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Enhancing optical fiber communication systems using repetition coding for improved signal fidelity and error reduction

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In optical communication systems, mitigating transmission errors caused by channel noise remains a critical challenge. This paper proposes bit repetition coding as a simple and effective method to enhance signal fidelity at the receiver. Our approach achieves a significant reduction in the bit error rate (BER), with simulations showing a decrease from 10^{-3} to 10^{-10} as the repetition count increases from 3 to 7. Furthermore, the clarity of the received signal improves consistently, with errors approaching zero at optimal repetition levels. This balance between simplicity and performance demonstrates the potential of repetition coding as a robust solution to transmission noise. Beyond its practical benefits, the study opens new pathways for designing resilient optical communication systems and highlights the relevance of repetition coding in improving both system reliability and efficiency. Future research is encouraged to explore its integration into next-generation optical networks.

Keywords: optical communication systems, repetition coding (RC), bit error rate (BER), quality factor Q, error correction techniques, optical fiber transmission.

1. Introduction

Communication plays a central role in our daily lives, and thanks to telecommunication systems, the world has truly become a global village. Optical fiber transmission systems offer numerous advantages over traditional networks [1], such as the attenuation of electromagnetic disturbances [2], significantly higher data transfer speeds [3], and a much broader bandwidth that enables the transmission of large files [4]. These characteristics make optical systems an essential technology in modern communications.

KALONI *et al.* [5] and JIHAD *et al.* [6] discuss in their papers the operating principle of optical transmission chains, as well as various parameters found in these chains such as bandwidth and multiplexing techniques [7, 8]. Despite the quality of communication media and transmission techniques [9], disturbances still occur, leading to errors. In such cases, the received binary sequence may differ from the transmitted sequence.

However, despite the quality of communication media and transmission techniques, disturbances persist, leading to errors in transmitted data. As a result, the received binary sequence may differ from the transmitted sequence. To address this issue, error correcting codes (ECC) are commonly employed [10]. Various types of codes [11], such as Reed−Solomon (RS) codes [12], convolutional codes [13], and LDPC codes [14], have been extensively studied in the works of MIZUOCHI *et al.* [15], ABDUL-ALWAHAB *et al.* [16] and NAVIDPOUR *et al.* [17], which analyze their impact on optical transmission chains.

Nevertheless, these methods have a major drawback: their complexity at the decoder level and the large number of iterations required, which increase the signal-to-noise ratio (SNR) needed for accurate reception. This highlights a significant gap in the literature: the lack of studies focusing on balancing simplicity and performance in error correction for optical transmission systems [18].

In this context, repetition coding (RC) emerges as a simple yet effective technique to protect against errors caused by noise in a transmission channel [19]. Despite being a well-established technique, the application of repetition coding in optical communication systems has remained underexplored in scenarios involving low-power receivers and legacy infrastructure. Our approach aims to bridge this gap by demonstrating how repetition coding can be optimized to maintain error resilience while ensuring compatibility with such resource-constrained systems. Unlike more complex codes, repetition coding does not require intensive computations or complex processing at the receiver end. This makes the method particularly appealing for systems where simplicity is critical while still maintaining high performance.

In this paper, we explore the innovation introduced by repetition coding in the context of optical fiber transmission systems. We demonstrate how this approach offers a balanced solution between simplicity and efficiency by reducing receiver complexity while maximizing throughput. The values used in our simulations reflect those typically employed in optical fiber transmission systems, enabling a relevant comparison with other existing approaches. This study aims to address a gap in the literature by proposing an accessible and effective method to enhance the resilience of optical systems against disturbances.

2. Repetition coding (RC)

The theory of information, as proposed by SHANNON [20] in the 1940s, primarily aims to evaluate the performance of a telecommunication system in the presence of random disturbances (noise). In Shannon's paradigm, a source generates a message for a recipient. The source and the recipient are connected by a channel, which serves as the

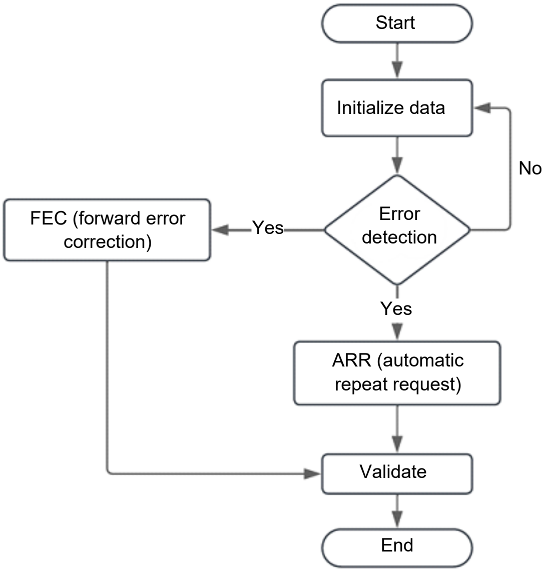

Fig. 1. Strategies for protecting against transmission errors.

