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RESEARCH ARTICLE

Optimizing High Data Rate Up to 2.5 Tbps Transmission using 64-Channel DWDM System with DCF and NRZ Modulation

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Abstract

Objectives: This study aims to enhance and optimize a modern communication system for high data rate transmission using Dense Wavelength Division Multiplexing (DWDM). The objectives include employing a 64-channel DWDM system, implementing different data speeds, and utilizing a dispersion compensation method. **Methods**: To achieve the objectives, we simulate and analyze the effects of Dispersion Compensation Fiber (DCF) in a DWDM system with 64 channels. The system employs Non-Return-to-Zero (NRZ) modulation format at varied bit rates and multiple energy levels. We propose a method for achieving data rates of 10 to 40 Gbps using NRZ modulation and Erbium-Doped Fiber Amplifier (EDFA) over a single-mode fiber transmission distance of 40 to 160 km, along with a dispersion compensation fiber of 8 to 32 km (DCF). The performance of the developed model is evaluated based on Quality Factor, Bit Error Rate (BER), Eye Height, and Threshold. These metrics are measured at two input energy levels from an optical power source, covering a communication capacity ranging from 0.625 Tbps to 2.5 Tbps. **Findings**: Through the simulations and analyses, we uncover the impact of dispersion and demonstrate the effectiveness of the proposed method in compensating for dispersion effects. Performance analysis of two different input transmitter power levels, -10 dBm is more efficient compared to 0 dBm input transmitter power in terms of bit error rate and quality factor. **Novelty**: This study presents a novel approach to improving modern communication systems by utilizing DWDM with a dispersion compensation method. The use of a 64-channel DWDM system, combined with the proposed NRZ modulation technique and dispersion compensation fiber, provides an efficient solution for achieving high data rates over long transmission distances while minimizing the effects of dispersion. The findings contribute to the advancement of communication systems for high data rate transmission.

Keywords: Dispersion effect; Bit Error Rate; Q-factor; Optisystem software; Erbium doped fiber amplifier

1 Introduction

The demand for high data transmission capacity in optical communication systems has driven the advancement of technologies such as Wavelength Division Multiplexing (WDM) and Dense Wavelength Division Multiplexing (DWDM)[1–3]. These systems enable the simultaneous transmission of multiple wavelengths over a single fiber, significantly enhancing the overall transmission capacity. Recent studies have explored various modulation schemes, including Return to Zero (RZ) and Non Return to Zero (NRZ), in DWDM systems to optimize data transmission performance. While NRZ modulation has shown promise in certain configurations, such as providing superior performance in some scenarios compared to RZ modulation, there remain significant research gaps regarding its effectiveness across different system parameters. The performance of DWDM systems is influenced by factors such as dispersion, nonlinear effects, and amplifier characteristics. Dispersion compensation techniques and optical amplifiers like Erbium Doped Fiber Amplifiers (EDFAs) play crucial roles in mitigating these effects and enhancing system performance. However, there is still a need to explore the optimal configurations and combinations of these components to maximize system efficiency and reliability. Existing literature highlights the importance of addressing issues such as dispersion compensation, nonlinear effects, and modulation scheme selection to improve the performance of DWDM systems. While several studies have investigated these aspects individually, there remains a gap in understanding how these factors interact and impact system performance holistically.

The performance investigation of a four channel DWDM system employing the NRZ and RZ modulation schemes with an 8 Gbps bit rate revealed values for the post compensation technique's q-factor and BER for both modulation schemes, with the NRZ modulation strategy yielding unsatisfactory results in this work[4,5]. Using NRZ rather than RZ, Performance Analysis of OWC system-based (S-2-S) connections yields much superior results for the full lengths tested. Additionally, while utilizing the NRZ, the transmitter and APD receiver aperture diameters are more likely to fluctuate in size than when using the RZ[6]. When compared to RZ modulation, NRZ modulation performs noticeably better in terms of the performance, dependability, and accessibility of an NRZ-based transmission system[7]. Performance Enhancement of DWDM Optical Fiber Communication Systems Using EDFA offers considerably superior transmission properties than other amplifiers for long-distance transmission based on the amplification approaches[8]. The DWDM system's study of 32x40 Gbps = 1.28 Tbps utilizing NRZ and RZ line coding shows that NRZ line coding is better. According to the findings, the bit error rate reduces, and the Q-factor rises as power increases[9]. NRZ performs remarkably well in comparison to CSRZ and duobinary Modulation schemes and provides high quality factors and a low BER in various circumstances, according to an analysis of NRZ, CSRZ, and duobinary Modulation formats to compare their performance based on different parameters like data rate, fiber length, and laser power. Additionally, raising the amplifier gain and laser powers results in noticeable increases[10].

