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# Impact of Modulation Schemes on Nonlinear Interference For High-Speed Optical Links

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## Abstract

Communications systems based on fiber optics suffer from nonlinear effects. These nonlinear effects severely restrict wavelength division multiplexing (WDM) and thus impair the performance of the optical transmission system. A Polarization Combiner (PC) is one of the promising techniques that mitigates the nonlinear effects, especially interference. This work proposes a system that use PC with different modulation schemes including Return to Zero (RZ), Non-Return to Zero (NRZ), and Carrier-Suppressed Return-to-Zero (CSRZ) in a nonlinear optical fiber communication system. The performance of the proposed system was tested under different conditions, including changing the input power and at data transfer rates including (100 and 200) Gbps. It was shown from the results that the modulation form RZ provides the best performance, as nonlinear effects in optical fibers are decreased. Moreover, when the transmission distance is equal to 60 km, the RZ gives a Q-factor equal to 8.4. However, the Q-factors are equal to 1.44 and 6 when using NRZ and CSRZ respectively.

Keywords: Modulation schemes, Nonlinear interference, Optical fiber, Polarization combiner, Q-factor

## Introduction

The demand for high-speed communications systems is increasing to meet the need for development in communication services [1-3]. Wavelength division multiplexing (WDM) is used as a suitable way to provide a high-speed communication system. When sending large data over long distances, problems related to dispersion and non-linear effects increase. Nonlinear effects are considered one of the most prominent obstacles to fiber optic systems [4]. One solution may be to increase the power of transmitted light in optical systems, but there is a high possibility of losing control over nonlinear effects. Therefore, increasing nonlinear effects will lead to deterioration in the efficiency of the communication system.

One of the most important topics discussed in fiber optic research is how to find solutions to nonlinear effects [5-11]. The most prominent of these solutions is to keep the overall dispersion low by compensating for dispersion using optical fibers with back-dispersion. In this case the Dispersion Compensation Fiber (DCF) and Single Mode Fiber (SMF) techniques are used [12-13]. Often, the modulation schemes Return to Zero (RZ) and Non-Return to Zero (NRZ) are used in standard spaces. RZ is often used more than NRZ in SMF. While NRZ can achieve better performance than RZ in WDM systems, because NRZ has higher spectral efficiency.

Nonlinear effects in fiber optics arise from the interaction between light and the fiber's material properties. These effects can introduce distortion, noise, and crosstalk in optical networks, thereby restricting the network's performance and capacity. Nevertheless, various techniques can be employed to counteract these nonlinear effects and enhance signal quality [14-15]. Nonlinear dispersion can be corrected through optical phase conjugation, a method that inverts the signal wavelength and phase. Some methods include using low noise amplifiers, adjusting their gain and saturation, and optimizing their spacing and placement. One method for mitigating nonlinear effects is nonlinear phase noise cancellation. This technique eliminates phase noise induced by nonlinearities through the use of phase estimation algorithms. Another approach to mitigating nonlinear effects is modulation format optimization. This involves selecting the most suitable modulation format for the signal, and balancing the trade-off between spectral efficiency and robustness. Optimizing fiber design entails choosing the most suitable fiber for transmission by evaluating parameters that affect nonlinear effects, including core diameter, effective area, nonlinear coefficient, and chromatic dispersion [16-20]. These considerations help reduce nonlinear impacts and enhance transmission quality.

Recent advancements in optical multiplexing and de-multiplexing methods, utilizing delay lines, have emerged as effective means to mitigate various nonlinear effects. Additionally, polarization techniques and optimization of channel spacing have been utilized to reduce interference with transmitted signals [21-23]. However, despite these efforts, nonlinear crosstalk on primary channels remains insufficiently suppressed, leading to low system efficiency that necessitates improvement. The characteristics of nonlinear fibers are closely linked to modulation formats, and under high data rates, crosstalk behavior varies, influenced by the resilience of modulation formats [24-25]. This study delves into assessing the robustness of NRZ, RZ, and Carrier-Suppressed Return-to-Zero (CSRZ) modulations against nonlinear effects at a high data rate of 100 Gbps.

A Polarization Combiner (PC) plays a vital role in controlling nonlinear effects, particularly interference, in optical fiber communication systems. Nonlinear effects like Four-Wave Mixing (FWM) and Cross-Phase Modulation (XPM) arise when high-intensity light waves interact within the fiber, generating new wavelengths and phase shifts that disrupt the original signal [26]. By merging two orthogonally polarized light beams, a PC effectively lowers the power density in any single polarization state, thus reducing the impact of these nonlinear interactions. This interference reduction is crucial for preserving signal integrity, especially in dense wavelength-division multiplexing (DWDM) systems where closely spaced channels can significantly affect each other through nonlinear crosstalk [27].