medium of communication. This channel is subject to disturbances that create a discrepancy between the transmitted and received messages. To combat these transmission errors, error-correcting codes are employed. The principle behind these codes is to add symbols to the information to be transmitted according to predefined rules. Upon reception, it is verified whether the rule used during transmission is adhered to. If not, errors in transmission can be detected or corrected [21]. Strategies for protecting against transmission errors are shown in Fig. 1 [22].

There are several error-correcting codes available, including block codes, convolutional codes, turbo codes, and LDPC codes [22]. These encoders allow for maximum message reliability by using an increased number of redundancy bits and highly complex coding algorithms. However, the longer the message, the more expensive it becomes to use a channel. Therefore, as the algorithms and calculations become more complex, the cost of error-correcting memory increases, making the system more expensive. Consequently, there is a trade-off between error correction and the higher cost of the system.

Repetition coding provides a simple solution to protect against communication errors caused by noise in a channel. It is a straightforward channel coding technique. This method involves sending multiple copies of each bit during transmission. In this study, we demonstrate how the selection of the repetition factor can be optimized based on the constraints of the communication system, such as the available power budget and processing capabilities. By adjusting the number of repetitions, it is possible to strike a balance between error correction efficiency and system simplicity, making repetition coding particularly effective in low-complexity environments prone to noise. In other

T a b l e 1. Example of repetition coding (RC) with three bits.

Message source (bits to transmit)	Encoded message (codeword) RC = 3
0	000
1	111

T a b l e 2. Coding and decoding technique of repetition coding.

Message source	0 0 1 0 1 1 0
Encoded message	000 000 111 000 111 111 000
Received message	000 100 110 000 111 110 000
Decoded message	0 0 1 0 1 1 0

words, this repetition code encodes the transmission of bits over a certain number of stolen bits. For example, if the bit repetition is done on three bits, Table 1 would result.

Decoding is achieved through majority voting. Table 2 illustrates an example of message transmission using the repetition coding technique.

3. Transmission chain in optical systems

The optical transmission chain relies on a series of functional blocks that ensure the efficient and reliable transmission of data [23]. Data is encoded and modulated onto optical signals using techniques such as amplitude [24], frequency [25], or phase modulation [26], protected by error-correcting codes like Reed–Solomon [27,28] or LDPC [29]. The transmission block converts electrical signals into optical signals using light sources [30], optical modulators [31,32], and amplifiers to strengthen the signal [33,34]. The channel block uses optical fibers and technologies like wavelength division multiplexing (WDM) to increase transmission capacity [35,36], complemented by dispersion compensation techniques [37] and quality control [38]. Finally, the reception block reconverts optical signals to electrical signals [39], demodulates them [40], and applies error correction to ensure faithful data extraction [41-44].

4. Mathematical model

The transmission wave in optical communication systems is defined by several technical characteristics that influence overall system performance.

It is important to note that the mathematical models presented in this section align closely with the assumptions used in the OptiSystem simulation software. These assumptions include idealized channel behavior, linear modulation characteristics, and noise patterns consistent with optical communication standards. Ensuring this alignment enhances the accuracy of the simulation results and validates the performance metrics obtained, such as the Q-factor and bit error rate (BER).

4.1. Wavelength λ

Wavelength λ represents the light wave used for data transmission, typically measured in nanometers. Common wavelengths include 850, 1300, and 1550 nm, with minimal attenuation at the latter (see Fig. 2).

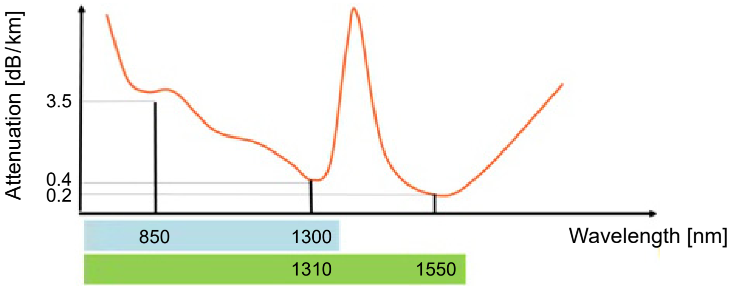

Fig. 2. Attenuation as function of wavelength.