The performance assessment of dispersion compensation fiber (DCF) on NRZ and RZ modulation schemes underscores the critical impact of power optimization and dispersion adjustment on optical transmission systems. As transmitter power increases, the Q-factor decreases and the BER rises, emphasizing the need for careful power management. NRZ consistently outperforms RZ in BER, even across varied DCF lengths, highlighting NRZ's superiority in minimizing errors. These findings accentuate the importance of strategic parameter optimization for enhanced optical transmission system efficacy[11].

With ultrahigh data rates of 1 Tbps and 2.5 Tbps for 32 and 64 channels, respectively, both with 100 GHz and 75 GHz spacing, and corresponding spectral efficiency of 0.40 bit/s/Hz and 0.53 bit/s/Hz, CSRZ, DRZ, and MDRZ modulation techniques were used to analyze an extremely dense WDM network. The CSRZ modulation technique, which has 32 channels and 75 GHz spacing, thus performs the best, with strong nonlinear and dispersion tolerance, across a transmission distance of 4250 km. The best Max. Q factor with changing laser power is served by the MDRZ modulation scheme, which has 32 channels, 100 GHz spacing, and 250 km fiber length. It also exhibits strong tolerance for nonlinear effects[12]. As the transmission power levels are raised, the Q-Factor, BER, Eye height, and RMS Jitter values for NRZ and RZ modulation schemes at data transmission speeds of 10 Gbps all get better. When compared to the RZ modulation standard, the NRZ modulation format offers superior performance[13].

Based on the literature review on the post dispersion compensatory technique and NRZ modulation formats gives much better results on the form of eye para meter like quality factor, bit error rate and eye opening, also the popular amplifier known as the Erbium Doped Fiber Amplifier (EDFA), which has a very broad spectral bandwidth, is included in DWDM technology, allowing it to thrive. As a result, EDFA may boost multiple optical signals in a batch, facilitating high-capacity transmission, and EDFA-DWDM systems work together to satiate the enormous demand of today's traffic and bandwidth-hungry applications by abruptly increasing optical fiber transmission capacity. Due to the existence of phenomena along the fiber, such as dispersion and nonlinearities, DWDM performance is limited[14].

In this study, we've simulated a 64-channel DWDM system utilizing NRZ modulation setup, with varying transmission distances and bit rates with the first channel's central frequency set at 193.4 THz and channel spacing at 100 GHz. We have examined the DWDM transmitter's two different input power levels, -10 dBm and 0 dBm. In direction to increase OSNR, EDFA is utilized as an optical amplifier, while DCF aids in dispersion effect rectification. Utilizing Optisystem software, this performance study and characterization of the arrangement is carried out. This work differs from previous studies in its holistic approach towards evaluating the performance of NRZ modulation in DWDM systems. By considering the interaction of dispersion compensation techniques, amplifier characteristics, and modulation schemes, we aim to provide insights into optimizing system design for high-capacity optical communication networks. This research seeks to contribute to the ongoing efforts to enhance the performance and efficiency of DWDM systems, addressing critical research gaps identified in recent literature and providing valuable insights for future advancements in optical communication technology.

