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Scalable Inter-Satellite Optical Wireless Communication Based on CWDM and EDFAs for 6G and NTN Backhaul

Sara Alshwani[1], Azhar Ahmed Bilal[2], and Dr. Alaan Ghazi[3*]

[1]Software Department, Collage of Computer Science and Information Technology, University of Kirkuk, Iraq. saraadnan@uokirkuk.edu.iq, https://orcid.org/0009-0008-6791-2326

[2]Software Department, Collage of Computer Science and Information Technology, University of Kirkuk, Iraq. azhar-ahmed@uokirkuk.edu.iq, https://orcid.org/0009-0006-4224-059x

[3*]Department of Electronic and Control Technologies Engineering, Technical Engineering College Kirkuk, Northern Technical University, Mosul, Iraq. alaan.ghazi@ntu.edu.iq, https://orcid.org/0000-0002-1265-0428

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Abstract

This study presents a scalable inter-satellite optical wireless communication (IS-OWC) system based on coarse wavelength division multiplexing (CWDM) and high-power erbium-doped fiber amplifiers (EDFAs) to support high-bandwidth data transmission to address 6G and non-terrestrial network (NTN) backhaul needs. An 18-channel CWDM arrangement supports an aggregated data rate of 180 Gbps through 5500 km optical wireless link. Every channel takes up a unique wavelength (1270–1610 nm with 20 nm separation), designed to provide maximum interference protection and high spectral efficiency. Signal amplification is ensured by EDFAs to provide data continuity over long distances. Performance parameters like bit error ratio (BER) and Q-factor exhibit reliable transmission up to 4500 km and degradation beyond this distance to warrant error correction and sophisticated modulation to support far-range use cases. The study demonstrates the promise of CWDM-based IS-OWC with EDFAs to be an economical high-speed option for 6G and NTN backhaul to offer mass-scale access in remote and underserved regions

Keywords: IS-OWC, CWDM, Erbium-Doped Fiber Amplifiers, 6G Backhaul, Non-Terrestrial Networks, Internet of Things, Space-Based Optical Networks.

1 Introduction

1.1 Background and Motivation

The ever-increasing amounts of data traffic globally through the widespread acceptance of Internet of Things (IoT) devices, high-definition TV and video, or any application with high-volume data has put more demands on telecommunications networks than ever before (Kilanioti et al., 2019; Kulkarni & Pandey, 2024; Sathya et al., 2023; Mehta & Malhotra, 2024; Saeed et al., 2024; Menon & Nair, 2024). The call for more speed, greater dependability, and increased capability to transmit data is particularly urgent with the emergence of 6G (Tataria et al., 2021; Sharma & Desai, 2024; Ameen, 2018), which

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*Corresponding author: Department of Electronic and Control Technologies Engineering, Technical Engineering College Kirkuk, Northern Technical University, Mosul, Iraq.

has the promise to provide far greater data rates, zero latency, and pervasive connectivity, particularly to underserved and remote geographic spaces in which traditional ground networks are incapable of keeping up with worthy service demands (Alshwani et al., 2019).

Nonterritorial networks (NTNs) include satellites and other space-based communication systems, thus providing a promising approach to address these challenges. NTNs enable high-speed data transfer between any two points on Earth, thus extending connectivity far beyond the reach of terrestrial infrastructure (Mahboob & Liu, 2024). Inter-satellite communications have now materialized as active enablers of continuous, high-capacity data exchanges in NTN ecosystems (Wang et al., 2019). These systems enable satellites to relay data over long distances and allow the establishment of backhaul connections for 6G, which in turn provides a broad extension with consistent coverage (Elamassie & Uysal, 2023).

Inter-Satellite Optical Wireless Communication (IS-OWC) systems will be of specific interest to NTNs owing to their capability to support high-speed, secure, and interference-free data transfer. Unlike conventional radio frequency (RF) communication, IS-OWC relies on free-space optical (FSO) channels, which are suitable for space owing to the minimum interference from the atmosphere (Abdulwahid et al., 2024; Maraha et al., 2020; Aldawoodi & Bilge, 2024). This optical approach provides higher data rates and limits the frequency congestion. As a result, IS-OWC is increasingly seen as an essential technology for NTNs to support future 6G backhaul requirements.