Attenuation is typically expressed in dB/km and depends on the wavelength. Attenuation and its compensation are crucial for enabling long-distance transmissions in optical telecommunications. The general formula for calculating attenuation in an optical fiber is [45]

$$A = 10\log(P_e/P_s) \quad (1)$$

where A represents attenuation (in decibels), P_e denotes the optical power injected into the fiber (in watts), P_s represents the optical power at the output of the fiber (in watts). In practice, P_e and P_s are measured using a photodetector and a laser source to characterize attenuation in a given optical fiber installation.

4.2. Bit rate

Indicates the speed of data transmission, typically measured in Mbps (megabits per second), and is directly proportional to the system's bandwidth.

4.3. Optical power *P*

Denotes the strength of emitted light, measured in milliwatts (mW) or decibels-milliwatts (dBm), influencing the system's signal quality over long distances.

4.4. Bandwidth

Refers to the frequency range used for transmission, determining the data transmission speed and system capacity.

4.5. Attenuation

Measures the power loss during signal transmission through the optical medium, quantified in decibels per kilometer (dB/km) using the equation $\alpha = A/L$ (where α signifies

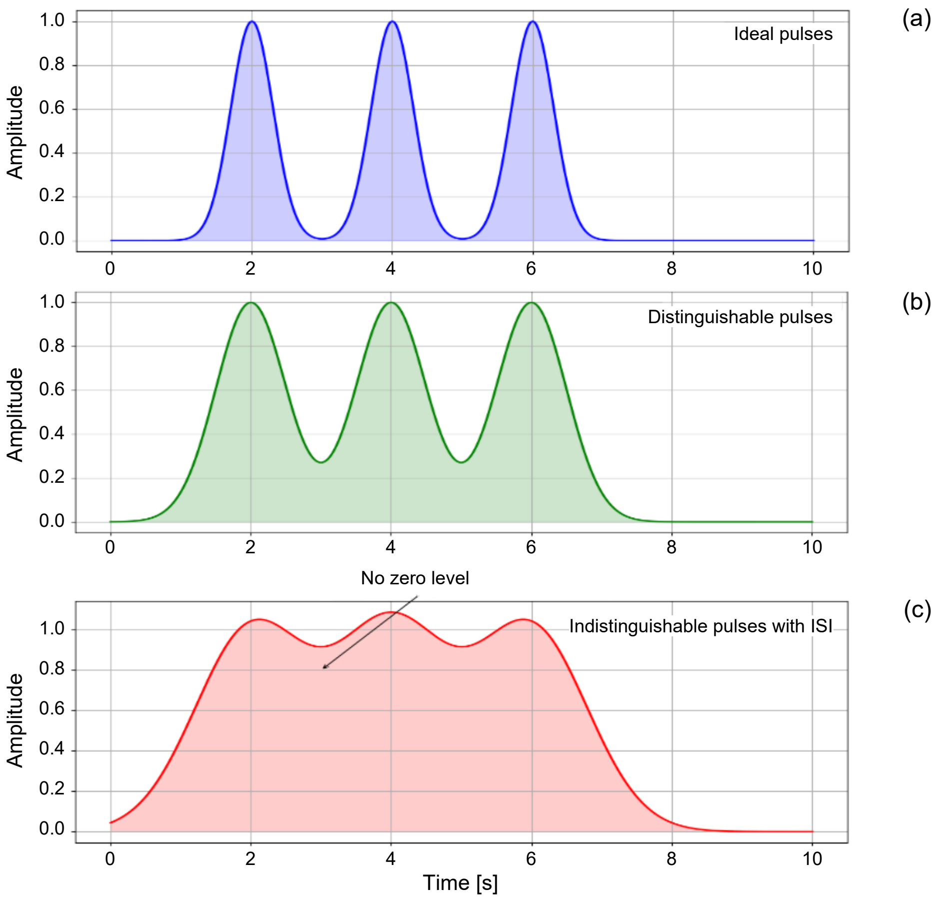

Fig. 3. An illustration using the binary digital configuration 10101. (a) Ideal pulses, (b) distinguishable pulses with overlap, and (c) indistinguishable pulses with ISI.

the attenuation coefficient in dB/km, A represents the total attenuation in dB, and L denotes the length of the fiber in km).

The coefficient α typically ranges from 0.2 dB/km for the most efficient single -mode fibers to 3 dB/km or more for standard quality multimode fibers.

4.6. Dispersion

Represents the spreading of light pulses over time due to varying propagation speeds of spectral components, causing intersymbol interference and reduced bit rates.

