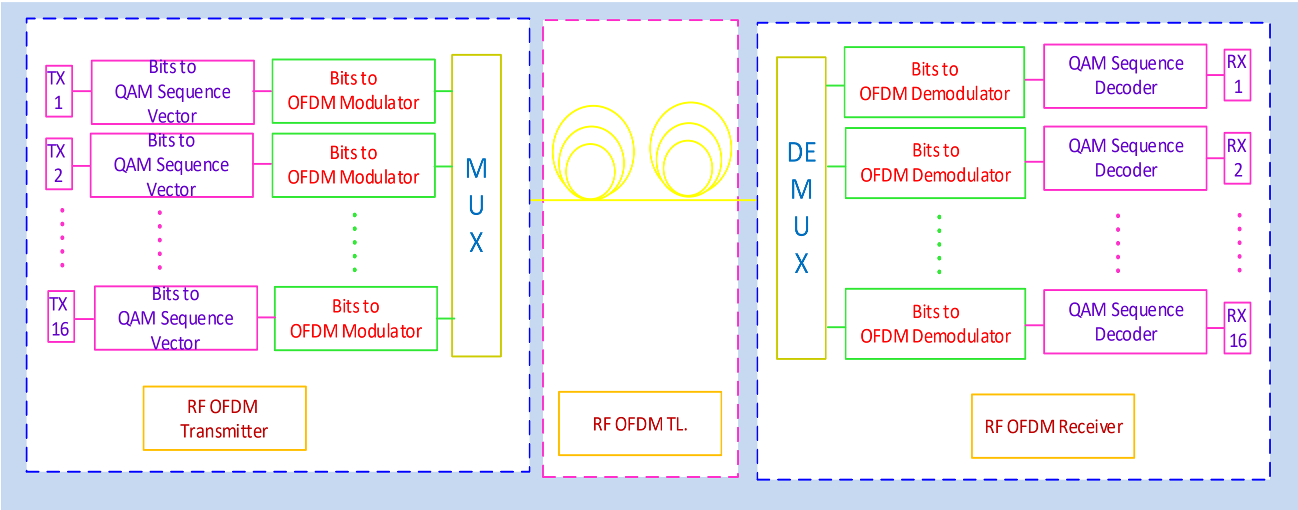


Figure 7. Analytical Model of OFDM System

Table 1: Parameters used in the current simulated system

Parameter	Quantity or Rank
Modulation	16 QAM
Bit rate	10 Gb/s
Channels Frequency	193.1 THz to 194.6 THz
Input Laser Power	-7 to 7
Symbol rate	2.5 G Symbol/s
Output Signal Type	Parameterized
OSA Filter Type	Rectangle
OSA Band Width	0.001 nm Unwrapped Phase
OFDM number of Subcarriers	512
Number of FFT Points	1024
Number of Prefix Points	0
EDFA and FWM	Included
Line SMF	5 Km
DCF	1 Km

6. Simulation Results and Discussion

In the system bandwidth, FWM created product terms locates at the frequencies of the channel.

Because this simulation setup uses OFDM Modulation, while the information signal extend it's top; the maximum point, their adjacent are at zero point (or null) which points orthogonality, in this way OFDM suppress interference while several signals interweaving, based on this orthogonal feature the de-multiplexer at the receiver end would separate the channels. As orthogonal means, signals multiplexed in a way that the peak of one signal take place at the null of the other nearby signals. In this search, results have shown that the effect of FWM decreases using OFDM technology for the communication system transmission. The spectrum results shown in figures- 7 and 8 before trying PMD Emulator and after using a PMD Emulator respectively in the circuit design having standards of 50 Km long, dispersion of 1.3

ps/GHz and of 0.2 dB/Km attenuation with dispersion slop 0.075 ps/nm/Km, to reform products of FWM. It was clear in the result figures that the efficiency of FWM enhanced from -67 dBm to -77 dBm after trying PMD Emulator; it is the effect of using PMD Emulator in the system design, in other side there was another reduction of FWM, and this one due to applying OFDM modulation. It can be noticed from the data results in table-2 which shows a huge power reduction of FWM comparing to the investigation done in 2019 Publication Journal mentioned in references by Habib Ullah and the rest researchers worked with in 'mitigation of FWM operating non-identical techniques of modulation and optical filters in dense WDM (DWDM) fiber optic communication systems. The analysis modified. Which they got reduction FWM power from -36 to -61 dBm by using modified duo-binary modulation against normal system.

