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Investigating the Performance of 64-Channel DWDM Systems with High Data Rates up to 2.5 Tbps at Varying Power Levels and Bit Rate

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Abstract

Objectives: This investigation evaluates the performance of DWDM 64-channel systems with RZ modulation under different bit rate and power level conditions. We need to understand the effects that transmission distance together with bit rate and optical input power have on key performance indicators which include both Quality Factor (Q-Factor) and Bit Error Rate (BER) and Eye Height. **Methods**: OptiSystem software operates as a DWDM emulator which applies RZ modulation during simulations at 10, 20, 30 and 40 Gbps bit rates. Two different optical input power levels (-10 dBm and 0 dBm) are evaluated at various distances between 40 km to 160 km while using single-mode fiber. This research investigates how changes in power level together with bit rate modifications affect system performance through performance metrics evaluation of Q-Factor, BER and Eye Height. **Findings**: Simulation outcomes demonstrate that raising optical input power to 0 dBm delivers superior system performance than using lower power of -10 dBm especially when transmitting over extended distances. The system produces enhanced Q-Factor performance along with decreased BER and higher Eye Height when working at 0 dBm. Higher bit rates at 30 and 40 Gbps result in a shorter signal maintenance distance because dispersion and nonlinear effects are more prone to degradation. The performance and stability remain higher when using bit rates at 10 Gbps compared to higher rates. **Novelty**: The research conducts a thorough examination of DWDM systems during RZ modulation while adjusting input power constraints and digital data speed. Data rate transmission distance relations in optical networks become visible through this research so do the necessary requirements of advanced dispersion management and nonlinear effects control for maintaining signal quality at high speeds.

Keywords: DWDM; RZ modulation; Bit Error Rate; Q-Factor; Optical input power; Eye Height; Dispersion; Nonlinear effects; OptiSystem software

1 Introduction

The exponential increase in bandwidth-intensive applications like cloud computing, 5G/6G mobile networks, high-definition video streaming, and real-time artificial intelligence has imposed unparalleled stress on optical communication systems with high capacity [1]. DWDM is becoming an indispensable technology to satisfy these needs, in that several wavelengths can be propagated through one fiber optic at the same time, maximizing spectral efficiency and system capacity [2]. DWDM can improve the utilization of bandwidth by supporting long-haul and high-bit-rate communication paths along with the high-bit rate data transmission, which are essential to the next-generation networks.

Although these merits are in place, DWDM systems are faced with serious limitations in high bit-rate transmission over long transmission distances. The main impairments are the chromatic dispersion and nonlinear effects in the fiber [3]. Chromatic dispersion will result in the temporal broadening of pulses resulting in inter-symbol interference (ISI) and increased Bit Error Rates (BER) [4]. Nonlinearities such as Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), and Four-Wave Mixing (FWM) are increasingly bad in systems with more channels and higher power levels, and significantly impair system performance [5], [6]. All these impairments limit the ability of DWDM systems to be scaled to higher capacity and longer reach.

To deal with these challenges, there are a number of mitigation strategies. Dispersion-Compensating Fibers (DCF), Fiber Bragg Gratings (FBG) and other advanced modulation formats are popular in overcoming chromatic dispersion and optical amplifiers, including Erbium-Doped Fiber Amplifiers (EDFA) or Raman amplifiers, extend the transmission distance [7], [8]. Despite their effectiveness, these techniques add trade-offs like extra insertion losses, amplifier noise, and nonlinear interactions which restrict the effectiveness of these techniques in the ultra-dense channel environment [9], [10]. This leads to the fact that the optimization of DWDM systems is very sensitive to the interrelations of transmission distance, bit rate and input power levels, which need to be well-balanced to ensure a reliable communication [11].

Recent publications have concentrated on the performance assessment of DWDM systems under different conditions, including 16- or 32-channel systems, fixed bit rates, or hybrid systems with the use of free-space optical (FSO) systems [12], [13]. In one instance, it was demonstrated that a 32 channel DWDM-FSO system operating under different rainy conditions could support reliable communication over input power of -10 dBm at 15km when light rain fell, but higher power levels were needed in the case of heavy rainfall [14]. Although this kind of research emphasizes the significance of environmental effects, it fails to sufficiently discuss the combined effect of dispersion and nonlinear impairments in fiber-based high-capacity DWDM systems.