Moreover, PCs improve the performance of optical communication systems by stabilizing polarization states, which is essential for minimizing polarization mode dispersion (PMD) and polarization-dependent loss (PDL). These aspects are particularly important in long-distance and high-capacity fiber optic networks where interference and dispersion can severely limit transmission distance and data rates [28]. By maintaining a stable polarization state, PCs provide more consistent signal quality and better tolerance to nonlinear effects, leading to enhanced overall system performance and reliability. This stability is critical for advanced modulation formats and coherent detection techniques, which are highly sensitive to polarization variations and nonlinear interference [29]. This paper is organized as follow: section 2 shows the suggested optical transmission schemes. Results and discussion are demonstrated in section 3. Finally, the conclusion is stated in section 4.

## Suggested Optical Transmission Schemes

To overcome the nonlinear effect , a polarization technique combined with different advanced modulation is suggested. The classical method is to suppress the nonlinear effect over long distance, where the nonlinearity especially increases in all active signals. Therefore, to solve this problem it has been proposed to introduce the orthogonally for the entire channel interaction by combining every two channel together and then linearly polarized with a specific rotation angle using a Polarization Combiner (PC). This work investigates the performance of a single channel under nonlinearity with and without polarization technique . The polarization scheme with different input power and data rates. The performance of proposed work studied in terms of the Q-Factor. This study introduces the design and simulation of CSRZ, RZ ,and NRZ for single channel, with and without PC over different transmission distance. In this part, designation & simulation of system of single channel have been introduced with 100 Gbps using 3 enhanced techniques CSRZ, RZ , and NRZ.

PC merges the two input signals into a single output port. The polarization combiner selects the appropriate polarization component from each signal at the input ports and combines them. Figure 1 illustrates the implementation of this model. Each input port is equipped with a linear polarizer, and the angle of each polarizer is determined by the device angle. Additionally, an angle of 90° is added to the device angle of the polarizer at input port 2 [30].

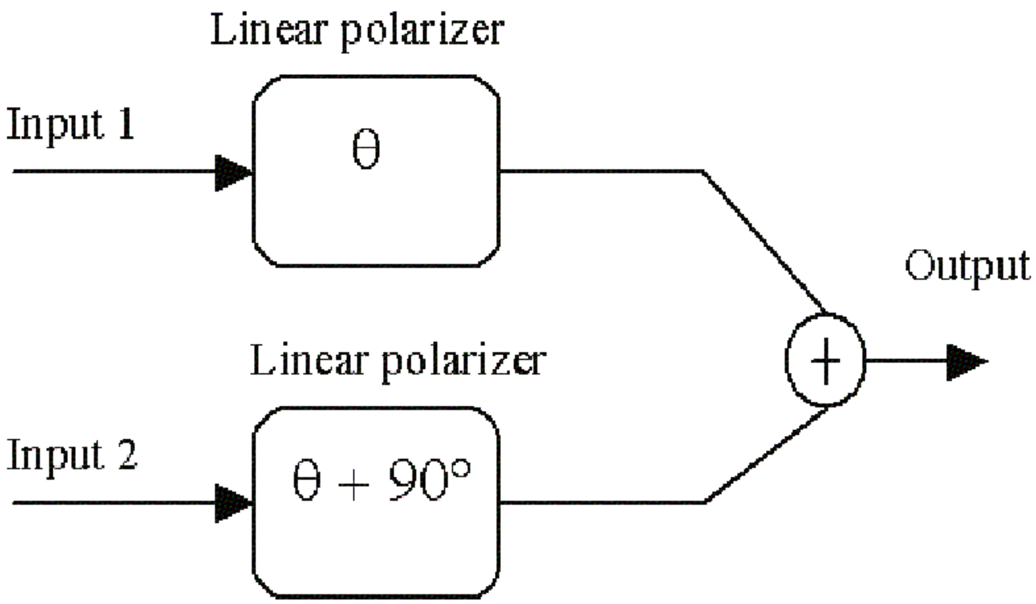


**Figure 1: The model of PC [30]**

Techniques to mitigate nonlinear effects in optical fiber systems include dispersion management, advanced modulation formats, and optical phase conjugation, each targeting dispersion control, peak signal power reduction, and nonlinear distortion counteraction, respectively [31]. Nonetheless, the polarization combiner (PC) surpasses these methods by directly focusing on the polarization state of light. By combining two orthogonally polarized beams, the PC effectively lowers the power density in any single polarization state, significantly reducing nonlinear effects such as FWM and XPM [32]. Table 1 lists the system parameters.

The proposed system layout, shown in Figure 2, features an external modulator using NRZ, RZ, and CSRZ modulation formats. A continuous wave laser generates a carrier signal at a frequency of 193 THz. Figure 3 details the modulation schemes. A Mach-Zehnder Modulator (MZM) modulates the light intensity. The optical link comprises three spans of Single-Mode Fiber, each followed by optical fiber amplifiers and Dispersion Compensation Fiber. The system has a noise figure of 5 dB and a gain of 20 dB. An Avalanche Photo Diode (APD) detects the optical signal, converting it to an electrical signal, which then passes through a low-pass Bessel filter. Subsequently, the received electrical signal appears in eye diagram.