Dispersion becomes particularly significant in high-speed systems and has been analytically determined for Gaussian-shaped pulses, given by the formula [46]

$$D_L = 2(2\sigma B_{opt}\sqrt{2})^4 \quad (2)$$

where D_L denotes dispersion, and σ represents pulse broadening.

4.7. Receiver sensitivity

The minimum optical power the receiver can interpret accurately, crucial for system reliability. The temporal response of digital systems is determined by the formula [47]

$$T_{\text{syst}} = \frac{0.35}{B_{\text{opt}}(\max)} \tag{3}$$

These parameters collectively dictate the effectiveness of optical communication systems in achieving reliable and efficient data transmission.

Figure 3 illustrates the increasing impact of disturbances, such as dispersion and inter-symbol interference (ISI), on signal quality in an optical transmission system. It highlights the progressive degradation of the signal, transitioning from an ideal state (a) to a state where the pulses become difficult to distinguish (c).

5. Eye diagram

An eye diagram is a graphical representation used to visualize and analyze optical communication signals (Fig. 4), particularly in digital transmission systems. It displays the optical waveform and allows for signal quality assessment by examining parameters such as pulse width, amplitude, and crosstalk. This diagram typically resembles the shape of an open eye and can be employed to diagnose transmission issues and optimize system performance.

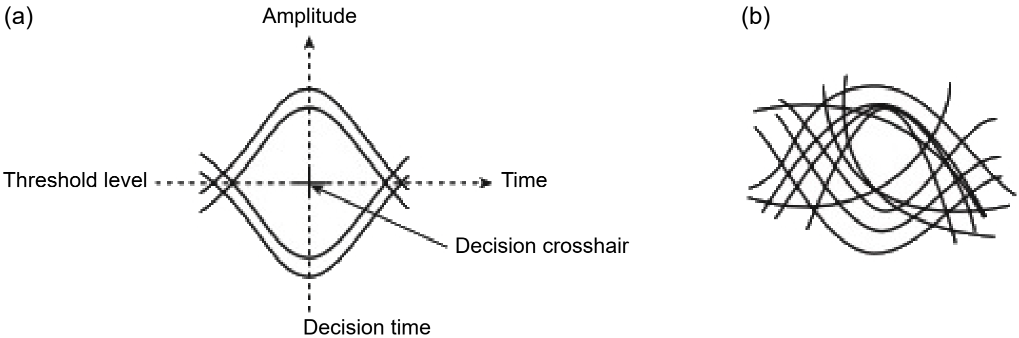

Fig. 4. Eye diagrams in binary digital transmission. (a) The diagram obtained with a bandwidth limitation but no additive noise (open eye). (b) The diagram obtained with a bandwidth limitation and additive noise (partially closed eye) [47].

The representation of an eye diagram in an optical communication system is based on the convolution of a data signal with the channel and receiver impulse response. This can be expressed as [48]

$$S(t) = \sum_{n=1}^{\infty} D_n P(t - nT) + N(T) \tag{4}$$

where $S(t)$ is the received signal, D_n represents data symbols (0 or 1), $P(t)$ is the waveform of the transmitted signal pulse, T is the symbol period, and $N(t)$ is the noise.

This model accounts for the effects of noise, crosstalk, and signal distortion, allowing for the evaluation of optical communication quality and identification of potential issues that may impact system performance.

The eye diagram is then generated by displaying the received signal $S(t)$ at high speed with samples taken in the middle of each data symbol, creating the characteristic shape of an open eye.

6. Simulation, results, and discussion

Our aim is to introduce a reliable, wide-range optical network communication system that meets quality and performance requirements by analyzing the point-to-point (P2P) gigabit principle within the MAN region using the OptiSystem program. Like all trans-

