Research Article

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Performance analysis of nonlinear crosstalk of WDM systems using modulation schemes criteria

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Abstract: Nonlinearities in optical fibers are regarded as the most significant barriers that endanger the effectiveness of the optical transmission system and pose a threat to communication quality. Four-wave mixing (FWM) is one of the most important nonlinear effects that greatly reduces the wavelength-division multiplexing (WDM) system performance at high data rates over extended transmission distances. This research examines, and assesses, numerically, the behavior of a 4-channel, 40 Gbps WDM system under the effect of the FWM under various tuning parameters, including dispersion, input power, and wavelength spacing. The system model was built using OptiSystem software, and then three different modulation formats, namely, Non-return-to-zero-frequency shift keying, Return-to-zero frequency shift keying, and differential phase shift keying (DPSK) are used to assess the FWM power penalty. The results demonstrate that the FWM power penalty obtained with 1 nm wavelength separation in the DPSK method is dramatically reduced to −35 dBm. This study also demonstrates that when power variation is taken into consideration, the DPSK modulation scheme delivers a lower bit error rate in comparison to other modulation schemes.

Keywords: nonlinear crosstalk, FWM, BER, FSK, modulation formats

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1 Introduction

Healthcare, engineering, and urban planning, among others, are examples of the top industries that require high data rates with large bandwidth to cope with the everyday increase in data processing requirements [1]. Optical fiber communication is proven to be the optimal solution to tackle these challenges due to the huge bandwidth in the visible light spectrum. The high bandwidth offered by the optical fiber can be used efficiently by adopting wavelength-division multiplexing (WDM); a technology where several modulated channels of different wavelengths (and different data rates) are transmitted simultaneously at the same time. With the WDM, the throughput of the fiber is maximized compared with a single-channel transmission. Expanding the system throughput requires either increasing the data rate per channel or increasing the number of transmitted channels for a given data rate [2–4]. A high number of channels necessitate a reduction in the channel spacing within the bandwidth. For high data rate transmission, the channel spacing becomes smaller, which leads to exciting nonlinearities in the optical fiber. Cross-phase modulation, stimulated Raman scattering (SRS), four-wave mixing (FWM), and self-phase modulation are examples of the major nonlinear effects in optical communication. FWM is defined as the generation of a new signal (fourth signal) as a result of the interplay among three co-propagated channels [5–10]. The refractive index dependence on the intensity variation of the input channels (third-order Kerr nonlinear effect) is responsible for the FWM effect which manifests as a crosstalk in WDM and is responsible for the degradation in the received signal.

Suppressing FWM is of great importance for high throughput, low noise, and high bit error rate (BER) transmission systems. Different techniques were proposed to mitigate this effect. The mitigation strategies ranged from introducing phase coherence among channels, manipulating the input power, using phase conjugation, the delay between channels, and different spacings between channels. However, other mitigation approaches rely on the use of advanced modulation techniques and optical filters [7,11–13]. Karim [14] studied a theoretical design of an optical multiplexer/demultiplexer using a polarization converter, combiners, and polarization beam splitters. The performance assessment of these two devices was performed numerically *via* simulation. An average total insertion loss of 1.2 dB of the multiplexer is obtained. Promising simulation results were obtained, where the MUX/DEMUX is an effective technique to compete with actual marketed multiplexers. Shaban *et al.* [15] examined the robustness of different modulation formats tested for FWM by using dispersion-shifted fiber (DSF). A 200 Gbps data rate with different fiber lengths is used to assess the performance of the optical. Experimentally, it was approved that a 14 dB reduction in the FWM capacity is achieved by using return-to-zero (RZ) modulation.

Mohammed and Abd [16] used pairing groups of unlike optical waves to mitigate the effect of FWM using an on-off keying transmission system. An 8-channel, with an 80 Gb/s data rate system, was simulated. Two modulation formats (Carrier suppressed return to zero (CSRZ) and Duo binary modulation class-1 (DBM-1)) are used to assess the proposed system's robustness. An optical fiber link of 60 km length and a 50 GHz spacing between the channels is examined. The FWM power penalty was suppressed using DBM-1 and CSRZ to lower than 41.38 and 47.97%, respectively, applying 12.5 dBm input power. Salim *et al.* [13] proposed a technique for mitigating the FWM effect by Odd-Even channel arrangement (OEC). The power variation effect was simulated in a 100 Gbps bit rate transmission system. OEC technique provided a 10 dB reduction in the FWM power.