2 Methodology

The performance of a 64-channel DWDM optical fiber communication system is planned at channel transmission speeds of 10, 20, 30, and 40 Gbps with different transmission distances. Approach in simulating the performance of a 64-channel DWDM optical fiber communication system stands out in several key aspects, offering novel insights into system behavior and optimization strategies. Leveraging OptiSystem software, our study integrates a comprehensive set of parameters and models to accurately replicate real-world conditions and evaluate system performance [8]. The testing methodology involved the systematic alteration of each parameter, such as power levels and dispersion compensating fiber (DCF) lengths, while employing NRZ modulation. By varying these parameters across different lengths and power levels, we aimed to capture their individual and cumulative effects on system performance.

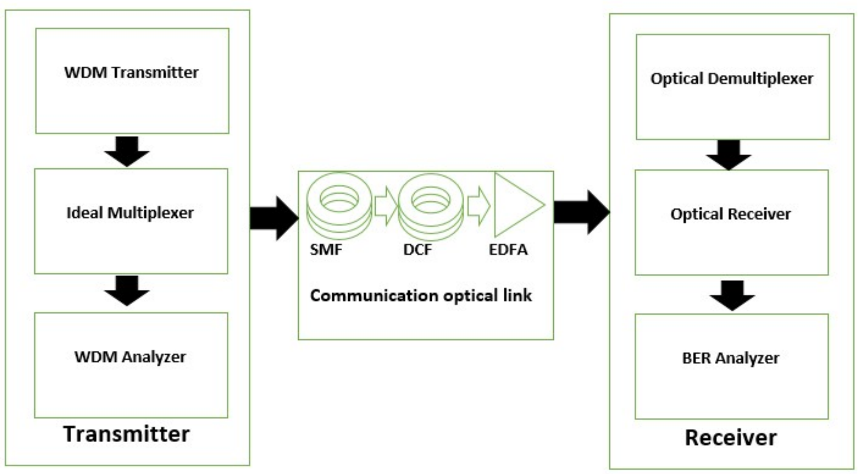

Fig 1. DWDM system modelling

The core three sections of the system model are depicted in Figure 1. A WDM transmitter, multiplexer, and analyzer make up the first portion. For the generation of different wavelength optical signals with 100GHz frequency spacing, 64 CW laser diodes are employed as the source. Using a DWDM multiplexer, these input optical signals are combined, enabling the use of a single optical fiber in the middle communication optical fiber link segment that consists of SMF, DCF, and EDFA. 40 km of Single Mode Fiber and 8 km of DCF with four loops are controlled by loops. Therefore, utilizing loop control, the total transmission lengths are 48km, 96km, 144km, and 192km.

The gain of an EDFA is succeeded through the supervision of stimulated emission, where erbium ions in the Fiber are excited to a higher energy level and then coherently release photons, amplifying the signal. The higher the gain, the more effectively the optical signal is amplified. Gain of an erbium-doped Fiber with a length of L is the ratio of the signal power at the Fiber output to the signal power injected at the Fiber input as:

$$G = \frac{P_s(L)}{P_s(O)}$$

The noise figure of an EDFA is a calculation of how much the amplifier contributes to the overall noise in the optical signal. As the optical signal passes through the EDFA, some additional noise is introduced, impacting the quality of the signal. The lower the noise figure, the better the amplifier performs in terms of minimizing additional noise. EDFA noise figure is particularly important in optical communication systems were maintaining a high signal-to-noise ratio is crucial for reliable and high-quality signal transmission. SNR reduction ratio from input to output of the amplifier is defined as Noise Figure,[15]

$$NF = \frac{SNR_{in}}{SNR_{out}}$$

The optical signal data is amplified for minimal insertion loss, better gain, and signal capability using the EDFA amplifier. At a length of roughly 10 m for an erbium-doped fiber (EDF), the usual EDFA gain per distance is 20–30 dB. However, the pump power, fiber type, and fiber length all have a restriction on the maximum power that may be produced by the amplifier. A continuous-wave laser (CW Laser) may be used as the light source for near-1550 nm pumps, and the pump is then paired with an information signal using a WDM coupler, allowing the EDF length to be up to 30 m depending on the EDFA setup. The selection of the light source is a crucial element that has a considerable impact on the effectiveness of EDFA[8]. In this work, we employ light sources operating in forward mode at 1550 nm.