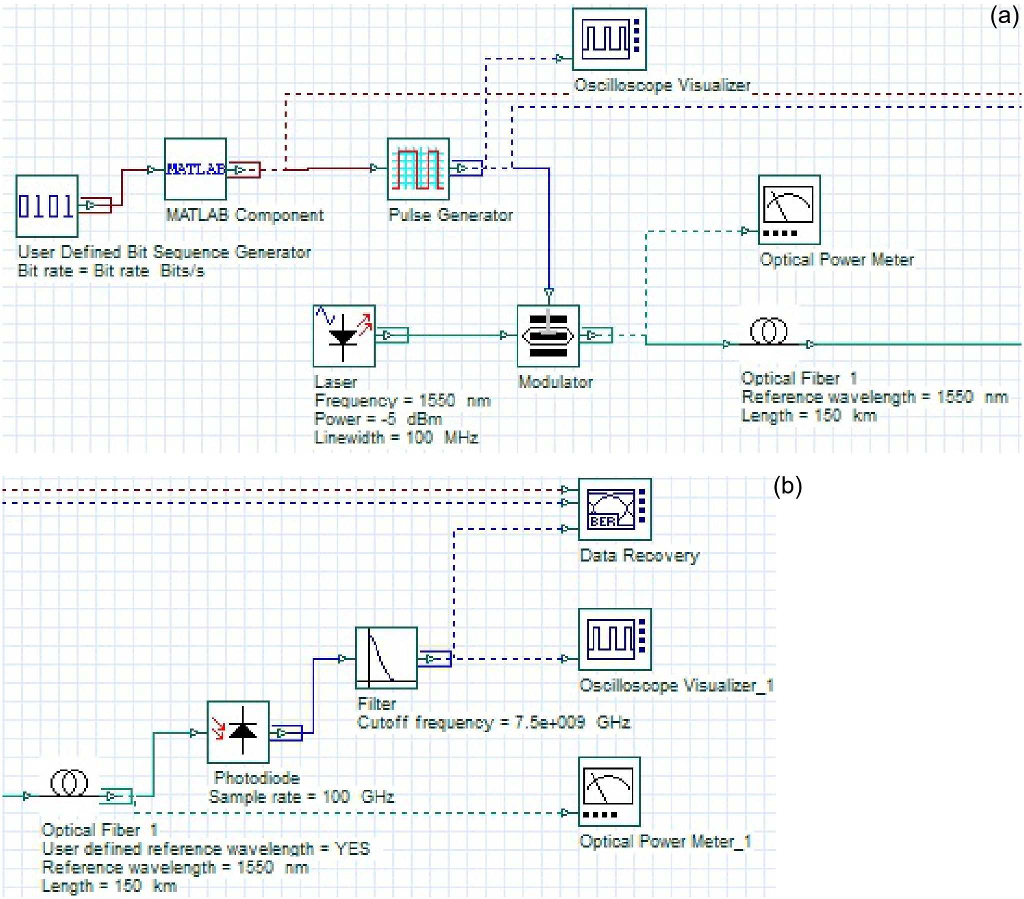

Fig. 5. Simulation setup. (a) Emission, and (b) reception.

T a b l e 3. Simulation setup parameters.

Transmission block	Laser	λ = 1550 nm
		P = [–5 ... 4] dBm
		BP = 100 MHz
	Modulator	Ext ration 20 dB
Channel block	Fiber	λ = 1550 nm
		α = 0.2 dB/km
		L = [50 ... 190] km
		D = 16.75 ps/nm·km
Receiver block	Photodiode	1 A/W
		λ = 1550 nm
		Sample rate 100 GHz
	Filter	$f_c = 7.5\times10^{-18}$ Hz
		Insertion loss 0 dB

mission systems, it is composed of three main components: the transmission block, the channel block, and the receiver block (see Fig. 5). This link is typically characterized by the parameters presented in Table 3.

Figure 5 illustrates the simulation setup. In the first stage, the [USBS] component is responsible for generating the data bits [01001…01] to be transmitted. Meanwhile, the [Mach–Zehnder] component encodes the bits onto the optical signal generated by the laser to inject them into the optical channel. The optical fiber serves as the propagation medium, allowing the transmission of optical information over long distances, which can reach up to 200 km, depending on our network setup.

During the propagation of the optical signal, the binary data undergoes attenuation, losses, and inter-symbol interference (ISI) caused by spectrum spreading. All these factors lead to an increase in bit detection errors by the photodiode placed at the third stage of the optical link, thereby degrading transmission quality. To mitigate the effects of ISI, we proposed a coding technique to protect the transmitted data bits.

The integration of the MATLAB component in the transmission chain enables precise control of bit repetition before pulse generation, optimizing encoding without adding complexity to modulation or reception. This approach enhances signal resilience to noise, reduces the bit error rate (BER), and ensures a more robust and adaptable error correction in noisy channels.

Table 3 contains the parameters corresponding to each block, outlining the specific characteristics and configurations necessary to achieve optimal system performance.

Two effective methods for analyzing and evaluating the performance of PON optical communication systems are the bit error rate (BER) and the Q-factor. The Q-factor represents the signal-to-noise ratio at the optimal decision point. Meanwhile, the

BER estimation method involves comparing the binary signal bits generated with those received. The BER can be calculated as follows:

$$\text{BER} = \frac{1}{4}\text{erfc}\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{1}{Q\sqrt{2\pi}}\exp\left(-\frac{Q^2}{2}\right) \tag{5}$$

6.1. Impact of data encoding

In our study, we innovatively utilized the repetition coding (RC) technique to facilitate optical information transmission across a 150 km optical fiber transmission line. This approach involves duplicating each bit multiple times, giving the receiver additional time to distinguish between received signals representing '1' or '0'. Our investigation encompassed several scenarios wherein we systematically varied the repetition count, ranging from RC = 2 to RC = 5. For each scenario, we meticulously computed both the bit error rate (BER) and the quality factor Q to comprehensively evaluate system performance, as illustrated in Fig. 6.