Hamadamin *et al.* [17] tested different modulation formulas to suppress the effect of nonlinearity. The simulation was done with a data rate system (40 Gbps) and RZ-differential phase shift keying (DPSK), Non-return-to-zero (NRZ), CSRZ, and modified duo binary return-to-zero) were used. The fiber connection was examined and the best performance was for NRZ where Q = 38 and the lowest performance was in the case of CSRZ where Q = 6. The performance of RZ-DPSK was good and had a clearer and wider eye pattern, also the simulation results showed that RZ-DPSK provides the best performance for the optical wave system and has a higher tolerance to linearity and dispersion among other modulation modes. Suresh *et al.* [18] deliberated the FWM, nonlinear effect which causes a reduction in the optical communication performance system. They dealt with the concept of orthogonal polarization in order to reduce the effect of mixing four waves, and various modification techniques were used with orthogonal polarization. To reduce FWM effects, Han *et al.* [19] exhibited that increasing dispersion factor techniques as well as dispersion-compensating fibers reduce the effect of FWM using three channels system with 100 GHz channel spacing.

For high-speed transmission systems, the frequency shift keying (FSK) technique has been used. An optical transmitter with a 40 Gbps RZ-FSK transmission rate is suggested by Shao *et al.* [7], adjusting the frequency tone spacing (FTS) of adjacent channels to 100 and 60 GHz has the potential to improve receiver performance. However, there is currently a lack of research on how modulation format, specifically, impacts nonlinear effects. Existing studies have primarily focused on power penalties after 80 km transmission length, which is reported as 0.58 and 0.46 dB for the FTS values mentioned above [12]. Therefore, it is important to note that increasing data transmission rates and transmission distances can lead to stronger nonlinear crosstalk which, in turn, generates the need to mitigate these effects for optimal system performance. Furthermore, additional investigation is needed to explore the relationship between modulation formats and nonlinear effects in optical transmission systems.

2 Comparison with existing works

The research gap highlighted by this work is that even though the scientists are trying to lower FWM impact by concentrating on parameters of channel spacing, several researchers suggested different models to suppress FWM by applying the technique of modulation, but no complete model designs to WDM could be applied to suppress and utilize FWM impact using all parameters of the system. Moreover, most of the previous works have complicated system designs which are expensive. The FWM nonlinearity effect in the WDM system is tackled using different techniques. Recently, there are a number of approaches that are suggested to reduce FWM in WDM system which is summarized in Table 1.

The aim of this work is to investigate and provide further insights into the relationship between frequency modulation format, FWM power, and their implications in optical transmission systems. The main objective is to compare the performance of three modulation techniques, namely, RZ-FSK, NRZ-FSK, and DPSK to optimize the system performance by reducing the FWM effect. In this work, two approaches (adjusting system parameters and modulation techniques) are combined to enhance system immunity against FWM. OptiSystem™ simulation version 2019 is used to perform all the numerical calculations.

3 System design

Frequency shift keying FSK is a modulation technique where the information is encoded on the light signal by

Table 1: Summary of recent FWM tackling approaches

Year	Authors	Paper title	Approach
2023	Kılınçarslan and Karlık [20]	"Combined impact of SRS, FWM and ASE noise in UDWDM/DWDM long-haul communication systems using EDFAs"	Adjusting system parameters
2022	Alsowaidi *et al.* [21]	"Performance Comparison of Different Modulation Formats for a 40 Gbps Hybrid Optical CDMA/DWDM System against ISI and FWM"	Advanced modulation formats
2022	Xie *et al.* [22]	"Machine learning applications for short reach optical communication"	Nonlinear signal processing techniques
2024	Jayanth *et al.* [23]	"Design of multiparameter fiber Bragg grating in optical transmission systems wavelength division multiplexing"	Advanced signal filtering techniques
2023	Luo *et al.* [24]	"Deep Learning-Aided Perturbation Model-Based Fiber Nonlinearity Compensation"	Emerging techniques