The WDM Demultiplexer, which separates the optical signals into 64 independent channels, makes up the final receiver portion. The optical receiver receives the demultiplexed signal outputs using APD after passing them via a BER analyzer. Using NRZ rather than RZ, Performance Analysis of OWC system-based (S-2-S) connections yields much superior results for the full lengths tested. Additionally, while utilizing the NRZ, the transmitter and APD receiver aperture diameters are more likely to fluctuate in size than when using the RZ[6]. The impact of altering each power on each length of the dispersion compensating fiber in both NRZ modulations will be examined for the parameters. We meticulously curated simulation parameters, as outlined in Table 1, encompassing communication capacity, input transmitter power, data rates, frequency spacing, and modulation parameters. These parameters reflect diverse operational scenarios, enabling a thorough investigation of system behavior across varying conditions. For the fiber parameters, detailed in Table 2, we considered critical attributes such as fiber length, dispersion, attenuation, differential group delay, dispersion slope, and PMD coefficient. These parameters are instrumental in understanding the impact of dispersion and attenuation on signal quality and transmission efficiency.

Table 1. Simulation parameters 64 channel DWDM System

Simulation Parameters	Value
Communication capacity	0.625 Tbps, 1.25 Tbps, 1.875 Tbps, 2.5 Tbps
Input transmitter power	10 dBm
Data Rates	10/20/30/40 Gbps
frequency spacing	100 GHz
Transmitter frequency	193.4 THz
Sequence length	128 bits
Modulation Extinction ratio	30 dBm
Sample per bit	64
Reference Wavelength	1550 nm

Table 2. Fiber parameters

Parameters	SMF	DCF
Fiber Length (km)	40,80,120,160	8,16,24,32
Dispersion(ps/nm/km)	17	-85
Attenuation (dB/km)	0.2	0.5
Differential group delay	0.2ps/km	0.2ps/km
Dispersion slop (ps/nm^2/km)	0.075	-0.3
PMD coefficient (ps/nm)	0.5	0.5

3 Results and Discussion

The Optisystem software is used to simulate the performance investigation of the DWDM optical communication model, and the Q-factor and BER are measured using a BER analyzer. In direction to study the performance analysis of the suggested

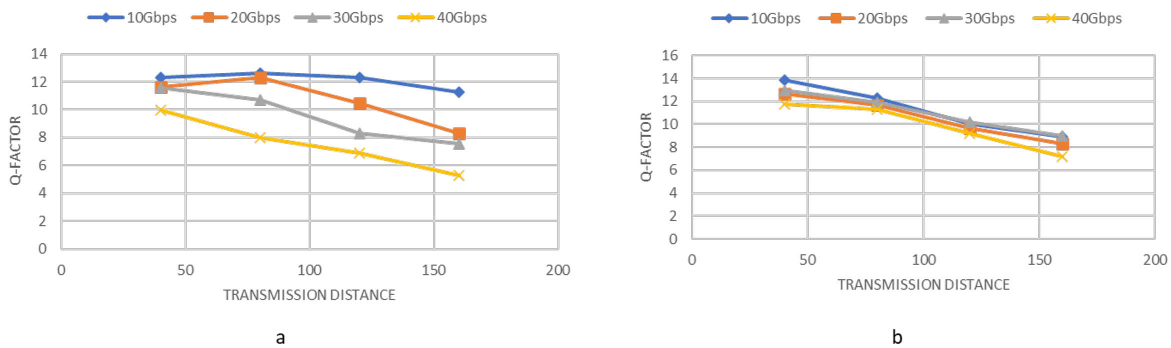

Fig 2. (a) Q-factor-transmission distance with several bit rates for -10 dBm Input Transmitter Power, (b) Q-factor-transmission distance with several bit rates for 0 dBm Input Transmitter Power

DWDM system model, an entire of 32 simulations are carried out utilizing an NRZ modulation system with several data rates (10, 20, 30, and 40 Gbps) and various input transmitter power levels (0 dBm and -10 dBm).