Based on the findings depicted in Fig. 6, a clear trend emerges as the number of repetition coding iterations increases: BER diminishes, or conversely, the quality factor Q improves. This inverse relationship between BER and Q, as indicated by Eq. (5), underscores the fidelity and reliability of our system.

Furthermore, Fig. 6 elucidates that upon reaching a coding scheme with 5 repetitions (RC = 5), the BER approaches approximately 0 ($Q = 2.5$). Consequently, there is no imperative to further increase the repetition count. This observation signifies the efficacy of the repetition coding approach in achieving optimal transmission performance, where the system attains a near-zero error rate and a commendable Q-factor.

Moreover, a detailed examination of the BER and Q-factor trends across varying repetition counts offers insights into the convergence of system performance metrics.

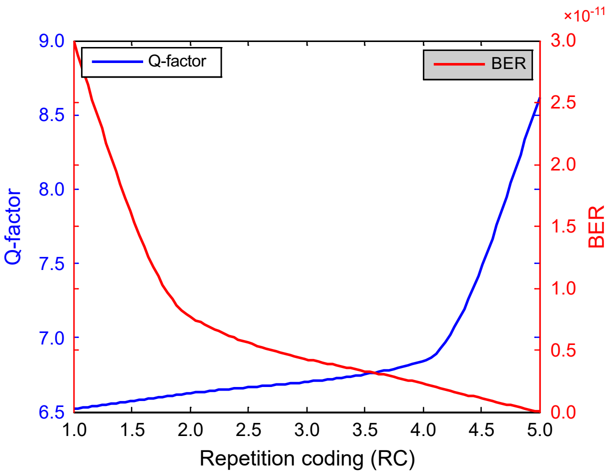

Fig. 6. Q-factor and BER *vs*. CP.

As the number of repetitions increases, the BER steadily declines, indicating improved error correction capabilities. Simultaneously, the *Q*-factor exhibits a corresponding ascent, signifying enhanced signal quality and resilience to noise interference. This corroborates the robustness and effectiveness of repetition coding in mitigating transmission errors and bolstering overall system reliability.

Additionally, it is worth noting that while increasing the repetition count beyond a certain threshold may yield marginal improvements in BER and *Q*-factor, the diminishing returns diminish as the coding complexity escalates. Therefore, achieving a balance between error correction efficacy and computational efficiency is essential in optimizing system performance.

In summary, the comprehensive analysis of BER and *Q*-factor variations with varying repetition counts underscores the effectiveness of repetition coding in enhancing the fidelity and reliability of optical communication systems. By elucidating the convergence of these performance metrics and identifying the optimal repetition count, our study provides valuable insights for the design and implementation of robust transmission solutions.

6.2. Impact of transmission power

In this simulation section, we considered the transmission power *P* taking values in the range from –5 to 4 dBm, with a data rate $D = 100$ Gbps over a distance of 150 km. These parameters are typical of the system under study. The results, depicted in Fig. 7, illustrate the relationship between optical power and the *Q*-factor.

Figure 7 reveals a notable trend: as the optical power increases from –5 to 4 dBm, indicating higher power received by the receiver, there is a corresponding improvement in *Q*-factor values. This improvement signifies enhanced system output. Furthermore, encoding enhances the resilience of data during its propagation through the transmission channel.

It is important to note that to meet optical network requirements, ensuring a BER of less than 10^{-9} and a *Q*-factor greater than 6, the optical power *P* must exceed 3 dBm.

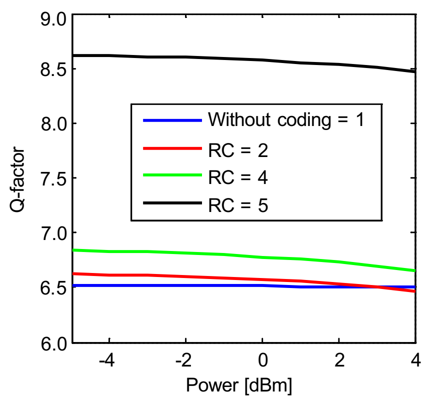

Fig. 7. *Q*-factor *vs.* power *P* for different value of repetition coding.