changing the optical wavelength. In this work, this modulation scheme is adopted to enhance the system performance in terms of the robustness against the FWM crosstalk. Two types of FSK transmission (*i.e.* NRZ-FSK and RZ-FSK). The system performance is tested using DPSK for comparison. In DPSK, the phase of the carrier signal is affected by the information. NRZ-FSK, RZ-FSK, and DPSK transmitter and receiver designs are depicted in Figures 1–3.

In this system, the transmitter configuration involves a couple of external sources of continuous wave (CW) signals that can vary in optical power from −20 to 5 dBm with an optical line width of 10 MHz. These channels are combined using a multiplexer to form a WDM signal. The optical signals are externally modulated using a pseudo-random bit sequence (PRBS) generated by a pulse generator, employing a NRZ modulation format. The first Mach-Zehnder modulator serves as an intensity modulator, while the second Mach-Zehnder modulator is driven by a 32 GHz sinusoidal signal. Hybrid dispersion compensation techniques are employed in the optical connection, using single-mode fiber (SMF) and DCF (dispersion compensation fiber). The optical link includes three erbium-doped fiber amplifiers (EDFAs) to compensate for the attenuation effect. A 14 dB EDFA with a 6 dB noise figure are utilized to amplify the signal in the transmitter.

At the receiver, the received FSK signal is demultiplexed using an optical bandpass filter. A PIN photodiode of 10 nA dark current and 0.8 A/w responsivity is used for direct signal detection. An electrical subtractor is employed to extract electrical signals, and finally, a fourth-order low-pass Bessel filter of 0.75 times the bit-rate 3 dB cut-off frequency is utilized. Table 2 shows additional details regarding the specific parameters and characteristics of the system setup. The signal can then be reconstructed using regenerators and sent straight to the BER analyzer. The DPSK sequence generator receives a 0,1 random sequence from the PRBS transmission architecture and sends it as two M-array pulses to the

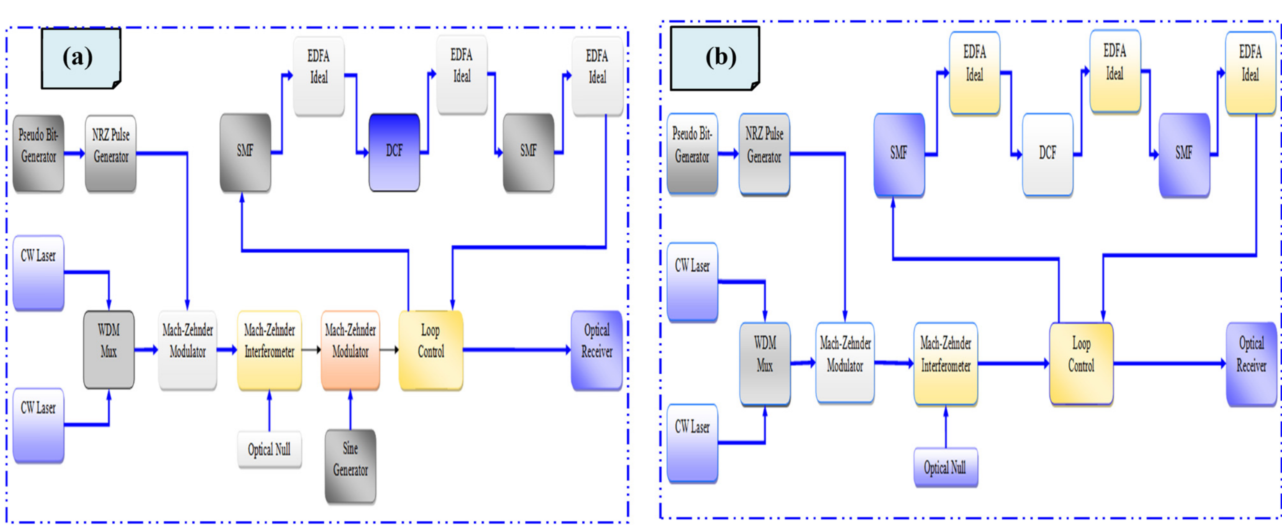

Figure 1: Schematic of the proposed transmitter design for (a) RZ-FSK and (b) NRZ-FSK.