The acceptable Quality factor rate is larger than 6 and the acceptable BER is 10^{-9} or a smaller amount, theoretically they ensure a high level of reliability and performance in optical communication systems, meeting the demands of modern data transmission and communication applications, for the best fiber optical communication system [6]. Subsequently, reviewing the performance investigation of a 64-channel DWDM system operating at speeds of 10, 20, 30, and 40 Gbps over distances of 40+8, 80+16, 120+32, and 160+48 km via an optical fiber, the system met the necessary standards for Q-factor and bit rate. The variable bit rates for the two distinct input transmitter powers, 0 dBm and -10 dBm, correspond to different transmission distances. According to earlier studies on a power optimization and dispersion compensation simulation for the NRZ modulation constant in the power delivery with respect to increasing DCF length, reduces Q-factor, and raises BER, as well as input power with respect to constant DCF length, reduces Q-factor, and raises BER [13].

As we raise transmission distance from 40 km to 160 km, the Q-factor falls. Figure 2**(a)** and **(b)** show both graphs, Q-factor Vs transmission distance with several bit rates for -10 dBm and 0 dBm input transmitter power. In other words, because of the increased nonlinear effect, the Q-factor likewise declines linearly as the bit rate is raised from 10 Gb/s to 40 Gb/s.

The BER vs. bit rate is shown in Figure 3**(a)** and **(b)** for -10 dBm and 0 dBm input transmitter power at several transmission distances. The BER increases as the bit rate is raised from 10 Gbps to 40 Gbps. In other words, the bit error rate falls as transmission distance increases from 40 to 160 kilometers due to dispersion effect. The dispersion causes the spreading of optical pulses as they travel through the fiber. There are two main types of dispersion: chromatic dispersion and polarization mode dispersion. Both types can lead to signal distortion and reduce signal quality over long distances.

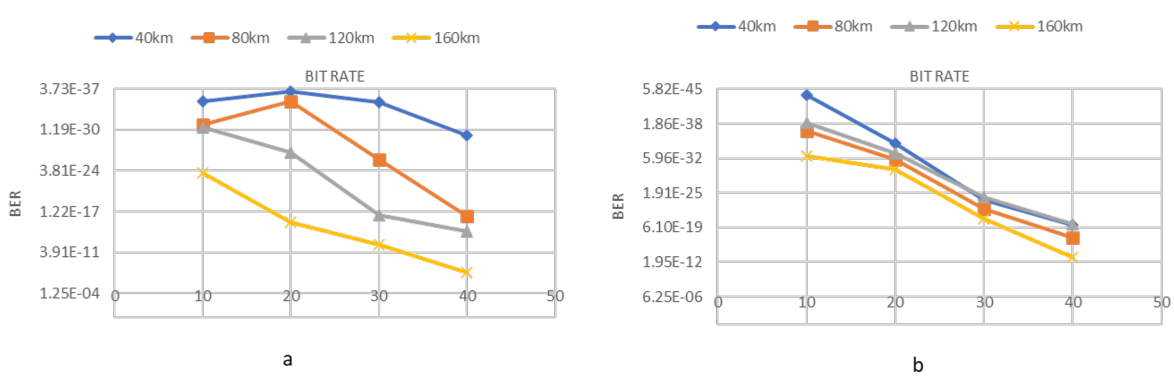

Fig 3. (a) BER-Bit Rate with several Transmission Distance for -10 dBm Input Transmitter Power, (b) BER-Bit Rate with several Transmission Distance for 0 dBm Input Transmitter Power

Figure 4**(a)** and **(b)** display two graphs of eye height against transmission distance for -10 dBm and 0 dBm input transmitter powers. In terms of eye height, the 0 dBm power level performs better than the -10 dBm power level at both power levels. The eye height decreases from 40 km to 160 km of transmission distance. In other words, the eye height rapidly lowers as the bit rate is raised up from 10 to 40 Gbps and it is because of Optical signals experience attenuation as they propagate through the optical fiber. This means that the signal power decreases with distance. As the transmission distance increases from 40 km to 160 km, the signal power gets attenuated more, leading to a decrease in the signal-to-noise ratio (SNR).