Notwithstanding these and many other advantages, there are some serious challenges for an IS-OWC that might deliver reliable communication over a long distance (Abdulwahid et al., 2024). Optical signals would weaken over large distances due, especially without adequate amplification, to power loss and probable interference. All these issues significantly reduce the quality of the signal when there are no robust solutions, leading to data transmission errors and reduced reliability. To address these barriers, there is a need for innovative methods to enhance IS-OWC systems, particularly through multiplexing techniques that can optimize spectral efficiency and amplifiers that can counteract signal degradation over long distances.

1.2 Problem Statement

Regarding this issue, the preservation of signal quality within ISOWC systems over long distances is emerging as a major challenge in NTNs because of the high demand for robust and scalable data transmission solutions. In a space-based environment, FSO channels involve less interference from the atmosphere; however, ensuring reliable communication between satellites separated by more than 5000 km faces serious threats owing to power losses and signal degradation (Abdulwahid et al., 2024). Conventional approaches to mitigate these issues, such as Dense Wavelength Division Multiplexing (DWDM), are often costly and complex (Basch et al., 2006). A simpler, cost-effective solution that supports high-capacity, low-latency, and interference-free data transmission is crucial for meeting the demands of 6G and NTN backhaul applications (Elamassie & Uysal, 2023).

1.3 Objectives

This work focuses on the design and analysis of an extended scalable IS-OWC system that overcomes the aggravation of signal degradation and interference arising in long-distance optical wireless communication. The specific objectives are:

1. Presenting a proposal for CWDM-based IS-OWC using high-power Erbium-Doped Fiber Amplifiers (EDFAs) to enable scalable and high-capacity data transmission up to 180 Gbps over 18 channels operating at distinct wavelengths from 1270 nm to 1610 nm.
2. The system should be optimally configured to enhance it in such a manner that it can effectively use the optical spectrum to achieve a reliable and high-capacity data transmission distance of up to 5500 km.
3. To evaluate the system performance for the main metrics of the BER and Q-factor in different ranges, we further analyzed the influence of signal degradation on system reliability.
4. Identification of all further techniques, including advanced modulation and error correction, is necessary to maintain signal integrity over distances greater than 4500 km.

1.4 Research Contribution

This study contributes to the development of high-capacity IS-OWC systems over long distances, tailored for NTNs and 6G backhaul applications. The proposed system with CWDM and high-power EDFA integration showed high potential for scalable and reliable delivery of the increasing data demands of 6G and a viable connectivity solution to space-based and underserved terrestrial networks. Future research will focus on enhancing the system performance for extended distances through advanced error correction and adaptive modulation techniques to meet the high-performance standards required for next-generation networks.

2 Literature Review

The rapid development of communication technologies, especially those working around 6G and NTNs, has motivated researchers to find innovative solutions for high-capacity, low-latency transmission of data over large distances (Azari et al., 2022; Imran et al., 2024). A significant technology that facilitates these aims is offered by WDM since it enhances the transmission efficiency by making several data streams travel through just one optical link (Mukherjee, 2002). The numerous advancements made in WDM and optical wireless communication explored in the examined studies are signal degradation through attenuation, interference, and nonlinear effects. Researchers have explored numerous methods, which involve multistage amplifier configurations, amplifier hybrid configurations, DSP-assisted solutions, and innovative modulation schemes, to enhance data fidelity and maximize transmission distance (D’Souza & Khatri, 2022).

For instance, (Kachhatiya & Prince, 2018) considered a 16-channel WDM-PON architecture with the objective of optimizing a mobile backhaul application, whereas (Saini et al., 2024) demonstrated a hybrid EDFA-Raman-EDFA amplifier setup that could effectively minimize bit error rates (BER) in WDM systems. Studies such as (Irfan et al., 2020) focused on receivers assisted by DSP to mitigate nonlinear effects in long-haul networks. These works mainly underlined the crucial role of sophisticated digital processing in maintaining clear signals. More recent research has focused on 6G requirements, with investigations into integrated space-air-ground network configurations, sub-terahertz technologies, and high-speed optical wireless receivers showcasing innovative approaches for increasing data rates and network capacity while maintaining reliability.