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**Table 1. Simulation Properties of the SMF and DCF**

| Parameters | Values | Unit |
|---|---|---|
| **SMF parameters** | | |
| Length | 25 | km |
| attenuation(α) | 0.2 | dB/km |
| dispersion slope(S) | 0.075 | $ps/nm^2.km$ |
| dispersion parameter(D) | 17 | $ps/nm.km$ |
| effective area | 70 | $\mu m^2$ |
| Differential Group Delay(DGD) | 0.2 | ps/km |
| **DCF parameters** | | |
| Length | 10 | km |
| attenuation (α) | 0.5 | dB/km |
| dispersion slope (S) | -0.3 | $ps/nm^2.km$ |
| dispersion parameter (D) | -85 | ps/nm.km |
| effective area | 22 | $\mu m^2$ |
| Differential Group Delay (DGD) | 0.2 | ps/km |

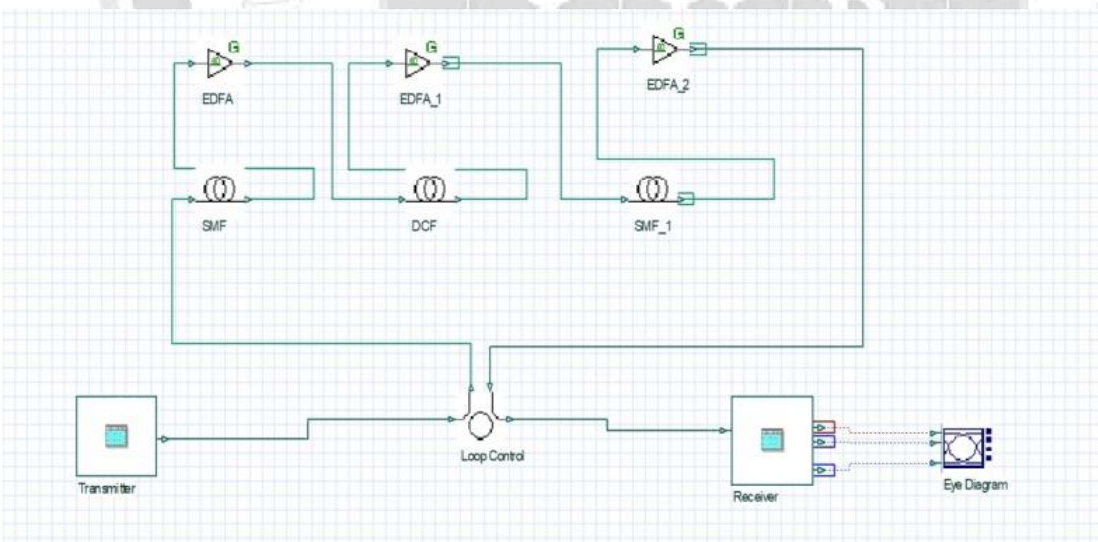


**Figure 2: Suggested optical system of single channel**

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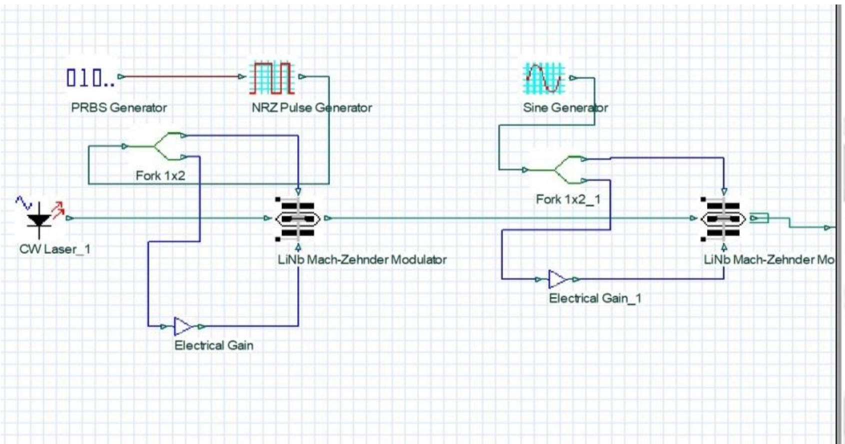
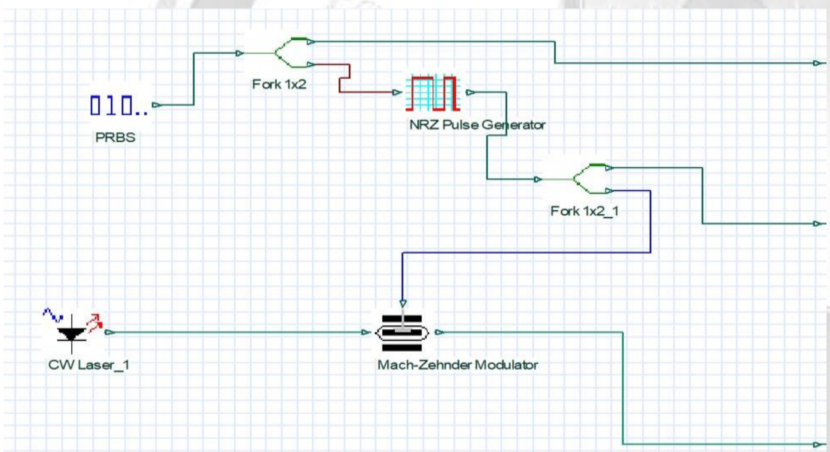
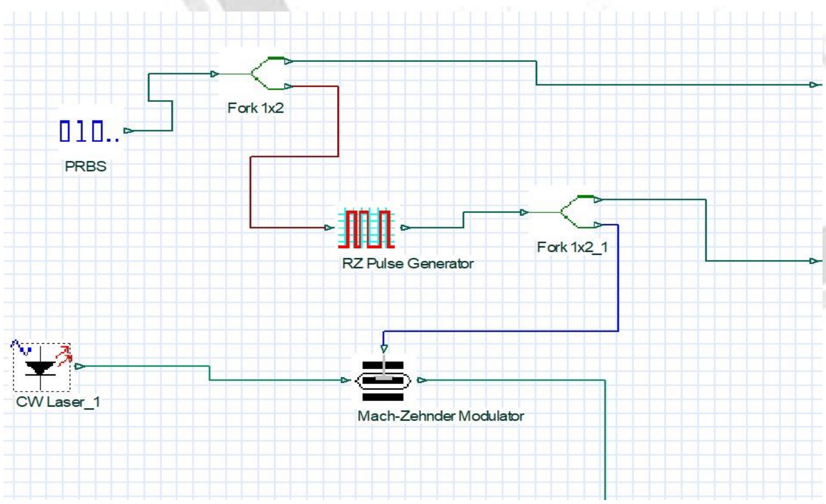