Moreover, much of the available research has focused on fewer channels, reduced bit rates or smaller input power selection [15], [16], [17]. Careful analyses of 64-channel DWDM systems- in terms of various bit rates, power handling, and long-haul ranges- are not very common in the literature. This is a deficiency that limits our knowledge of the synergistic effects of dispersion and nonlinear impairments at high capacities.

To fill this gap, the current study measures the performance of a 64-channel high-capacity DWDM system by systematically studying the joint effect of bit rate (10, 20, 30, and 40 Gbps), input power levels (-10 dBm and 0 dBm) and transmission distances (40 km and 160 km). Performance measures such as Q-factor, BER and eye height are also measured to determine the quality of signals under different operating conditions. This piece of work offers insightful information on trade-offs between system reach, signal integrity and bandwidth usage which can be useful in the design and optimization of new high-capacity DWDM optical networks in the future.

2 Literature Review

DWDM systems receive widespread application in long-haul optical communication networks because they boost optical fiber capacity through dense wavelength division multiplexing. Scientists continue studying ways to reduce the various performance-limiting problems of chromatic dispersion and nonlinear effects in high-capacity DWDM systems because data rate requirements continue escalating.

Research has extensively evaluated the ways chromatic dispersion affects system operational performance. The study demonstrated how system capacity reacts to chromatic dispersion which leads to signal pulse broadening and creates inter-symbol interference (ISI) [8], [9]. The system's capacity faces restriction because BER increases, and Q-Factor reduces. The article demonstrates that dispersion compensation fibers (DCF) effectively reduce these effects, but operational parameters and compensation levels continue to affect system performance [10], [11].

Three nonlinear distortion effects namely Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), and Four-Wave Mixing (FWM) serve as significant impairments in high-bit-rate systems. Higher bit rates experience significantly more nonlinear effects particularly when transmission distances become extensive [12]. The combination of SPM and XPM between channels while FWM generates new frequencies which diminishes signal quality [13]. The study revealed the necessity of utilizing optical phase conjugation and optical filtering techniques for reducing these effects which occur in nonlinear systems [14].

A thorough examination of power levels as they affect system performance exists in numerous research studies. The DWDM system performance improved when power levels reached 0 dBm and above. Simulations revealed higher Q-Factor values and reduced BER[15]. Higher power levels result in better signal-to-noise ratio (SNR) because of which system performance improves through decreased impairment effects[16]. System performance deteriorates throughout at -10 dBm power levels because noise disturbances reduce overall functionality[17].

Future research in DWDM technology concentrates on optimizing all the relationships between dispersion compensation structures with power levels and bit rate choices[18],[19]. DWDM system performance gets improved through the implementation of DPSK and coherent detection as advanced modulation and detection techniques which counteract nonlinearities and dispersion effects[20],[21]. Free-Space Optical (FSO) communication systems are impacted by rain-induced attenuation and scattering, which degrade signal quality, especially over long distances. DWDM-FSO systems offer high data rates but require optimization of input power levels to maintain performance in adverse weather[21]. The literature demonstrates the crucial importance of power management together with dispersion compensation and nonlinear effect mitigation because these methods provide optimal performance levels as DWDM systems extend their reach with increasing data rates.

3 Methodology

The evaluation of DWDM system performance with RZ modulation examines different power settings of −10 dBm and 0 dBm at 10 through 40 Gbps bit rates across 40 km to 160 km transmission distances. The main objective consists of understanding how system Q-Factor and Bit Error Rate appear along with Eye Height shapes when varying these parameters. The OptiSystem simulation software which serves as a standard platform for optical communication system design and simulation performed the necessary simulations.