The results shown by this investigation, upgraded better as compared to the investigation done in 2020, publication shown in references Habib Ullah Manzoor, Muhammad Zafar, Woo Young Kim and the rest friends, performed 'boosting regulation of FWM in two-way radical passive optical networking; DWDM-PON. Self-controlled light source make use of PMD-Emulator'. As they showed their work results improving FWM from -68 dBm to -73 dBm after putting in PMD emulator and after optical amplifier.

Figures- 10 and 11 show the BER when the power approaches to zero. We can notice from the two results that when the system works without PMD, BER is -0.31563 this value decreases to -0.317 after trying PMD and this characterizes better performance of the communication system design using PMD Emulator. We can see the overall enhancement of the system in figure- 14 the BER Analyzer after trying PMD emulator.

Table-2 gives signal quality data too, at 0.62 s bit period the receiver signal quality is 0.03944 this amount increases to 0.03979 at the same bit period after trying PMD, which tells us that the impairment is quantified perfectly, i.e. the power in the useful signal to the power in imperfections such as (noise power and distortion power) have improved. This shows of high quality evaluation of detection, as cleared in figures- 12 and 13.

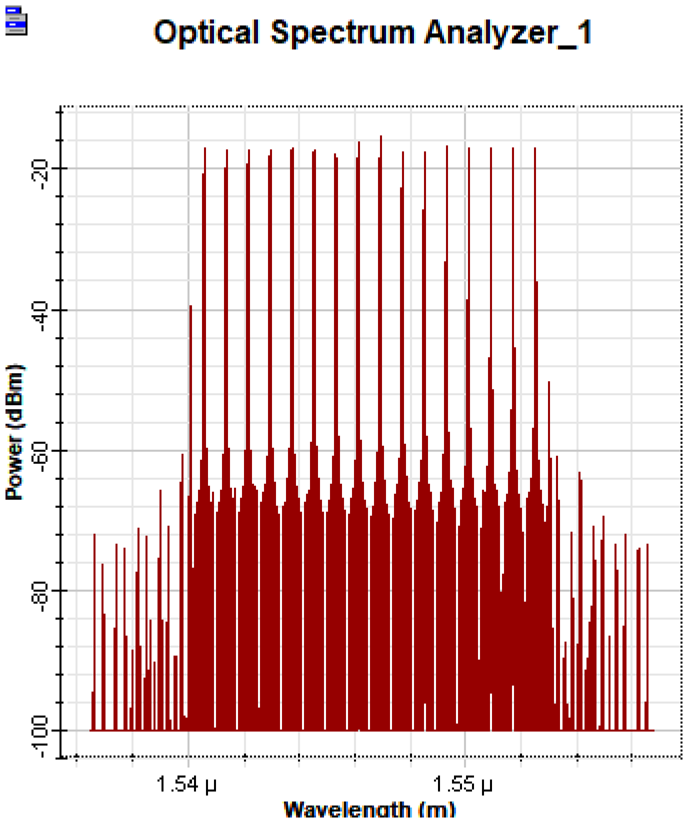


Figure 8. Spectrum in Receiver of 16 channel OFDM system before trying PMD Emulator