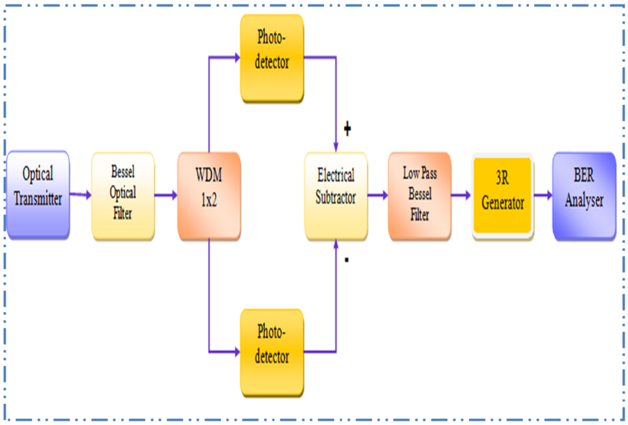

Figure 2: Schematic of the proposed receiver of RZ-FSK/NRZ-FSK.

Quadrature modulator. The Quadrature demodulator splits the received signal to a 2 M-array threshold detector (in the receiver), where it is conjoined and then sent to the DPSK demodulator.

FWM is generated when three photons are combined to produce the fourth channel that falls in the same spectrum of the propagated channels. The frequency of the newly generated channel is defined as $f_{ijk} = f_i + f_j - f_k$ (where f_i, f_j, and f_k are the frequencies of three propagated waves). If N channels are mixed in a WDM system, then the possible number of the generated FWM signals is expressed by $\frac{N^2(N-1)}{N}$. However, falling to suppress these signals produces a time-varying power defined by Shao *et al.* [7].

$$P_{\mathrm{FWM}} = \frac{1{,}024\pi^6}{n^4\lambda^2C^2}\left[\frac{D\chi 111 L_{\mathrm{eff}}}{A_{\mathrm{eff}}}\right]^2 (P_iP_jP_k)e^{-\alpha L} \times \frac{\alpha^2}{c\alpha^2 + 2\pi D_{\mathrm{e}}(\Delta f_{jk})}. \tag{1}$$

This equation takes into account factors such as input power values (P_i, P_j, and P_k) corresponding to the three co-propagated channels f_i, f_j, and f_k. Additionally, the third-order susceptibility ($\chi 111$), degeneracy factor (D), the effective area (A_{eff}), nonlinear length (L_{eff}), fiber chromatic dispersion (D_{c}), channel spacing (f_{ik}, f_{jk}), laser wavelength, fiber loss coefficient, total length (L), and the fiber refractive index (n) are considered. The value for D is chosen to be 3 for the two-tone systems and 6 for the three-tone systems. Also, L_{eff} is measured in cubic meters per watt second (15 m^3/W s). The noise power produced by the power calculated by Equation (1) is given by

$$N_{\mathrm{FWM}} = 2b^2P_{\mathrm{S}}\left(\frac{P_{\mathrm{FWM}}}{8}\right). \tag{2}$$

Equation (3) is used to determine the system performance in terms of the Q-factor when FWM, shot, and thermal noises are present.

$$Q = \frac{KP_{\mathrm{S}}}{\sqrt{N_{\mathrm{th}} + N_{\mathrm{sh}} + 2K^2P_{\mathrm{s}}^2 + C_{\mathrm{IM}}{}^{(m)}} + \sqrt{N_{\mathrm{th}}}}. \tag{3}$$

Here $C_{\mathrm{IM}}^{(m)}$ represents the FWM crosstalk, P_{s} is the power received at the receiver of a responsivity of k. N_{th} and N_{sh} are the thermal and shot noises, respectively. Finally, BER is obtained by