3.1 Mathematical Formulation and Metrics

1. **Q-Factor**: The **Q-Factor** is calculated as a measure of the signal-to-noise ratio (SNR). It is defined as:

$$Q = \frac{E_b}{\sigma}$$

   where E_b is the bit energy and σ is the standard deviation of the noise. A higher **Q-Factor** indicates better signal quality.
2. **Bit Error Rate (BER)**: The **BER** is a critical performance metric that quantifies the reliability of the system. It can be calculated using the following expression:

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right)$$

   where **erfc** is the complementary error function, and Q is the **Q-Factor**. A lower **BER** represents a more reliable communication system.
3. **Eye Height:** The Eye Height serves as an observable signal quality indicator obtained from the eye diagram received by the receiver. The Eye Height measurement shows signal quality by determining how much distortion exists within the signal as well as the extent to which dispersion and nonlinear effects degrade it[1],[2].

3.2 Simulation Steps

1. **System Design**: The system incorporated 64 operating channels based on Return-to-Zero (RZ) modulation format. Each transmission channel possessed 100 GHz separation that centred at 193.4 THz. The transmission link utilized Single Mode Fiber (SMF) while Dispersion Compensating Fiber (DCF) operated as dispersion compensation element.
2. **Transmission Parameters**: The simulation evaluated the system across four transmission distances starting from 40 km up to 160 km through 80 km and 120 km. Real-world conditions of dispersion and compensation were simulated by separating the transmission distances into SMF and DCF segments.
3. **Power Levels**: Two power measurement points served to evaluate the system: -10 dBm and 0 dBm. The system's performance depends on power levels because they both modify signal strength levels and signal-to-noise ratio relations.
4. **Bit Rates**: The research evaluated the system performance under four different data transfer speeds starting from 10 Gbps up to 40 Gbps. The performance evaluation of the system becomes possible through these various data throughput levels because they provide measurable outcomes at different measurement rates.
5. **Performance Evaluation**: Simulation runs included a measurement of Q-Factor and BER as well as Eye Height at the receiver to evaluate the system reliability and signal quality.

4 Simulation Setup

The simulation establishment examined a 64-channel DWDM system through different tests of bit rate and power level and transmission distance performance evaluations. OptiSystem simulation software operated the setup while abiding by the following parameters:

Table 1. Simulation Parameters

Parameter	Value/Details
Number of Channels	64
Channel Spacing	100 GHz
Central Frequency	193.4 THz
Bit Rates	10 Gbps, 20 Gbps, 30 Gbps, 40 Gbps
Transmission Distance (SMF)	40 km, 80 km, 120 km, 160 km
Transmission Fiber	SMF (Single Mode Fiber)
Compensation Fiber	DCF (Dispersion Compensating Fiber)
Modulation Format	Return-to-Zero (RZ)
Power Levels	-10 dBm, 0 dBm