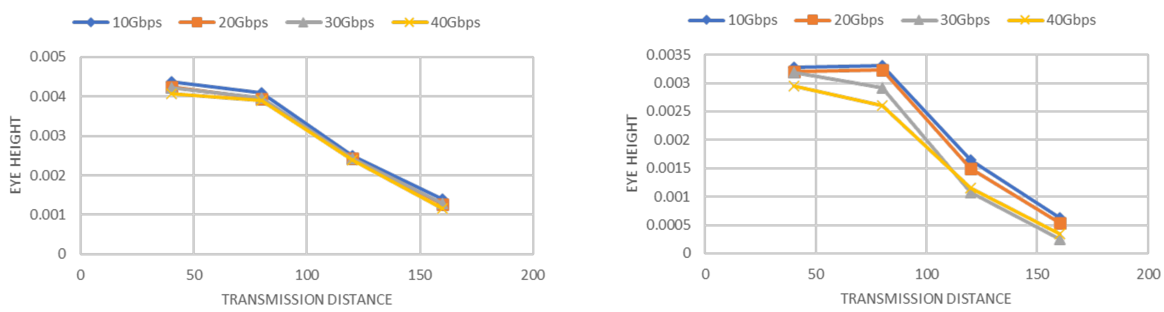

Fig 4. (a) Eye Height-Transmission Distance with several Bit Rate for -10 dBm Input Transmitter Power, (b) Eye Height-Transmission Distance with several Bit Rate for 0 dBm Input Transmitter Power

In Khalil et al. conducted a comparative analysis of NRZ modulation formats across various parameters including data rate, fiber length, and laser power. They found that NRZ modulation outperforms other schemes, with noticeable performance enhancements resulting from increased amplifier gain and laser powers[(10)].

Meanwhile, Sharma et al.'s study, increasing transmission power levels correlate with improved Q-Factor, BER, Eye height, and RMS Jitter values for NRZ modulation schemes operating at 10 Gbps data transmission speeds. However, in contrast to our present work where data transmission rates are set at -10 Gbps and 0 Gbps, Sharma et al. observed superior performance in terms of eye parameters[(12)].

4 Conclusion

The investigation of the 64-channel DWDM system employing the Dispersion compensation scheme for NRZ modulation at various data rates and input transmitter power levels has yielded valuable insights into its performance characteristics. We created and simulated a proposed model using a DCF with an EDFA amplifier to account for attenuation and dispersion effects. Our analysis focused on key performance metrics, including the Quality factor, eye height, bit error rate, and threshold, as the system operated under different conditions. We observed that as the transmission distance increases from 40 km to 160 km, the Q-factor declines due to the combined effects of attenuation and dispersion. Furthermore, raising the bit rate from 10 Gb/s to 40 Gb/s leads to a linear decline in the Q-factor due to the increased impact of nonlinear effects, which can degrade the overall signal quality in the optical communication system. Notably, our investigation demonstrated that for bit rates of 10, 20, 30, and 40 Gb/s per channel under the NRZ modulation scheme, both input transmitter power levels exhibited adequate performance to enable errorless transmission while minimizing dispersion. In particular, a 0 dBm input transmitter power level yielded superior results. It maintained fiber optical carrier quality for a 10 Gb/s bit rate at 40 km transmission distance, achieving a Q-factor of 13.82 and an impressively low BER of 8.46 x 10-44. Additionally, we observed a linear decline in the eye parameter as bit rates and transmission distances increased at both power levels. A higher eye height and threshold value indicated reduced dispersion, jitter, and synchronism, which bodes well for the overall reliability of fiber optical communication.

In conclusion, our investigation sheds light on the performance characteristics of the 64-channel DWDM system with Dispersion compensation under NRZ modulation. The findings underscore the importance of carefully considering transmission distance, bit rate, and input transmitter power levels in optimizing system performance. The achieved errorless transmission with minimized dispersion holds promise for the practical deployment of high-speed optical communication systems. As with any research, there are limitations to this study, and we encourage further exploration of other system configurations and future research to address them.

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