Some of the key studies are summarized in Table 1, including a short description of the pursued objectives, methodology used, and most important findings. This knowledge will build an understanding of the technical scenario and constitute grounds for developing scalable, high-capacity optical communication systems tailored for NTN/6G applications.

Table 1: Summary of Key Studies on Optical Communication and Network Enhancements for NTN and 6G Applications

Reference	Year	Study Objective	Methodology/Tools Used	Key Findings
(Kachhatiya & Prince, 2018)	2018	Propose a 16-channel WDM-PON architecture for mobile backhaul applications	Performance analysis of bit error rate (BER) and optical spectrum observation at the multiplexer output	Higher data rates reduce error-free reach; the proposed WDM-PON architecture outperforms existing systems
(Saini et al., 2024)	2019	Develop a multistage high-performance amplifier for WDM systems	Comparison of EDFA-Raman-EDFA hybrid amplifier with traditional Raman-EDFA setups	The hybrid amplifier improves quality factor, lowers BER, and provides wider eye opening, outperforming traditional methods
(Irfan et al., 2020)	2020	Design a 100 Gbps distortion-tolerant optical backhaul network	Digital Signal Processing (DSP)-assisted receiver to mitigate ASE noise and nonlinear effects	Achieved low BER and Q-factor of 5 over 300 km, proving effective in mitigating non-linear effects
(Singh & Malhotra, 2020)	2020	Propose a long-haul WDM-based inter-satellite OWC link with a novel modulation scheme	Numerical simulations using DQPSK-polarization shift keying	Enables reliable 16 × 100 Gbps transmission over 25,000 km with acceptable BER despite pointing error
(Araniti et al., 2021)	2021	Examine the potential of 6G NTNs for broad service delivery	Analyzes NTN constraints on NR procedures based on 3GPP specifications	Identified strengths and weaknesses of NR technology for NTNs, highlighting challenges and potential for 6G service expansion
(Umar et al., 2022)	2022	Assess the performance of a multitier space-air-ground network for 6G using mmWave and THz	Analyzed association probability, network capacity, and outage probability through simulations	Validates the use of NTNs with mmWave and THz capabilities to enhance data rates, reduce outage, and improve network capacity
(Kremenetska et al., 2021)	2021	Explore high-altitude NTNs using optical wavelengths for multilevel space communication	Comparison of Shannon channel capacity for various satellite communication scenarios	Analyzed multi-level satellite configurations, achieving up to 100 Gbit/s throughput and highlighting areas for future research
(Shalma & Shalma, 2022)	2022	Design a sub-terahertz wireless backhaul for 6G with	New power allocation algorithm for optimal backhaul performance	Achieved over 1 Tbps for 1 km with reduced complexity and

		reduced complexity		computational delay
(Sarbazi et al., 2023)	2022	Optimize high-speed receivers for 6G optical wireless networks	Design and optimization of non-imaging angle diversity receivers (ADR)	Compact ADR design achieved 12 Gb/s over 3m with a low-complexity solution for receiver bandwidth and FOV
(Matarneh, 2024)	2023	Assess MIMO-based FSO with WDM for 6G	Integration of MIMO with WDM for RoFSO systems	Achieved 80 Gbps over 2.2 km with WDM-MIMO, significantly enhancing capacity and performance
(Gargari et al., 2023)	2023	Enhance 6G IAB performance with sub-terahertz links	Greedy algorithm for frequency band allocation; custom Sionna simulator extension	Achieves 4× user throughput and 50% latency reduction compared to mmWave-only networks
(Nimura et al., 2023)	2023	Enable ultra-high-density antenna fronthaul with high data rates for 5G+	SDM, WDM, SCM for multi-channel transmission	Achieved 10.51 Tbit/s over 10.1 km with 4608 channels, showing advanced multiplexing's potential
(Christofidis et al., 2023)	2023	Develop a spatially-diverse optical fronthaul network for 6G	SDP-tMP approach with sharp interleave filter network	Achieved 336 Gbps per wavelength and spatial dimension, enhancing energy efficiency
(Fayad et al., 2024)	2024	Survey enabling technologies for 6G optical fronthaul	Analysis of PON architectures for 6G development	Highlights the importance of combining optical technologies to meet 6G's high-capacity, low-latency needs