System Components and Configuration

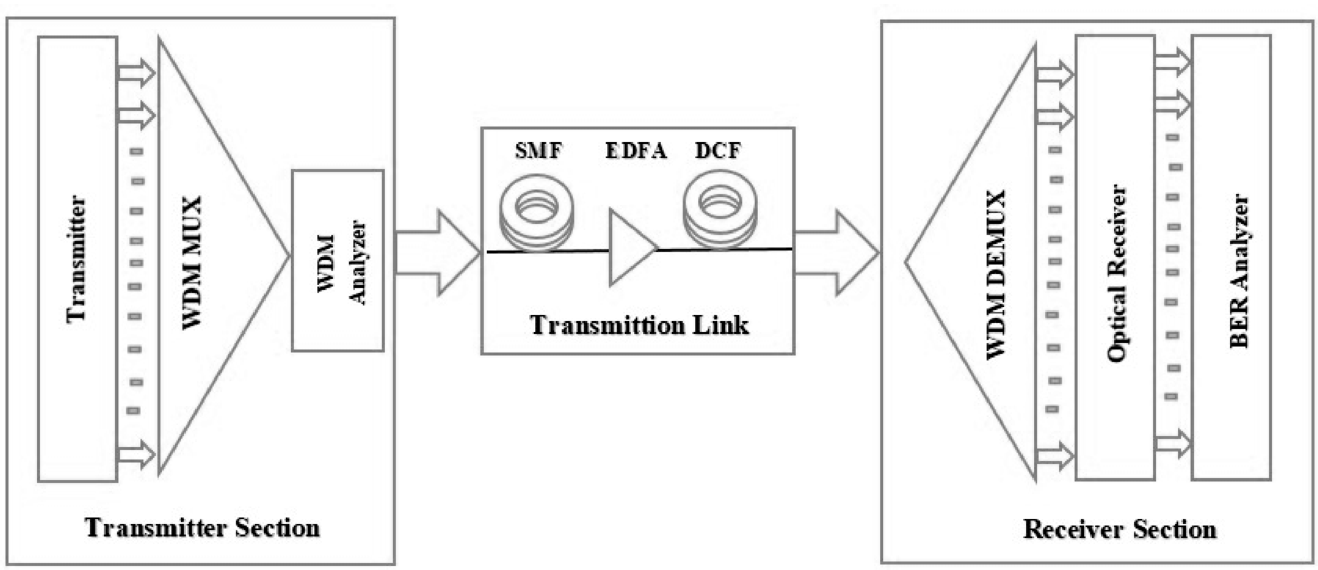

Fig 1. Block diagram of system configuration

1. **Transmitter**: The transmitter outputs optical signals through RZ modulation at bit rates which include 10, 20, 30 and 40 Gbps.
2. **Transmission Line**: The transmission line consists of Single Mode Fiber (SMF) where the experiment takes place across various distances beginning with 40 km up to 80 km and continuing to 120 km and finally reaching 160 km to examine long-haul transmission conditions.
3. **Dispersion Compensation**: Employing Dispersion Compensating Fiber (DCF) for dispersion management allows researchers to measure how Q-Factor and BER as well as Eye Height performance changes while transmitting signals through long distances.
4. **Receiver**: The receiver notices the transmitted signal following its fiber passage to determine Q-Factor performance and compute BER results and Eye Height measurements from the received waveform.
5. **Signal Quality Analysis**: The received signal permits Q-Factor measurement by using bit energy to noise ratio while BER values derive from signal reception and Eye Height values can be obtained from the receiver-generated eye diagram.

The simulation design helps evaluate system performance while evaluating the 64-channel DWDM under different operational conditions to enhance practical high-speed optical communication systems.

5 Results and Discussion

The analysis of the 64-channel DWDM system under different bit rates (10, 20, 30, and 40 Gbps), input power (0 dBm and -10 dBm), and transmission distances (40 to 160 km) in the system shows a few decisive tendencies, the shortcomings of the earlier work, and the enhancement of the results with RZ modulation. Major parameters that are examined are Q-factor, Bit Error Rate (BER) and Eye Height.

5.1 Q-Factor Analysis

Figure 2 shows the change in the Q-factor with transmission distance. As anticipated, Q- factor declines with distance at all bit rates because of the additive effect of chromatic dispersion and nonlinear interactions like Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), and Four-Wave Mixing (FWM) [4], [12], [13].