A-Scheme of CSRZ




B- Scheme of NRZ




C- Scheme of RZ

**Figure 3: Optical transmitter system design of single channel for A- CSRZ, B- NRZ, C- RZ**

## Results:

By using the Optisystem program (version 21), the optical transmission system is simulated and examined. In this work, the effectiveness of the nonlinear effect is investigated over a range of transmission distances and modulation types. In the simulation, different shapes of On-Off Keying (OOK) modulation are suggested, designed and simulated. In addition, this work proposes an efficient technique in term of orthogonal channels which is combined with modulation schemes. The suggested modulations provide good resistance to signal fading, nonlinearity and attenuation. The suggested techniques were examined on single channel and the performance evaluation of the proposed system was done with various types of modulation. Three encoding approaches are used to evaluate the effectiveness of OOK Modulation (NRZ, RZ, and CSRZ). Thereafter, the data rate increases to 100, checking and calculating with each increase in the data rate, additionally various types of modulation are used at each increase in the data rate.

These comparisons are made in terms of system performance and distance, as well as the received power and quality factor. This section explains the results of a single channel transmission system with three modulation schemes which are NRZ, RZ and CSRZ. This simulation completes 1-2 spans for each with 60 Km length and bit rates ranging from 100 to 200 Gbps. The performance shows Q-factor versus input power variation (-0.5 : 2: 20 dBm). Simulation results demonstrate better performance with RZ (in state of singular channel) with and without using orthogonal channels using polarization. The results of single channel can be divided into three types as follows:

### A- Results of single channel using at 100 Gbps data rate

Figure 4 illustrates the achievement of systems with singular channels at proposed design modulation schemes. The figure explains the input power variation versus Q-Factor for three modulation scheme types. From the comparison between the modulations, it can be realized that the RZ modulating shows better performance for different data rates of 100 & 200 Gbps.

At data rates of 100 Gbps, at low values of the input powers, the modulation types used appear to be almost similar in their performance and show a similar system performance for all. When input powers are high, the effect of non-linear phenomenon appears on the types of modulation schemes used. In this context, RZ modulation type appears more resistant to this phenomenon and seems to be the best compared to other types. For example, at input power of 20 dBm, the Q-factor equal to 8.21 based on RZ modulation while for NRZ, CSRZ the Q-factor values were 1.37 , 3.76039 respectively .