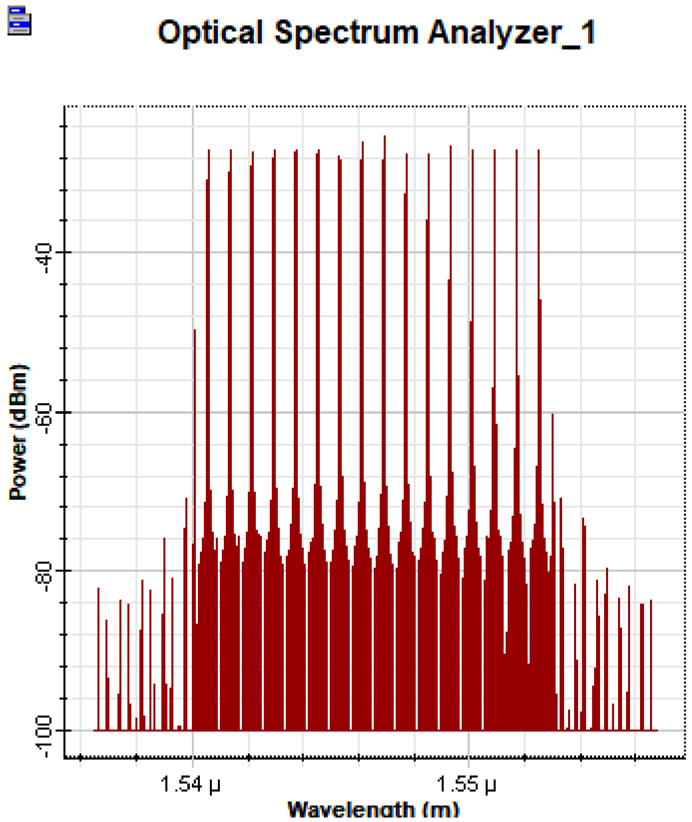


Figure 9. Spectrum in Receiver of 16 channel OFDM system after trying PMD Emulator