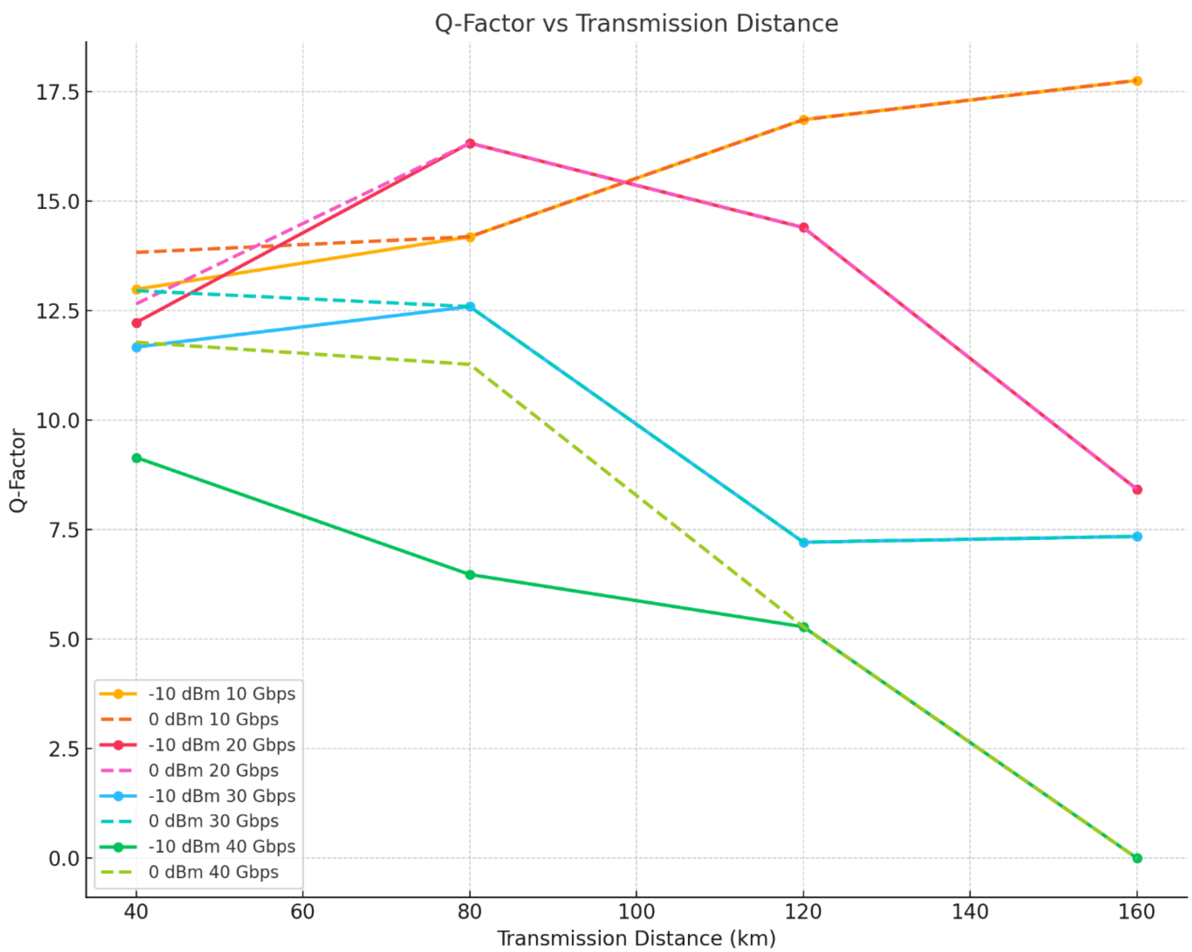

Fig 2. Q-Factor vs Transmission Distance

The Q-factor is over 13 at 10 Gbps at 160 km with an input of 0 dBm, which means that the Q-factor is quite strong to perform long-haul transmission. But at 40 Gbps the Q-factor drops off, particularly at -10 dBm, which is indicative of the increased sensitivity of higher bit rates to inter-symbol interference (ISI) and nonlinear impairments. This observation contrasts with the system based on NRZ according to Thummar et al. (2024) [4] where even moderate bit-rates over long distances lead to the degradation of the Q-factor. RZ modulation is believed to perform better because it has a built-in pulse shaping to decrease dispersion induced broadening and counteract accumulated nonlinear phase shifts.

Interestingly, increased input power is known to increase SNR, but this increases nonlinear effects, resulting in a trade-off in optimum system performance. This finding can be compared to the previous works(14),(15), which have emphasized moderate power levels as the balance between signal strength and nonlinear distortion. Contrary to the previous statements about DCF being entirely compensating the dispersion in the range of larger than 100km(18), we find that impairments remain in some instances, particularly at 30-40Gbps, highlighting the necessity to implement hybrid or enhanced compensation methods, including machine-learning-based approaches to compensation and digital backpropagation(21),(22).

5.2 Bit Error rate (BER) Discussion

Figure 3 shows the trends of BER over a range of transmission distances and power levels. BER at 0 dBm is less than 107000 at 1020 Gbps over 160km but above 3040 Gbps, BER rises rapidly after 120km. BER values are much larger at -10 dBm at all bit rates, and 40 Gbps is larger than 10 -4 at 160 km.