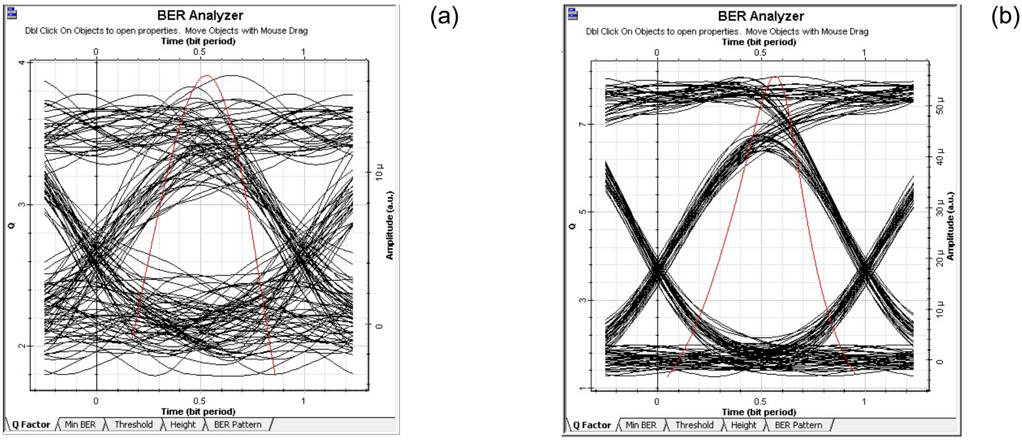

Fig. 8. Eye diagram of downlink shown in BER analyzer (the red curve represents Q-factor). Eye diagram with (a) $P = -5$ dBm, and (b) $P = 4$ dBm.

Figure 8(a) and (b) illustrate the downlink eye diagram results obtained at different optical power levels, specifically –5 and 4 dBm, respectively. The eye diagram's bevel edge gradient serves as an indicator of the system's resilience to time errors. A steeper gradient suggests a more robust system, better equipped to tolerate timing variations and maintain signal integrity.

6.3. Impact of transmission distance length

In this simulation section, building on the previous simulations, we considered the signal transmission power $P = 3$ dBm and the transmission data rate $D = 100$ Gbps. The length of the optical link L varies within the range from 50 to 190 km. The results regarding the Q-factor are depicted in Fig. 9.

Figure 9 illustrates the evolution of transmission system performance Q relative to transmission distance L. It is noticeable that performance deteriorates as distance

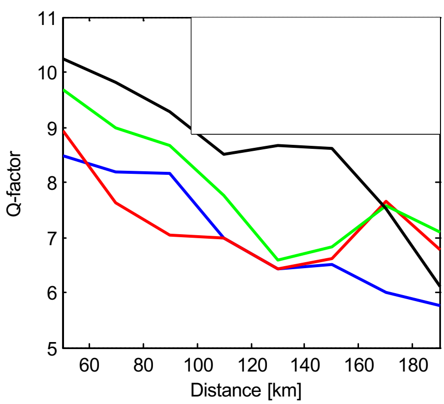

Fig. 9. Q-factor *vs.* distance L.

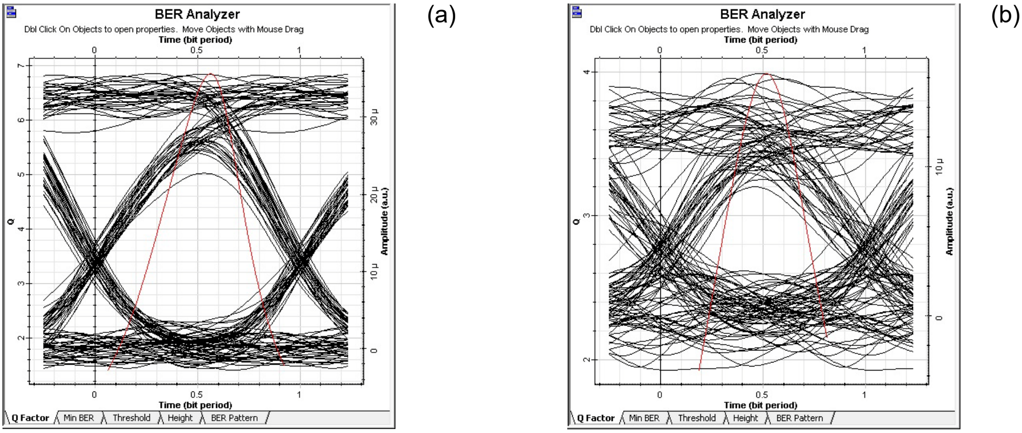

Fig. 10. Eye diagram of downlink shown in BER analyzer (the red curve represents Q-factor). Eye diagram with (a) $L = 10$ km, and (b) $L = 30$ km.

increases due to dispersions occurring during data propagation. Additionally, the figure demonstrates that data encoding helps protect data during its propagation in the channel, thereby enhancing the optical link further.