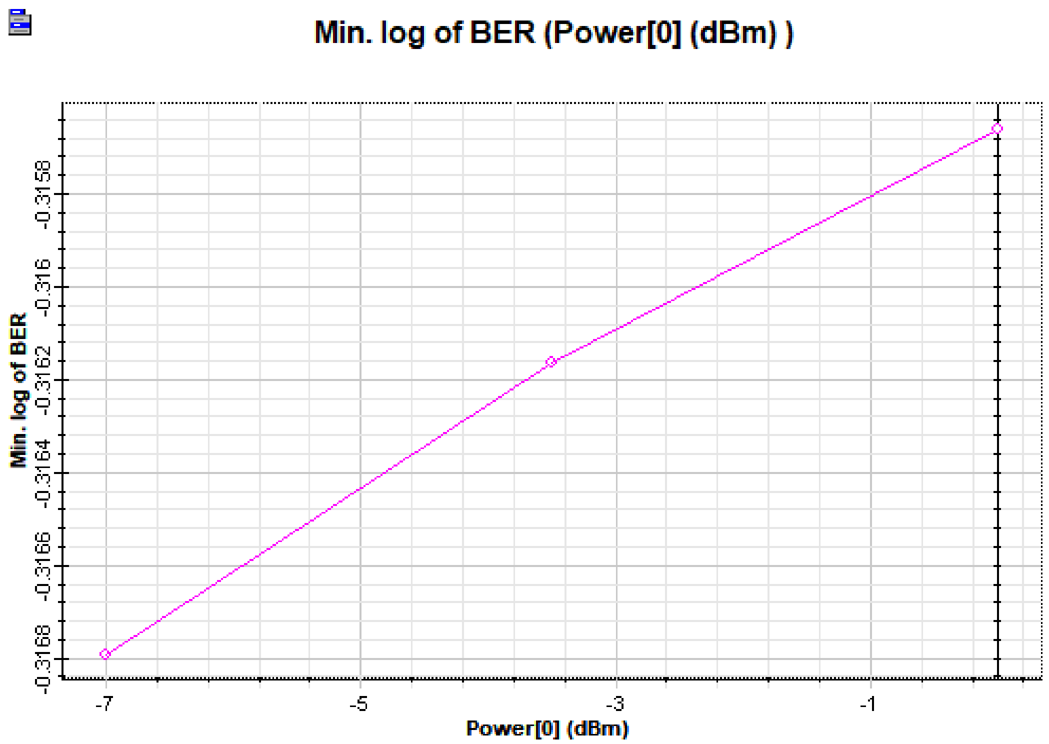


Figure 10. BER vs Power before trying PMD Emulator

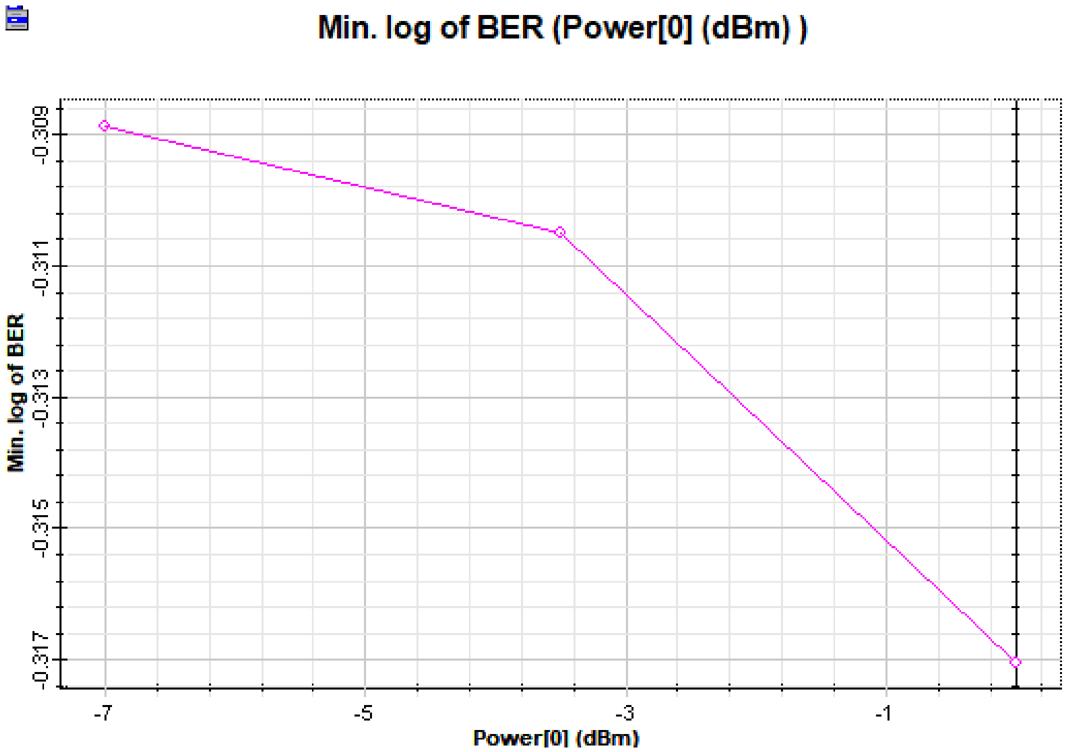


Figure 11. BER vs Power after trying PMD Emulator

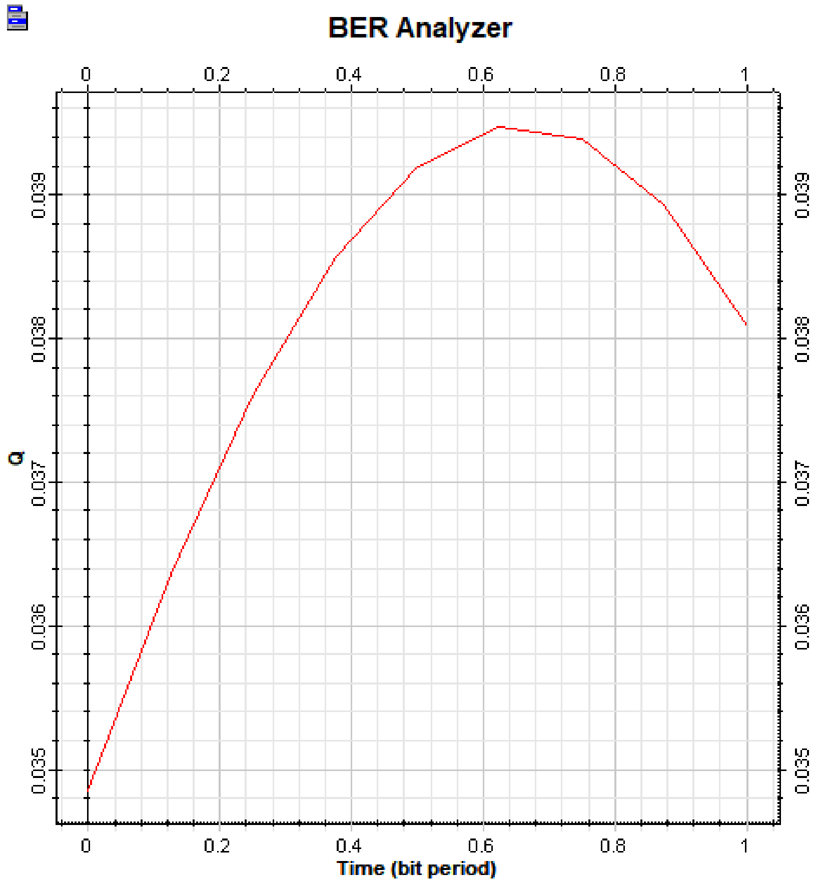


Figure 12. Signal Quality before trying PMD Emulator

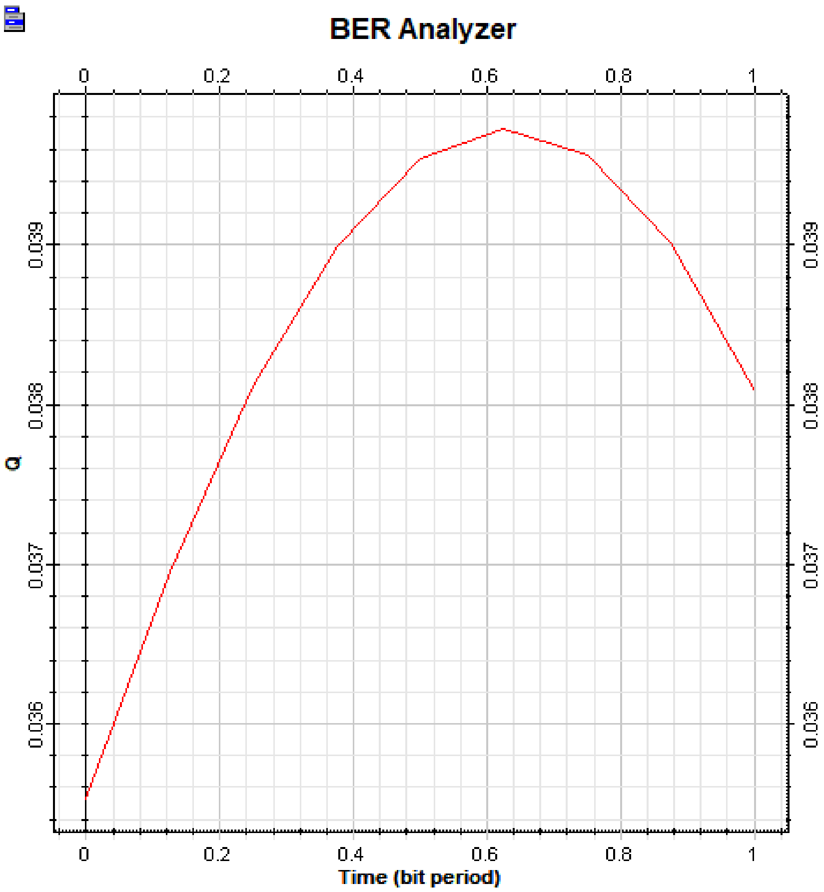


Figure 13. Signal Quality after trying PMD Emulator

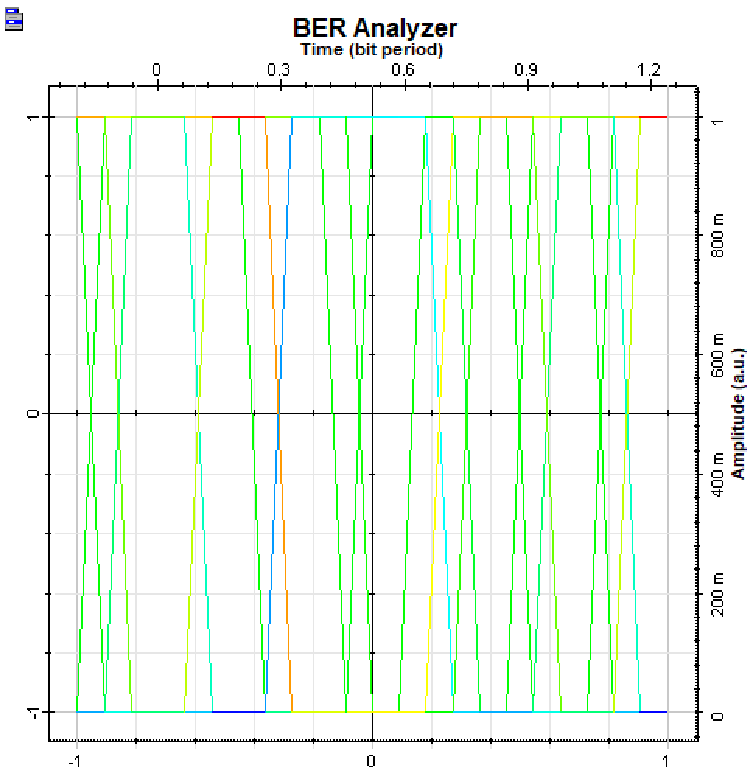


Figure 14. The BER Analyzer after trying PMD Emulator

Table 2: Data of the Results Output Figures

Figure No.	Description	Before Trying PMD-Emulator	After Trying PMD-Emulator
8, 9	Receiver Spectrum	FWM = -67 dBm	FWM = -77 dBm
10, 11	BER vs Power	-0.31563	-0.317
12, 13	Signal Quality	0.03944 at 0.62s Bit-Period	0.03979 at 0.62s Bit-Period

7. Conclusion