Although recent studies have advanced the capabilities of optical communication systems for NTNs and future 6G infrastructure (Mohammed et al., 2024), significant challenges remain in achieving reliable, high-capacity data transmission over extended distances in space-based environments (Ghazi et al., 2021; Ghazi et al., 2020). Various approaches, including WDM, DSP-assisted receivers, and multistage amplification techniques, have successfully mitigated some limitations, such as signal attenuation and nonlinear impairments, in medium-distance transmissions (Hassan et al., 2023; Ghazi et al., 2021). However, most existing solutions focus on short- to medium-range optical backhaul (Ghazi et al., 2021), with limited emphasis on the long-distance intersatellite links required for fully operational NTNs (Mahmood et al., 2020). Although effective, traditional DWDM systems are often complex and costly, particularly for applications demanding high scalability and spectral efficiency. This gap indicates the need for a more practical, scalable, and cost-effective solution that can maintain data integrity over long distances, fulfilling the high data demands of 6G, and supporting remote connectivity.

Our study addresses this gap by proposing a scalable IS-OWC system that leverages CWDM and high-power EDFAs to support high-capacity data transmission over extensive distances. Because the wavelength channel spacing for CWDM is much wider, multiplexing is considerably less complex and expensive. Therefore, interference will be smaller, which will allow a strong interference-free signal transmission capable of withstanding long-distance links. Integrated high-power EDFAs can provide considerable signal amplification, which might support losses for large distances and provide reliable data transfer. Performance evaluation can be drawn based on the main metrics, such as the BER and Q-factor. Our work shows that the proposed configuration can meet NTN backhaul demands over distances up to 5500 km. In this study, we have identified scalability, cost-effectiveness, and signal integrity issues raised in the literature by providing a feasible solution that will be beneficial for extending the reach of NTN and 6G connectivity.

3 Methods

3.1 Experimental Setup

The system is reconstructed in OptiSystem and is represented in Figure 1, realizing an 18-channel CWDM scheme that best fits high-speed, scalable data transmission at a total rate of 180 Gbps, intended for IS-OWC and NTN backhaul applications in the upcoming 6G era. If channel 18 operates at a different wavelength, ranging from 1270 nm to 1610 nm in increments of 20 nm, this not only minimizes interference among channels, but also uses the optical spectrum efficiently. Each optical transmitter was configured with high power (approximately 30 dBm) to enhance the signal strength over long distances, making the system suitable for both terrestrial and satellite-based communication.

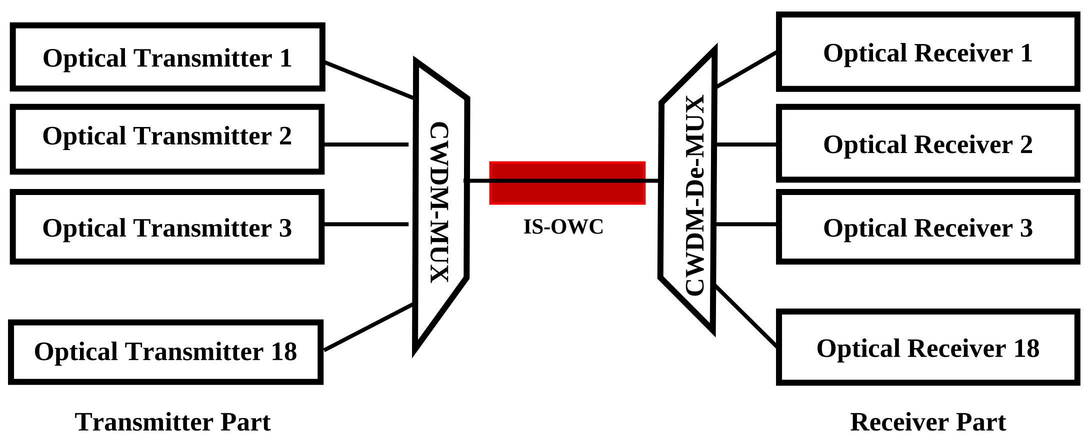

Figure 1: 18-channel of CWDM over IS-OWC

To handle such an aggregate data rate of 180 Gbps, the MUX ideally aggregates the signals coming from all 18 channels and sends them through an OWC channel of approximately 5500 km, representative of the far distances in the NTN and satellite-based networks. The strength of the signal would be amplified using an EDFA, ensuring that after attenuation over such a distance, the signal would still be sufficiently strong, even over free-space optical channels. EDFA's high power of an EDFA plays a crucial role in maintaining the signal quality, compensating for losses that typically occur in long-range optical transmission.