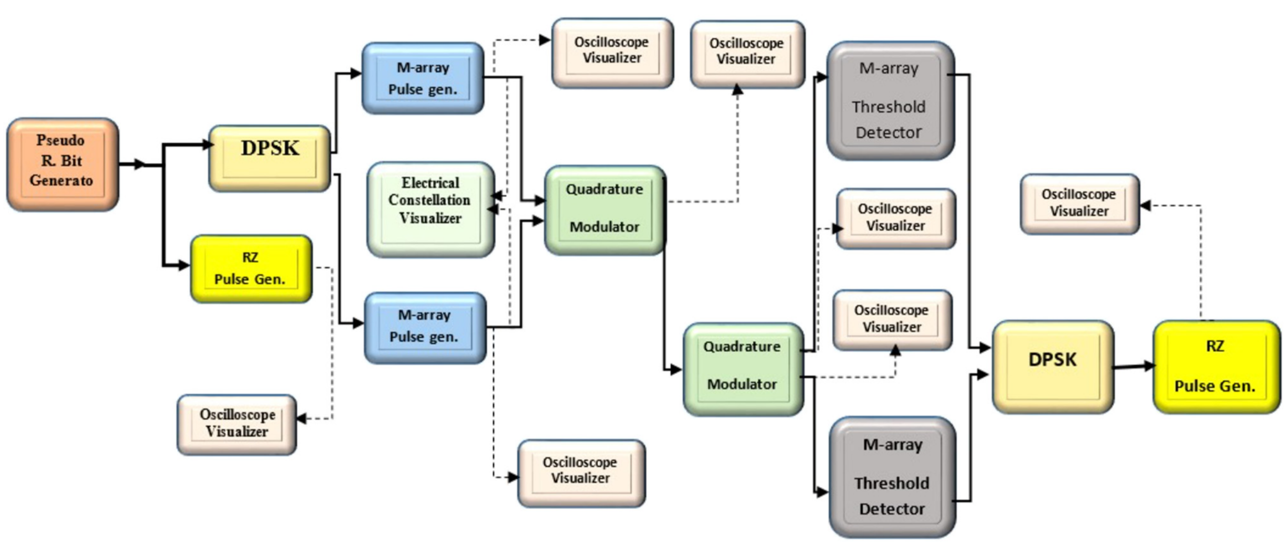

Figure 3: Simulated model for the transmitter and receiver for DPSK.

Table 2: Model specifications

Parameters	Unit	Values
Fiber length (L)	km	120
Input power (P_i)	dBm	−20 to 5
Wavelength ($\Delta\lambda$)	nm	0.1–1
Dispersion	ps/nm km	0–18
Nonlinear index of refraction	n_2	1.4
Cross-effective area (A_{eff})	μm^2	70 for SMF and 22 for DCF
Noise figure	dB	4
Attenuation (α)	(dB/km)	0.2
Channel numbers		3
Fiber type		SMF + DCF
PIN responsivity 1	(A/W)	1

$$\text{BER} = 0.5 \times \text{erfc}\left[\frac{Q}{\sqrt{2}}\right]. \tag{4}$$

4 Results and discussion

In this study, four channels each of 40 Gbps are simulated using two different modulation schemes. FSK, as well as DPSK, modulation techniques are tested to estimate the robustness of the transmission link in terms of FWM noise. The analysis first examined the effect of different parameters (wavelength spacing, laser power, and fiber dispersion) on the overall FWM power penalty after a 100 km transmission distance. Finally, the optical link performance is assessed using the BER and eye diagram. The flow chart of our proposed work is explained in Figure 4.