On the bases of the results, it is possible to conclude that OFDM viewed as a favorable applicant for high capacity transmission systems for the time being and ahead. In the system, its evidence decreases the effect of nonlinearity, which attacks the channel as ISI that called FWM when WDM used for transmitting multiple channels together. This investigation, therefore, has proposed using this advanced modulation technique OFDM with PMD-Emulator utilization together in fiber optic communication systems transmitting a bundle of carriers along a single fiber line with different colors that called WDM. These two techniques are used for decreasing the FWM appear among the channel signals. As we can see in the results and discussion section, the improvement of the transmission channels has been done by testing the circuit design with and without using PMD-Emulator with utilization of OFDM advanced modulation technique.

The circuit design simulation done by using Optisystem-15 software program, the results of received spectrums difference of the two cases showed, without using PMD-Emulator -67dBm FWM power strength, this result decreased to -77dBm when we used PMD-Emulator in the design and we raised our signal quality value from 0.03944 to 0.03979. Finally, this investigation shows that the results of implementing OFDM and PMD-Emulator together give higher FWM suppression improvement versus the results of the researchers got by using other techniques as mentioned in simulation results and discussion section in detail.

In future, we can extend the process of evaluation of WDM performance to examine with other available techniques in various groups for minimizing impact of nonlinear breakdown WDM optical fiber communication system.

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