The ideal Demux at the receiving end splits a single optical signal back into the original 18 channels at each corresponding wavelength. Each demultiplexed channel is first processed through a photodetector to convert the optical form back into electrical form, followed by a lowpass raised cosine filter with a cutoff frequency fixed to 0.75 times the bit rate for reduced high-frequency noise. This filtering is an important step in the process, as the assurance of correct BER assessment is considered necessary when distortion is minimal, and the signal will be ready for clear and reliable analysis. The BER analyzers then evaluate each channel individually to measure the data integrity, providing insight into the system's reliability over long distances, which is particularly important for NTN and 6G backhaul applications.

The integration of CWDM and EDFA technologies into an intersatellite communication system can enable high-speed and scalable data transmission. It can achieve 180 Gbps while maintaining signal quality over a longer distance. With a channel spacing of 20 nm, the CWDM system performance would be nearly at an interference 'sweet spot' to optimize the balance between adjacent channel interference and cost. For that reason, it would serve medium-capacity systems perfectly, where simplicity and robustness are key considerations. Figure 2-18-channel CWDM configuration: color gradient from light green to dark blue to visually clarify the wavelength distribution across the CWDM spectrum. This arrangement supports clear differentiation between channels and highlights the advantages of CWDM's wider channel separation, which helps maintain signal integrity in satellite-based and terrestrial optical networks, meeting the high-speed and high-capacity demands of future 6G and NTN applications.

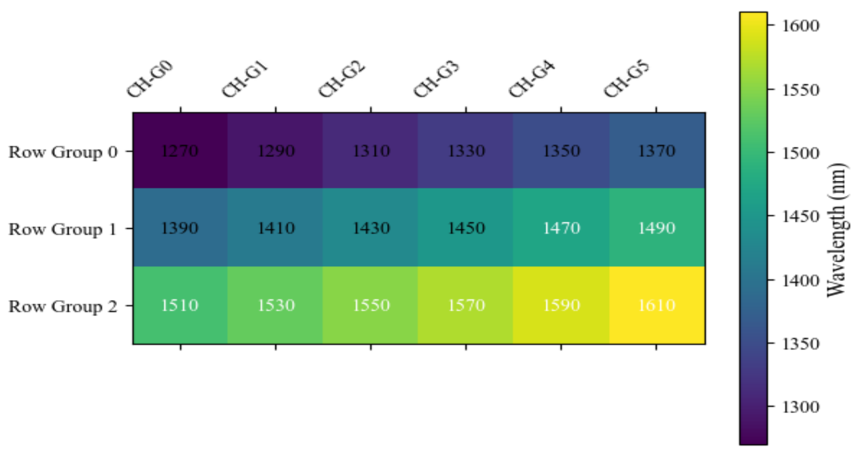

Figure 2: CWDM wavelength based on 20 nm channel spacing

3.2 Coarse Wavelength Division Multiplexing

CWDM is an optical communication technology, whereby wider channel spacing allows the transmission of multiple data streams over a single optical fiber. In contrast, Dense Wavelength Division Multiplexing has channels that are separated by 20 nm in general use, ranging from 1270 nm to 1610 nm. This wide spacing reduces the interference between channels, allowing for simpler, lower-cost filters and transmitters without requiring the temperature control of lasers. CWDM is commonly used in metropolitan area networks and space-based communications owing to its cost efficiency and robust performance.

3.3 Erbium-Doped Fiber Amplifiers

The Erbium-doped fiber amplifier is a form of optical amplifier designed to boost signal transmission in fiber optics communication without prior conversion to an electrical signal. These amplifiers work very efficiently in the wavelength region of ~ 1550 nm, which corresponds well with the transmission window of typical fiber-optic cables where the signal loss is minimal. EDFAs are used in CWDM systems for efficient amplification of a DWDM signal over long-distance transmission at minimum signal loss. This capability is particularly valuable in satellite communication, where signals must travel across vast distances.