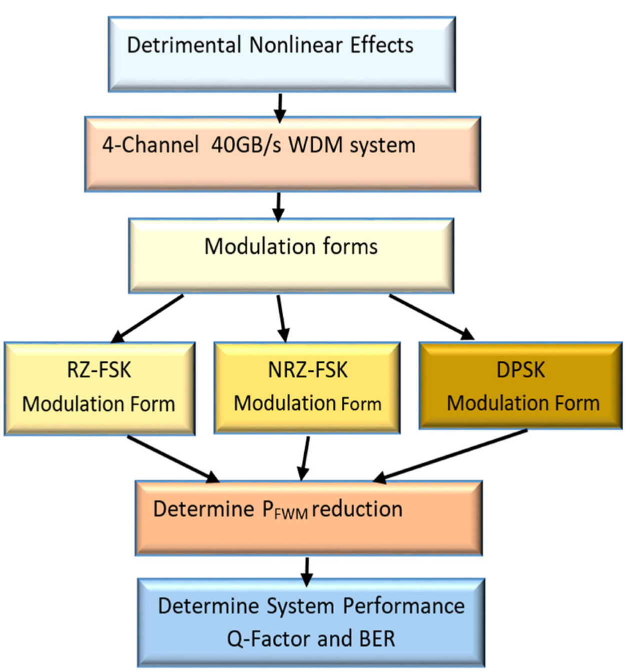

Figure 4: Measurement methodology.

4.1 FWM performance evaluation

4.1.1 Effect of wavelength spacing

To assess the impact of changing the wavelength spacing of the three modulation schemes mentioned on the FWM power level, a simulation-based research is conducted. Figure 5 shows that the method of frequency channel spacing significantly reduces the FWM in both modulation types (NRZ-FSK and RZ-FSK). This is because the increase in spacing reduces the likelihood that the frequencies may be inferred from one to another. Figure 5 also explains that the DPSK modulation format responds more quickly to FWM reduction than FSK modulation. The power of FWM is lower with DPSK compared to NRZ-FSK (−35 dBm *vs* −13 dBm), at a spacing of 1 nm.

4.1.2 Laser power

The CW laser's power is a significant variable that can be used to mitigate the FWM effect. Increasing the pump power within the fiber results in an increase in FWM power, which varies inversely with the A_{eff} of the fiber. Again, DPSK outperformed other variants and provided a superior decrease in FWM power. Using 3 dBm input power will make the value of FWM reach −32 dBm in

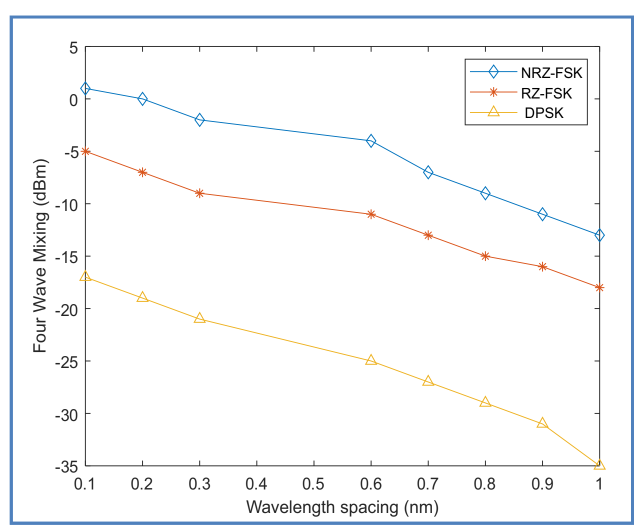

Figure 5: FWM *vs* wavelength spacing for different modulation techniques.

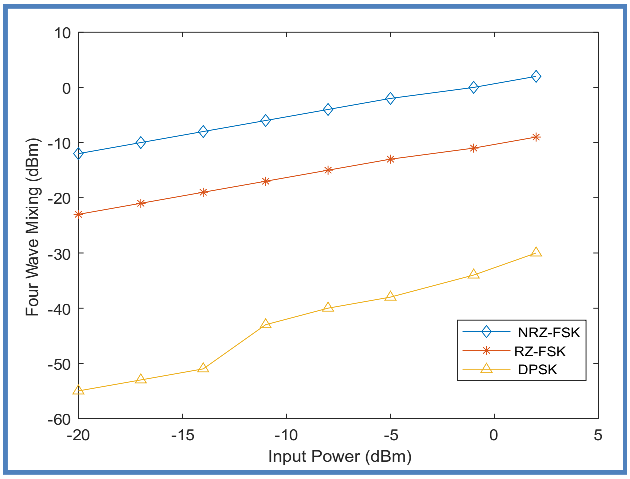

Figure 6: FWM *vs* laser power.