It is widely understood that as the distance between the transmitter and receiver increases, the rate at which the receiving performance deteriorates due to fiber loss slows down. To ensure optimal signal quality at the receiver, it is crucial to consider this attenuation over distance during transmission.

In practical terms, to meet the specified requirements of a BER less than 10^{-9} and a Q-factor greater than 6, the transmission distance L should ideally be kept under 170 km. However, beyond this distance, the use of optical amplifiers becomes necessary to compensate for signal loss and extend transmission distances while maintaining acceptable signal quality.

In Fig. 10(a), the eye diagram for a binary system with minimal distortion and no additive noise is displayed. It can be observed that the diagram is open, and the decision time corresponds to the center of the opening when the system length $L = 10$ km. The effect of practical impairments on the pulses (*i.e.*, intersymbol interference and noise) is to reduce the size of the eye or close it, as shown in Fig. 10(b). Therefore, for reliable transmission, it is essential to keep the eye open.

6.4. Interpretation of results

Our comparative analysis of different coding methods reveals intriguing insights into their performance concerning BER and complexity. Reed–Solomon (RS) exhibits a BER of 10^{-9} with moderate complexity [16]. Similarly, the frame error rate (FEC) coding method demonstrates a BER of 10^{-10} alongside moderate complexity [15]. In contrast, the low density parity check (LDPC) method boasts a lower BER of 10^{-3} but at the expense of high complexity [49]. Another contender, Luby transform (LT), achieves a BER of 10^{-4} with a moderate level of complexity [49].

Table 4. Comparison of coding methods.

	Code	BER	Complexity
[16]	Reed−Solomon (RS)	10^{-9}	Medium
[15]	Frame error rate (FEC)	10^{-10}	Medium
[49]	Low density parity check (LDPC)	10^{-3}	High
	Luby transform (LT)	10^{-4}	Medium
Our results	Repetition coding (RC)	10^{-11}	Low

However, our repetition coding method surpasses all others in the comparison, showcasing a remarkably low BER of 10^{-11}. What is more, repetition coding distinguishes itself by boasting the lowest complexity among all the considered methods, making it an appealing choice for practical implementation in communication systems.

While LDPC offers a lower BER compared to repetition coding, its high complexity may limit its feasibility in certain applications. On the other hand, Reed−Solomon (RS) and frame error rate codes (FEC) demonstrate moderate BER values with medium complexity.

In summary, our comparative analysis highlights the effectiveness of repetition coding in achieving low BER values with minimal complexity, making it a promising coding method for enhancing signal quality and reducing errors in communication systems (see Table 4).

Upon thorough analysis of the simulation outcomes, several significant observations emerge, shedding light on the effectiveness of repetition coding in enhancing optical communication systems.

The incorporation of error-correcting codes, particularly repetition coding, proves to be indispensable for ensuring robust transmission performance in optical fiber networks. By leveraging repetition coding, the system effectively mitigates the disruptive effects of channel-induced noise, thereby enhancing the reliability and integrity of signal reception.

Our findings unequivocally demonstrate the superiority of systems employing repetition coding over non-coded counterparts. Specifically, these coded systems exhibit substantially lower BER and higher Q-factor, underscoring the efficacy of repetition coding in improving transmission reliability.

In addition to enhancing performance metrics, the adoption of repetition coding facilitates the optimization of the transmission system architecture. Unlike traditional error-correcting codes, which often introduce algorithmic complexities, repetition coding offers a streamlined approach to error correction, simplifying the reception process without compromising effectiveness.

Furthermore, our analysis reveals a direct correlation between the number of repetitions and the system's information correction capabilities. Systems achieve optimal performance with approximately 5 repetitions, highlighting the importance of choosing an appropriate repetition count for maximizing transmission reliability.

Moreover, increasing power levels lead to improved system performance, while extending transmission distances results in a gradual decline in performance due to increased signal attenuation.

Overall, our comprehensive examination of simulation outcomes validates the effectiveness of repetition coding in enhancing optical communication systems. These findings underscore the practical utility of repetition coding as a viable solution for mitigating channel noise and optimizing transmission performance in real-world scenarios.

7. Conclusion

Repetition coding has proven to be a simple and effective solution for error correction in optical communication systems, achieving a BER of 10^{-11} while reducing receiver complexity. This method ensures reliable transmission, even over long distances and at high data rates. In the future, its optimization and integration with advanced technologies such as WDM, could further enhance the efficiency and resilience of next-generation optical networks.

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