The idea behind optical communication systems for reaching 180 Gbps involves combining multiple CWDM channels into one robust and scalable configuration. Inter-satellite communication systems based on CWDM with the support of high-power EDFAs will be ready to reach data rates in compliance with increasingly growing demands on bandwidth in space networks. The transmission capability of 180 Gbps is vital for applications that require rapid, high-capacity data exchange, such as Earth observations, satellite constellations, and real-time communication between satellite nodes.

3.4 Evaluation Metrics

3.4.1 Bit Error Ratio (BER)

The BER is a key performance factor in digital communication systems. BER signifies the ratio of erroneous bits received to the total number of bits transmitted, thus providing a quantitative assessment of the accuracy of the data. The greater the BER value, the greater the number of errors present, which results in a decrease in signal quality or an increase in noise in the channel. In optical networks, BER helps identify how well a system maintains data integrity over distance and under various conditions such as amplifier noise and interference. A lower BER is ideal for efficient and reliable communications.

The BER is calculated as:

$$BER = \frac{Number\ of\ erroneous\ bits}{Total\ number\ of\ transmitted\ bits} \tag{1}$$

Equation 1 calculates the number of errors per data stream, and the reasons why the BER is a simple but effective metric for system performance evaluation are based on this. Factors such as signal-to-noise ratio, channel conditions, and modulation techniques directly influence the BER, which is typically expressed in scientific notation for clarity in high-performance systems (e.g., 10-7 for very low error rates).

3.4.2 Q Factor

Another important parameter for both optical and communication systems is the quality factor (Q factor) of the system, which should be understood as indicating the quality of the signal by comparing the power signal and noise. Indeed, the Q-factor informs about the "eye-opening" in an eye diagram, which is a visualization technique used to analyze the clarity of the signal given in digital communication. A higher Q factor indicates a clearer signal quality and a lower likelihood of errors, as it suggests a more distinct separation between signal levels. The Q factor is particularly useful for identifying thresholds at which optical systems require correction or amplification to maintain their performance.

The Q factor is often represented as:

$$Q = \frac{V1 - V0}{\sigma 1 + \sigma 0} \tag{2}$$

where V1 and V0 are the average voltages of the logical '1' and '0' levels, respectively, and σ1 and σ0 are the standard deviations of these levels. The above equation reflects how well separated signal levels are desirable for a low error probability. The Q factor is a measure of the clarity of the signal and hence allows the engineer to optimize the performance versus the error rate balancing act, guiding decisions about how much amplification and correction should be used in the optical communications network.

4 Results and Discussion

The 18-channel system performance over distance was examined based on the results of the BER and Q-factor, which provide detailed insight into the performance of this system in high-power EDFA for CWDM over IS-OWC.

4.1 Model Performance: Quantitative Results

The quantitative results of the BER and Q-factor for the 18-channel CWDM system covering different distances ranging from 3500 to 6000 km are summarized in figure 3 and figure 4.