DPSK, meanwhile, NRZ-FSK reaches zero dBm (when applying similar parameters), which eventually indicates that DPSK gives more optimum achievement in lowering FWM influence than others as shown in Figure 6.

4.1.3 Dispersion

The chromatic dispersion is proven to have a significant impact on the FWM effect. The presence of chromatic dispersion forces various signals to move at different group velocities. As a result, the effectiveness of mixing will be reduced overall when the various waves alternatively overlap inside and outside the phase. Figure 7 shows that decreasing the FWM for nearly all types of modulation used can be accomplished by increasing the dispersion. A

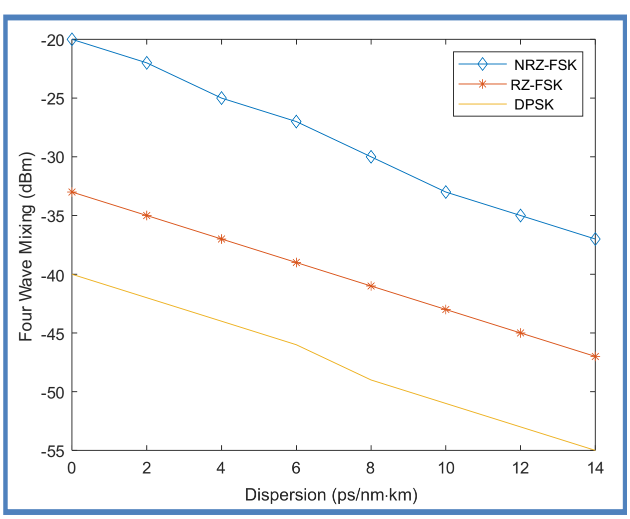

Figure 7: Dispersion effect on the FWM.

−55 dBm FWM is achieved in the DPSK modulation technique at 14 ps/nm/km dispersion compared to −38 dBm for NRZ-FSK

4.2 Optical link performance evaluation

OptiSystem™ simulator is used to assess the system performance, and the predetermined modulations are used to examine the impact of the power input on the bit-error rate of the optical link. Increased laser power will lower the BER for all employed modulation techniques, as can be seen in Figure 8. Depending on the characteristics of each technique, BER behaved differently for each modulation. The system performance for DPSK indicates that the minimal

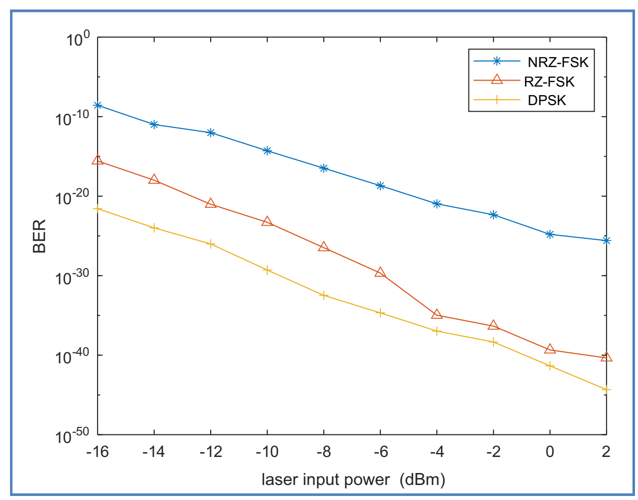

Figure 8: BER *vs* input power.

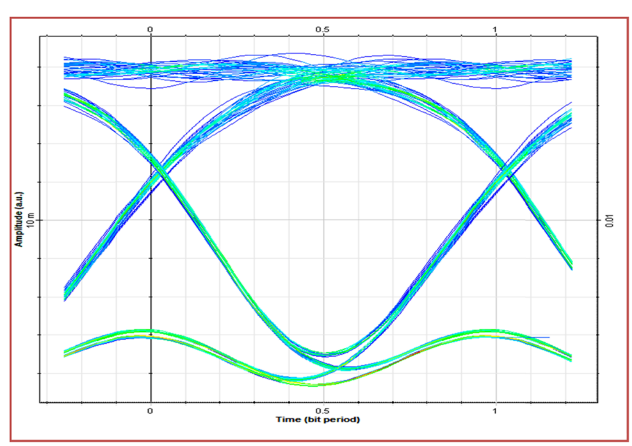

Figure 9: Eye diagram plot for NRZ-FSK modulation scheme.