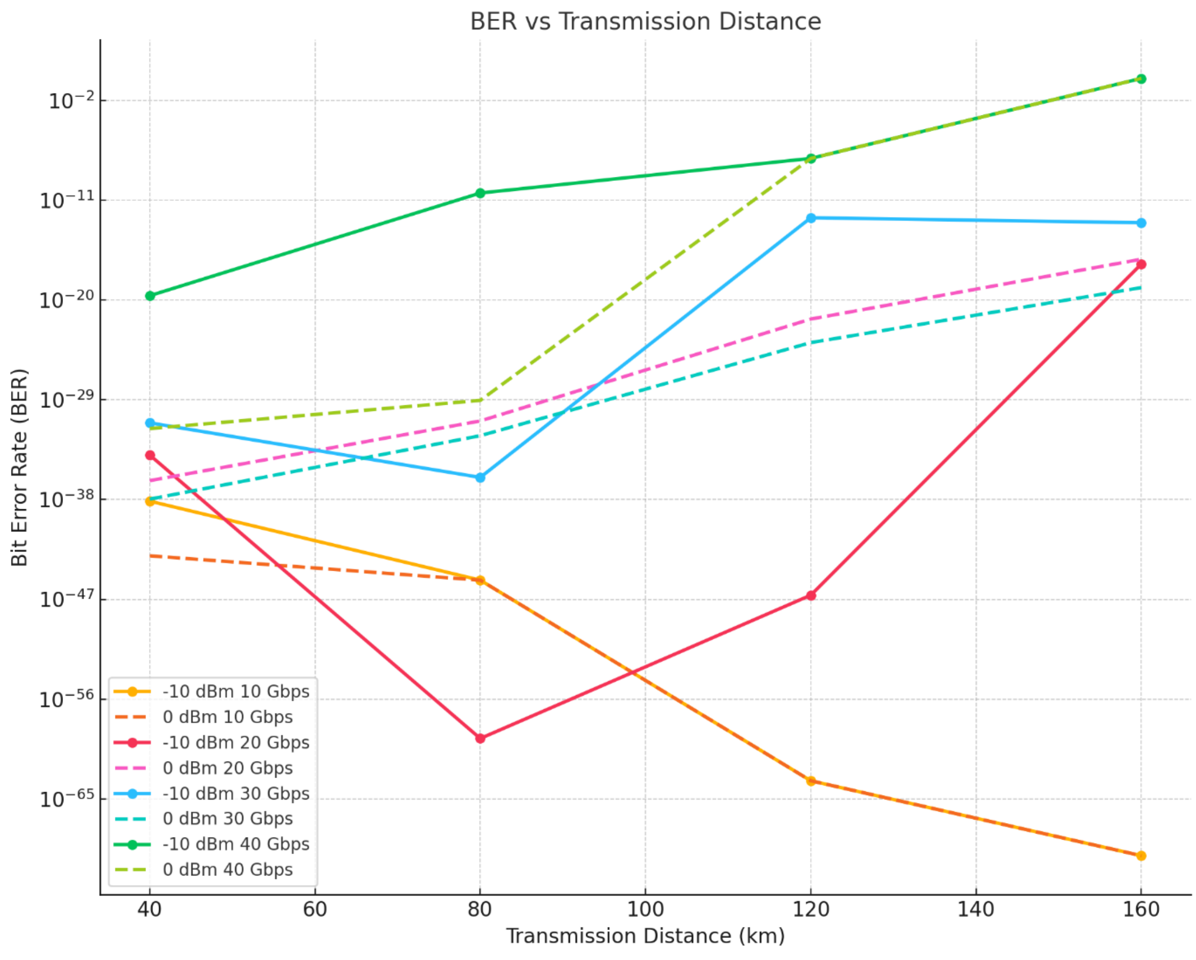

Fig 3. BER vs Transmission Distance

These findings indicate that less bit rate more severely affected both dispersion and nonlinear effects, which is consistent with the prior research(16),(17). The enhanced performance of BER at the 0 dBm indication indicates that the middle power levels increase SNR and restrict the nonlinear distortion. As compared to previous 32 channel DWDM analyses(21), the 64-channel system presented by us has amplified nonlinear interactions owing to smaller channel separation, and thus, power and bit-rate optimization must be carried out carefully.

The actual findings are also critically insightful, as previous research mainly concerns either low-bit-rate or few-channel systems[(12),(13)], this study shows that the high-capacity DWDM systems must be optimized holistically in terms of bit rate, power and distance to achieve reasonable BER. This understanding fills the gap in the research presented in the introduction that reveals a gap in literature considering systematic analysis and 64-channel high-speed networks.