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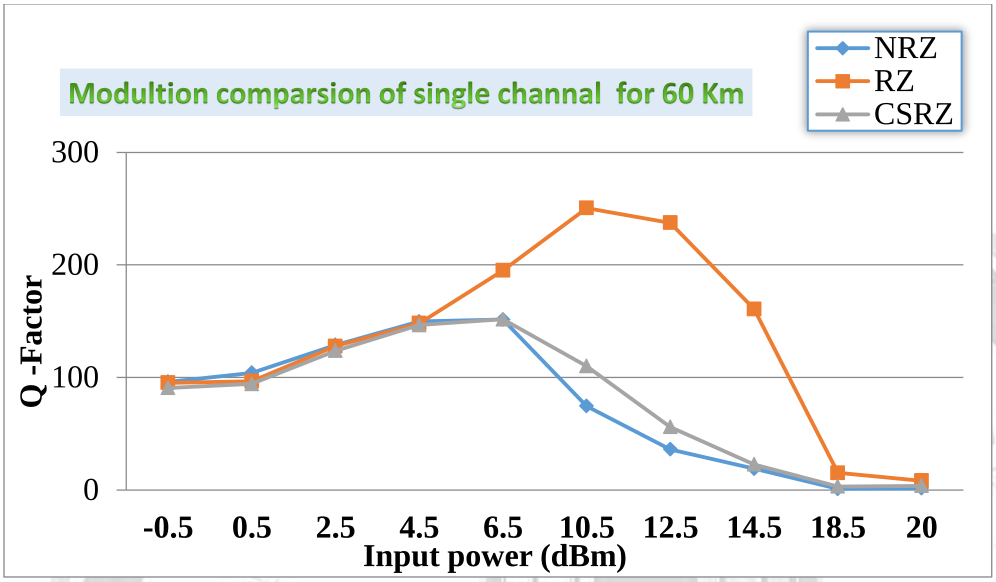


**Figure 4: Q-Factor versus laser power of single channel of different modulation schemes**

Figure 5 shows three schemes of modulation with different power of input in systems of singular channels at 60km fiber length. The comparison among different modulation forms has been simulated at 100 Gbps where it can be seen that RZ modulation introduce better performance than other modulation scheme.

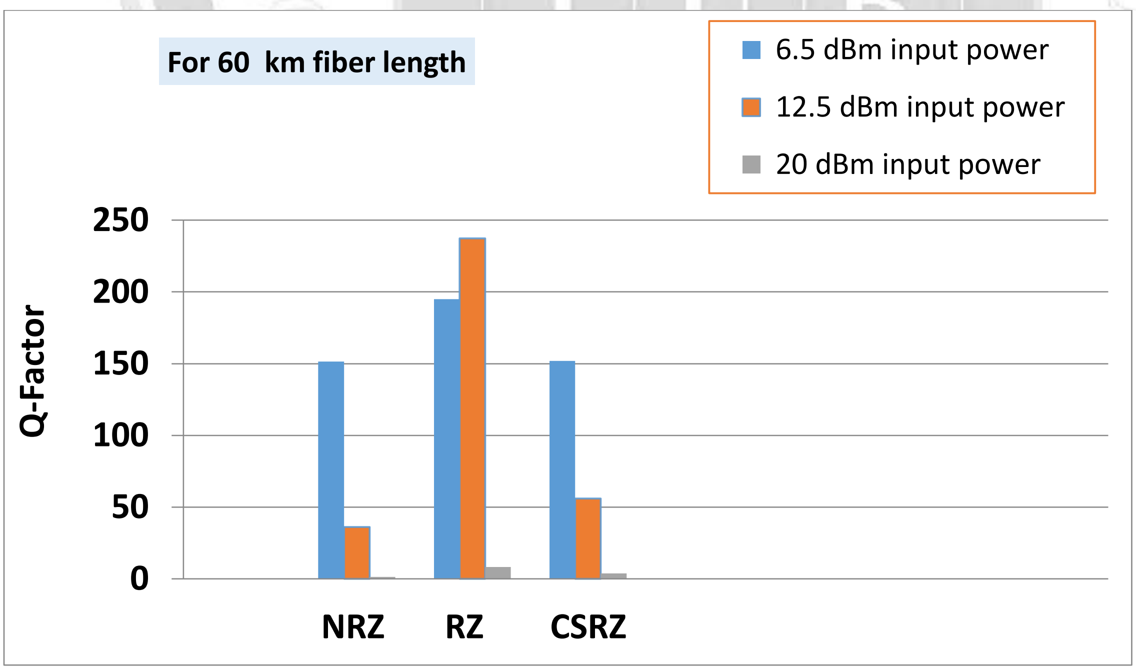


**Figure 5: Statistical representation of Q-factor for different three modulations at 60km and 100 Gbps data rate**

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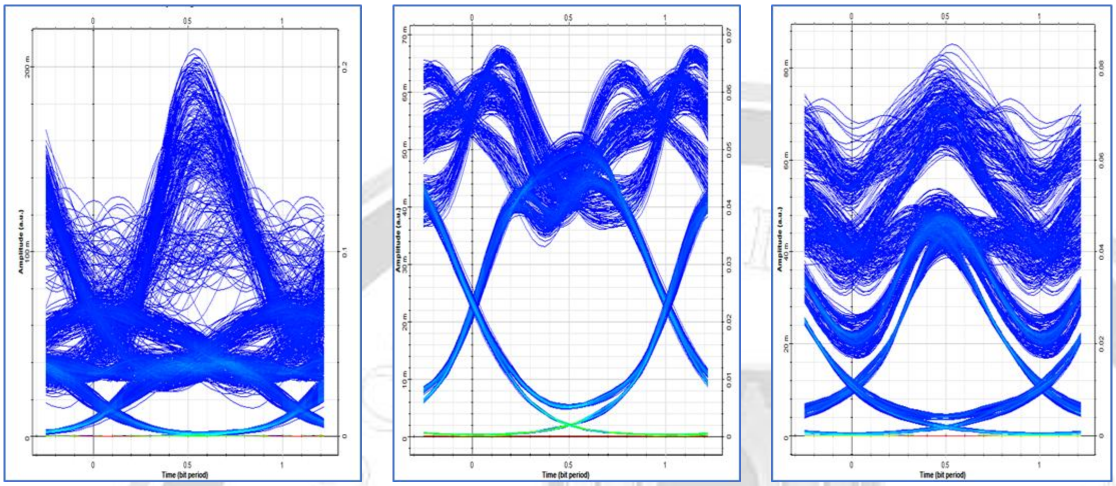