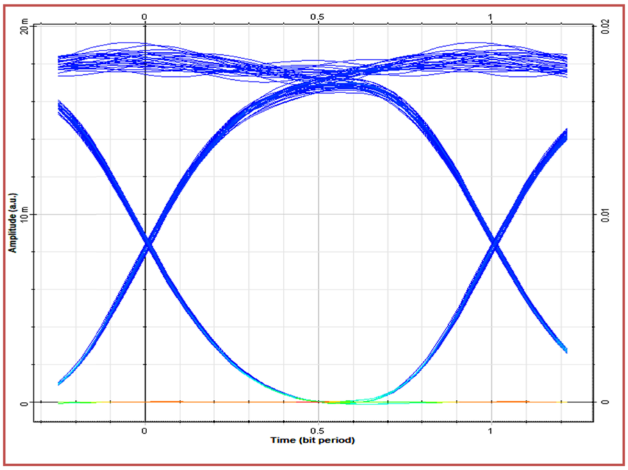

Figure 10: Eye diagram plot for RZ-FSK modulation scheme.

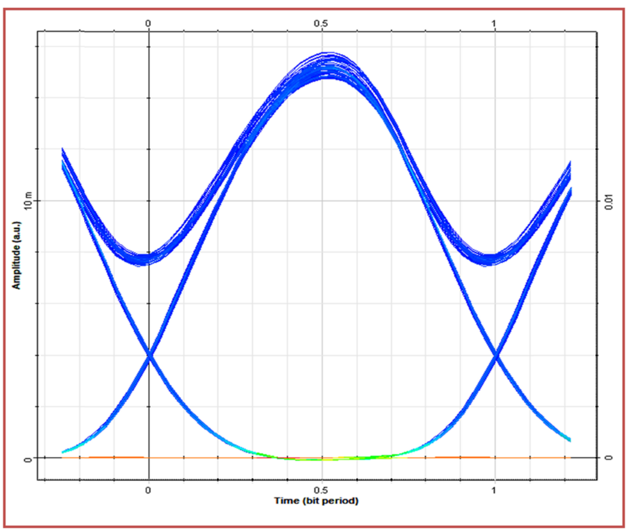

Figure 11: Eye diagram plot for DPSK modulation scheme.

value for BER is 4.5×10^{45} at an input power of 2 dBm. In contrast, for the same input power, NRZ-FSK provides a BER value in the range of 2.5×10^{-26}.

Additionally, the Eye diagram and BER pattern have been calculated from Figures 9–11. As can be observed, the DPSK has a higher Eye Diagram for the BER pattern than NRZ-FSK and RZ-FSK. The improvement in the system quality in the DPSK example reflects the modulation signal's resilience to the nonlinear impact.

5 Conclusion

Scalable and more reliable long-haul WDM optical systems are prone to unavoidable limitations due to fiber nonlinearities. FWM is considered one of the leading nonlinear effects that affect the system performance and deteriorates the BER. In this work, a thorough investigation to examine the robustness of the three different modulation techniques RZ-FSK, NRZ-FSK, and DPSK against the effects of FWM is presented. The system performance is tested based on different scenarios, including wavelength spacing, laser input power, and dispersion. The findings demonstrate that for all simulated parameters, a reduction in the FWM power level with a reduced BER level is achieved in DPSK. Therefore, this work suggests that utilizing DPSK with 1 nm spacing when the FWM power level is −35 dBm is the optimal method for reducing the FWM power. For future work, deep learning and AI can be used to mitigate the effect of nonlinear crosstalk through the prediction of the best scenario in complex WDM networks.

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