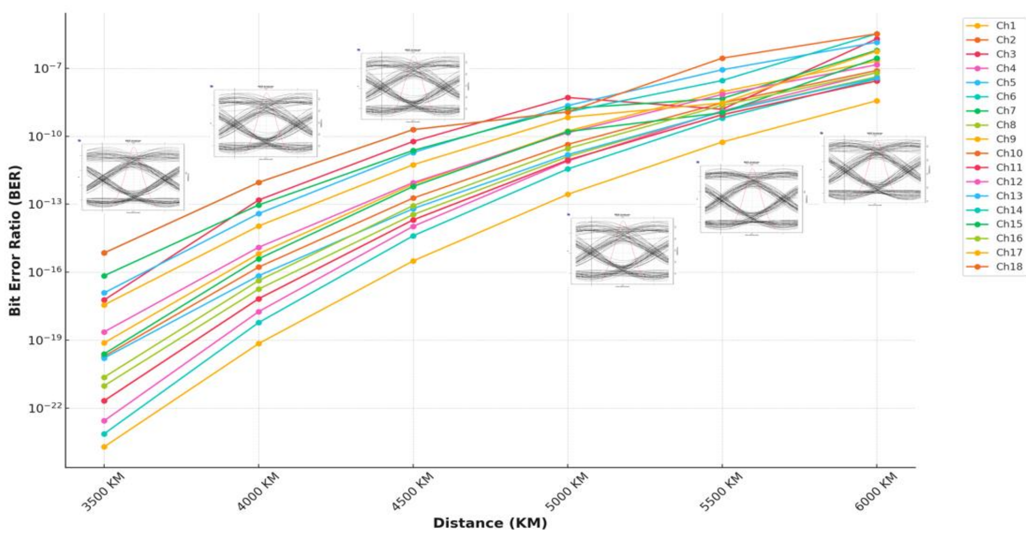

Figure 3: Bit Error Ratio for 18 Channels

The increase in the Bit Error Rate (BER) with distance demonstrates a significant rise, particularly under extended distances, reaching levels that render reliable communication unacceptable at 6000 km for some channels. Similarly, the Q-factor exhibited an exponential decline as the distance increased. For several channels, the Q-factor falls below the threshold limit of 6 at a distance of 6000 km, indicating severe degradation in signal quality. Notably, channel variability plays a crucial role in performance differences because channels such as Ch6 and Ch9 show greater resilience, maintaining higher Q-factor values and lower BER levels. In contrast, channels such as Ch3, Ch14, and Ch18 experienced rapid deterioration, highlighting their vulnerability under increased distances.

These results show that the CWDM system behaves remarkably well for up to approximately 4500 km, and beyond this length, additional techniques, such as error correction or amplifiers of higher quality, are required for reliable data transmission.

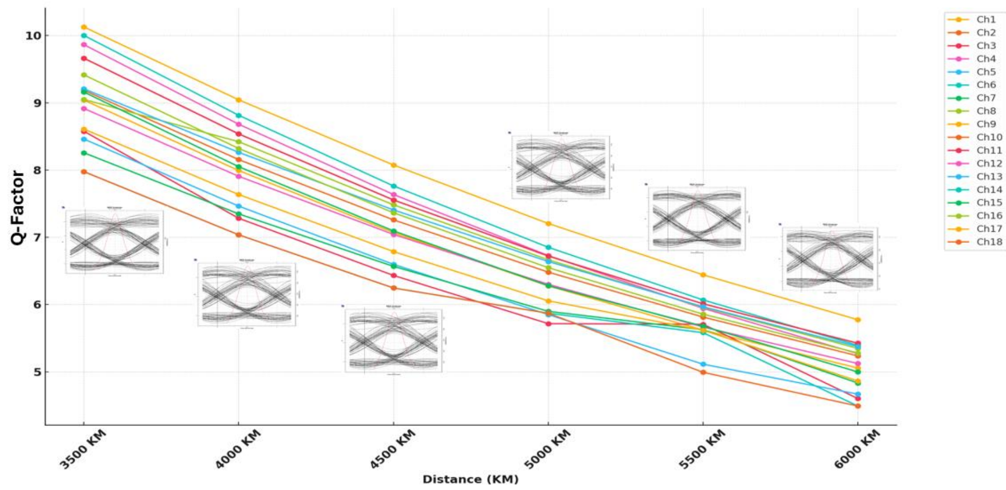

Figure 4: Q-Factor for 18 Channels

4.2 Comparative Insights on Distance-Based Optical Network Performance

This work offers an insightful comparative study on the performance of the optical network system against distance and channel behavior and the prospects it offers with 6G and Non-Terrestrial Network (NTN) backhaul system applicability. The model worked well under close distances from 3500 to 4500 km with low Bit Error Rate (BER) and high Q-factor and can be used in short- and medium-distance applicability without the need to correct the signal further. Performance degradation is noticed and improvement needs like error correction algorithms or advanced amplification techniques are required to sustain quality when the distance is 5000 km. As the distance increases to 5500 to 6000 km, the BER increases substantially and the Q-factor reduces below the threshold value in some channels and reflects the need for advanced methods like adaptive modulation, hybrid optical-electric repeater configurations, or similar innovations to ensure system dependability