5.3 Eye Height Evaluation

Eye Height is a direct measure of signal clarity, which reduces with distance and power, especially at higher bit rates (Figure 3). An example is that at 0 dBm, the Eye Height is greater than 0.003 at 10 Gbps at 160km, and under -10 dBm at 40 Gbps, the height of the eye is nearer to zero. This suggests that increasing input power maintains signal integrity and increasing bit rates become compromised to greater ISI and nonlinear impairments.

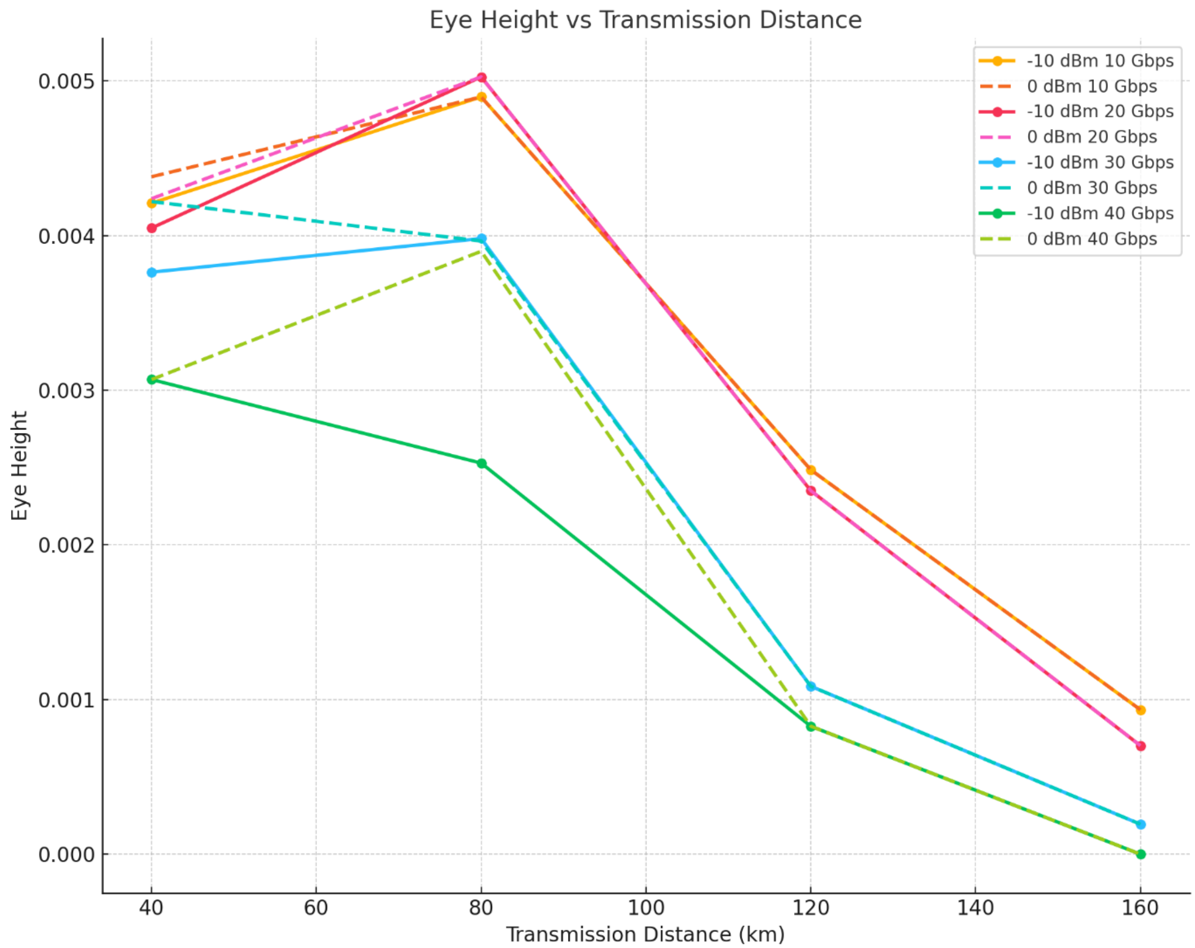

Fig 4. Eye Height vs Transmission Distance

RZ modulation has a broader eye opening under the same conditions, as compared to previous NRZ-based studies[(4)], which testifies to its superiority in the high-capacity DWDM system. Besides, this assessment also reveals a shortcoming of previous research: most of the papers provide performance figures without an analysis of trade-offs among bit rate, power, and distance[(15),(16),(17)]. This problem is proved by our results because it is necessary to pay careful attention to modulation choice and power management to ensure the quality of signals, particularly in ultra-dense channel conditions.