(A) (B) (C)

**Figure 6: Eye diagram performance of single channel of three modulation schemes at 100 Gbps: (A) NRZ, (B) RZ, (C) CSRZ**

Figure 6 exhibits eye diagram in single channel of three kinds of modulation strategies of power at input of 20 dBm and transmission distance of 60km and 200GHz channel spacing. This figure exhibits the best opening eye in case of RZ modulation rather than other types.

### B) Results of single channel at 200 Gbps data rate

Figure 7 illustrates achievement of systems with singular channels at proposed approach (modulation schemes). This figure explains the input power variation versus Q-Factor for three modulation scheme kinds. From the comparison between the modulations it can be realized that the RZ modulating shows better performance for different data rate 100 & 200 Gbps.

When data rates are 200 Gbps, the performance values of the system are almost halved due to the high data rate from 100 to 200 Gbps. At low power values, there is little difference in performance because the NRZ modulation type shows progress in performance values in their performance to other modulation . When input powers are high, the effect of non-linear phenomenon appears on the types of modulation used. In this context, RZ modulation type appears more resistant to this phenomenon and may be best compared to other types. For example, at input power of 20 dBm, the Q-factor is equal to 4.76 based on RZ modulation while for NRZ, CSRZ the Q-factor values are 1.106, 2.08813 respectively .