On an individual channel performance level, good channels like Ch6 and Ch9 both exhibit lower BER and better Q-factor with negligible effect of distance increases. Such channels can be further optimized to be used in high data integrity required applications over long distances. Weak channels like Ch3, Ch14, and Ch18 degrade more with distance and are suited to be chosen for special treatment like wavelength reshuffling or extra amplification to make them perform better. A comparison of centralized and federated methods still provides the advantages of the federated system. Centralized methods, in which data are gathered on a central server, are vulnerable to security attacks and require a wide data transfer bandwidth. The federated method, however, performs local data processing and communicates only updates, which translates to greater privacy and lower bandwidth usage. Federated systems also facilitate scalability for training by allowing independent processing at each node, which contributes to the performance of the global model without compromising the security.

When 6G and NTN backhaul, applications are considered, the system performs well for distances up to 4500 km and is thus appropriate for regional or short-haul configurations. For distances beyond 5000 km, new modulation schemes, better error-correction mechanisms, or hybrid amplification techniques may have to be used to realize quality for long-haul backhaul applications. Data privacy is guaranteed in this work by the federated method followed, while the analysis of BER and Q-factor offers a comprehensive understanding of the variation in performance with distance. These findings provide valuable information for optimizing the system for different distance requirements and help facilitate further development of high-performance, secure, and efficient optical networks.

5 Conclusion

Based on this study, the performance of an 18-channel CWDM system with high-power EDFAs is examined over 3500–6000 km. Results showed that BER and Q-factor values were within desired ranges up to 4500 km, but both decreased drastically beyond this distance, suggesting difficulty in signal integrity with long reach. Some channels like Ch6 and Ch9 remained strong with small BERs and high Q-factors, whereas others like Ch3 and Ch18 were more prone to degradation. Having this level of performance in mind, the system could be very well adapted to medium-range optical transmission like 6G and NTN backhaul where it could comfortably support high-capacity data transmission with ease. In longer reaches, however, one needs to utilize supplementary methods like advanced error correction, adaptive modulation, or hybrid amplification to maintain data quality and reliability. Further work to extend the reach of this system to greater distance through techniques like forward error correction, hybrid amplification, and adaptive modulation would be beneficial. It would make the CWDM system more suitable for long-distance communication with desired performance requirements to meet future networking needs and high-quality scalable data transfer in future networks.

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The authors declare that there is no acknowledgement for this paper.

Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

Author Contribution

The authors confirm their contribution to the paper as follows:

Study conception and design: Alaan Ghazi

Data collection: Sara Alshwani, Azhar Ahmed Bilal, Alaan Ghazi

Analysis and interpretation of results: Sara Alshwani, Azhar Ahmed Bilal, Alaan Ghazi

Draft manuscript preparation: Sara Alshwani, Azhar Ahmed Bilal, Alaan Ghazi

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Authors Biography

Sara Alshwani, is as a Lecturer in the Software Department, College of Computer Science and Information Technology, University of Kirkuk, Iraq. My fields of interest are Computer Science, Fiber optical, network communication, received a bachelor’s degree from the University of Kirkuk, Iraq in 2007, as well as a Master program from the University of Sulaymaniyah. Iraq in 2017.

Azhar Ahmed Bilal received her B.Sc. degree in Software Engineering Techniques from Northern Technical University at Kirkuk, Iraq in 2004, and her Master's degree in Computer Engineering from Gazi University, Ankara, Turkey in 2024. She is an Assistant Lecturer in the Department of Software, College of Computer Science and Information Technology, University of Kirkuk, Iraq. Besides, working in the Department of Electronic Computer Center, at the Presidency of the University of Kirkuk, Iraq. Specializing in the fields of: Natural Language Processing, Artificial Intelligence, Deep Learning, Data Mining, Machine Learning.

Dr. Alaan Ghazi obtained a Bachelor's degree of computer science from the University of Kirkuk in 2013, He pursued his M.Sc degree in Information Technology and graduated in 2016 from the School of Computing, University Utara Malaysia, Malaysia. Finally, he received her PhD, in Information and Communications Technology at the School of Human Development and Techno-communication at the University Malaysia Perlis, Malaysia in 2022. He is currently a Lecturer at Department of Electronic and Control Technologies Engineering, Technical Engineering College Kirkuk, Northern Technical University, Mosul, Iraq.