5.4 Researcher Insights and Comparison with Literature

This research has validated that RZ modulation is much more advantageous than NRZ, especially when it comes to high-capacity (64 channel) DWDM systems. However, unlike the earlier work that considers fewer numbers of channels or lower bit rates [12],[13], this study shows the cumulative nature of dispersion and nonlinearities in the long-haul, high-bit-rate, and high-power cases.

- Trade-off Analysis: Increase in power improves Q-factor and Eye height but may also strengthen nonlinear distortions with increasing bit rate.
- Modulation Effectiveness: RZ modulation is always better than NRZ in preserving the quality of the signals and reducing the effects of dispersion that leads to degradation.
- Distance and Bit rate limitations: High Bit rates are only useful over moderate distances unless some advanced compensation schemes are used.

These results are consistent with and expand on the past literature [16],[17],[18],[21],[22], indicating the significance of integrating optimization of bit rate, power and distance. The research offers some practical design recommendations to high-capacity DWDM networks, especially to backbone and metro-scale networks that current belief may require lower bit rates or hybrid compensation mechanisms to ensure the reliability of the system at very large capacity.

6 Conclusion

The results of this study demonstrate that higher power levels (0 dBm) significantly improve the performance of a 64-channel DWDM system, particularly at higher bit rates and longer transmission distances. The key findings can be summarized as follows:

1. **Higher Power Levels Enhance Performance**: The 0 dBm power level consistently results in higher Q-Factor, lower BER, and better Eye Height compared to -10 dBm, particularly for longer transmission distances and higher bit rates.
2. **Impact of Transmission Distance**: Longer transmission distances lead to increased signal degradation, especially for higher bit rates. Dispersion and nonlinear effects contribute to this degradation, but the effects are more manageable at higher power levels.
3. **Bit Rate Sensitivity**: Higher bit rates (30 Gbps and 40 Gbps) are more susceptible to dispersion and nonlinearities and show significant degradation in Q-Factor, BER, and Eye Height. Lower bit rates (10 Gbps) offer better signal quality and reliability over long distances, especially at 0 dBm.
4. **Optimization Recommendations**: The optimal operating conditions for long-distance DWDM systems include using bit rates of 10 Gbps along with power levels of 0 dBm to achieve both low BER and high Q-Factor. The performance enhancement of DWDM systems at elevated bit rates depends fundamentally on dispersion compensation combined with nonlinear effect mitigation techniques.
5. **Novelty**: This research novelty stems from a complete study which determines the joint power-level-bit-rate-distance relationship for DWDM 64-channel systems when focused on speed-enhanced communication networks using 2.5 Tbps rates. The study creates a performance evaluation between NRZ and RZ modulation by showing RZ modulation delivers better results than NRZ at both high bit rates and extended transmission distances.
6. **Prospects and Future Research**: The upcoming investigation should concentrate on advanced modulation methods including QPSK, 16-QAM and OFDM to improve DWDM system functionality at higher data speeds. Research needs to explore the combination of optical amplifiers together with mixed compensation schemes which integrate DCF with both Fiber Bragg Grating (FBG) and hybrid solutions for effective nonlinear impairment reduction. The development of AI-based optimization algorithms together with machine learning methods will enable adaptive power level and dispersion compensation methods which lead to more reliable communication systems and increased efficiency.

Long-distance high-capacity optical communication benefits from DWDM system optimization through an integrated approach of power management coupled with correct bit rate selection together with dispersion compensation techniques. The research conclusions provide meaningful insights to boost the reliability along with the performance of forthcoming optical network infrastructure. Future research activities should concentrate on using superior modulation techniques along with optical amplifiers alongside mixed compensation schemes for maximizing system performance.

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