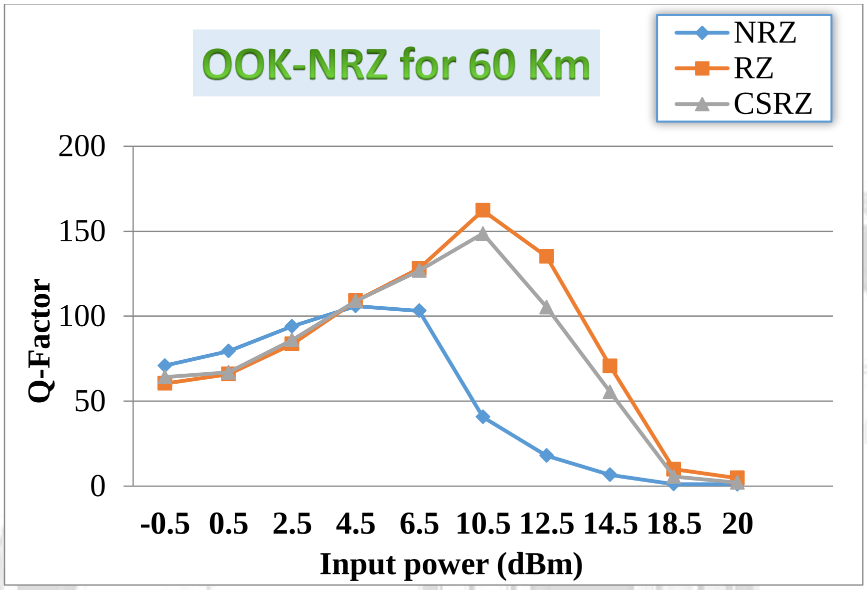


**Figure 7: Q-factor versus power of input of single channel of different modulation schemes at 20 Gbps**

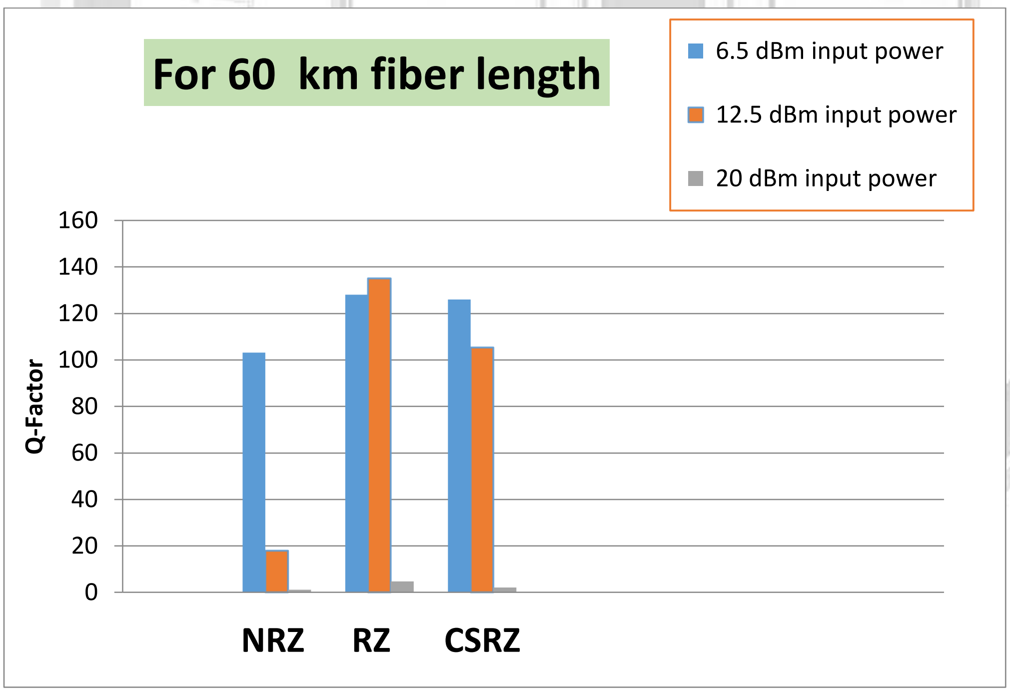


**Figure 8: Statistical representation of Q-factor for various three modulations at 60km and 200 Gbps data rate**

Figure 8 shows the statistical description of Q-factor for three modulation types at different power at input of systems with single channels at 60km fiber length. The comparison among different modulation formats has been simulated at 100 Gbps and 200 Gbps data rates. It can be seen that RZ modulation provides better performance than other modulation schemes, where the behavior is similar to 100 Gbps as a data rate.

### C) Results of single channel at 100 Gbps data rate with orthogonal channel technique

Figure 9 illustrates single channel performance using proposed polarization combiner technique (orthogonal channel). This figure explains the input power variation versus Q-Factor for three modulation schemes. From the comparison between the modulations, it can be seen that the RZ modulating provided better performance at different data rates of 100 Gbps .

At data rates of 100 Gbps, and at low power values, there is little difference in performance; the NRZ modulation type shows progress in performance values in their performance to other modulation . When input powers are high, the effect of non-linear phenomenon appears on the types of modulation used. In this context, RZ modulation type appears more resistant to this phenomenon and seems to be the best compared to other types. For example, at input power of 20 dBm, the Q-factor is 8.4 based on RZ modulation while for NRZ and CSRZ the Q-factor values were 1.44 and 6 respectively .

Figure 10 shows the statistical description of for 3 formats of modulation with different input power levels for singular channels at 60km fiber length with the Orthogonal Channel technique. The comparison of different modulation forms has been simulated at 100 Gbps data rate. It can be seen that RZ modulation introduces better performance than other modulation schemes where the behavior is similar to 100 Gbps data rate.

On the other hand, the technical results of the orthogonal channel shows improved performance compared to the traditional method under the same conditions. Consequently, the orthogonal technique shows great efficiency in reducing the non-linear phenomenon supported by the RZ modulation type.

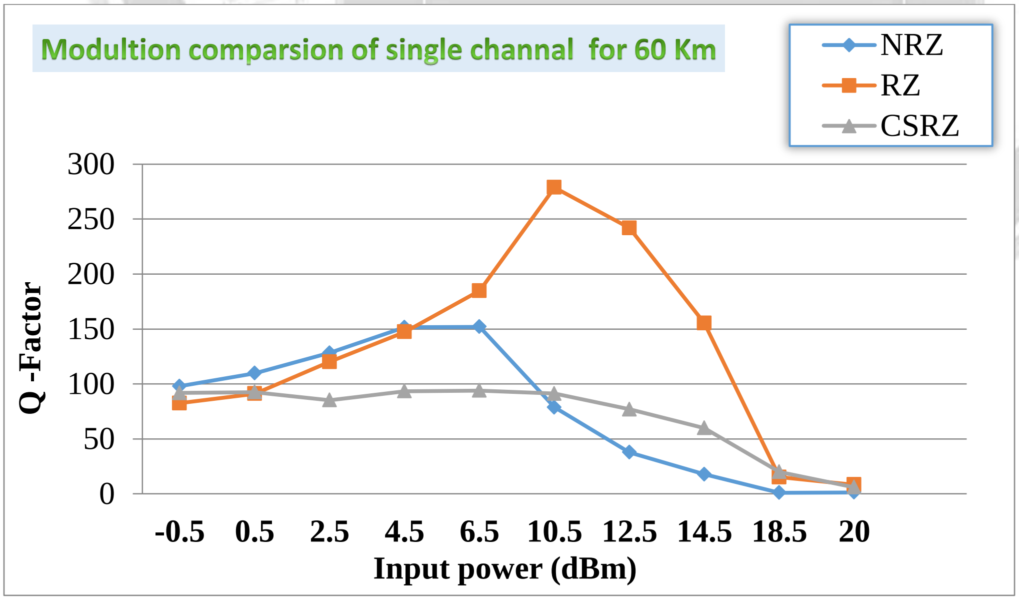


**Figure 9: Q-factor versus power of input of single channel for different modulation schemes at 100 Gbps with orthogonal channel technique**

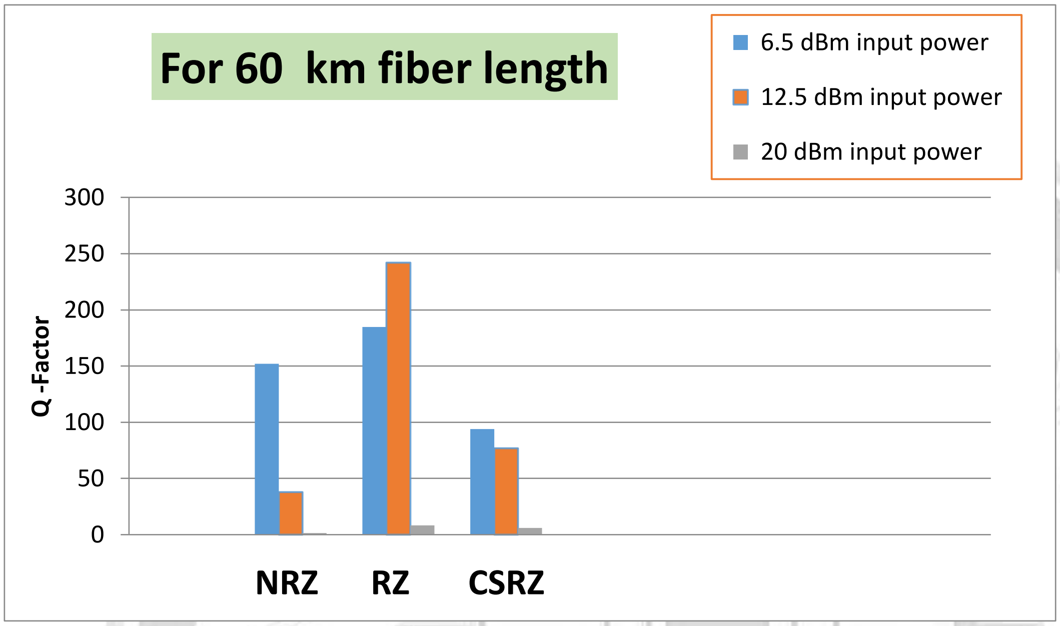


**Figure 10: Statistical representation of Q-factor for different three modulations at 60km and 100 Gbps data rate using orthogonal technique**

## Conclusion:

This paper aims to evaluate the performance of optical transmission systems at high data transfer rates and for several types of modulation schemes (RZ, NRZ, CSRZ). The results show that RZ gives the best performance in comparison to other types of modulation schemes. In addition, leveraging the orthogonality properties of the Polarization Combiner (PC) has a positive effect on the system performance. When using RZ, the value of the Q-Factor is equal to 8.4 at a distance of 60 km and at the input power of 20 dBm. When varying the input power values, RZ also provides the best performance when it is compared with other types of modulation. Finally, RZ demonstrates superior robustness against non-linear effects, particularly interference at high transmission rates.

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# تأثير مخططات التضمين على التداخل غير الخطي للوصلات الضوئية عالية السرعة

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**الخلاصة**

تعاني أنظمة الاتصالات المعتمدة على الألياف الضوئية من تأثيرات غير خطية. هذه التأثيرات غير الخطية تقيد بشدة تعدد الإرسال بتقسيم الطول الموجي (WDM) وبالتالي تضعف أداء نظام النقل البصري. يعد مجمع الاستقطاب (PC) أحد التقنيات الواعدة التي تخفف من التأثيرات غير الخطية، وخاصة التداخل. يقترح هذا العمل نظامًا مجمع الاستقطاب مع مخططات تضمين مختلفة بما في ذلك العودة إلى الصفر (RZ)، وعدم العودة إلى الصفر (NRZ)، والعودة إلى الصفر (CSRZ) التي تمنعها الموجة الحاملة في نظام اتصالات الألياف الضوئية غير الخطي. تم اختبار أداء النظام المقترح تحت ظروف مختلفة، بما في ذلك تغيير قدرة الإدخال وبمعدلات نقل البيانات بما في ذلك (100 و 200) جيجابت في الثانية. لقد تبين من النتائج أن شكل التشكيل RZ يقدم أفضل أداء، حيث أن التأثيرات غير الخطية في الألياف الضوئية تنخفض. علاوة على ذلك، عندما تكون مسافة الإرسال تساوي 60 كم، فإن RZ يعطي عامل Q يساوي 8.4. من ناحية اخرى ، فإن عوامل Q تساوي 1.44 و6 عند استخدام NRZ وCSRZ على التوالي.

**الكلمات الدالة:** مخططات التضمين، التداخل غير الخطي، الألياف الضوئية، مجمع الاستقطاب، عامل النوعية