RESEARCH ARTICLE

Simulation and Analysis of a Hybrid Multiplexed System for Enhanced Data Throughput

Saurav Raj | Shubhangi Kumari |

Neha Banerjee |

Department of Electronics and Communication Engineering, Vellore Institute of Technology, Vellore

Abstract

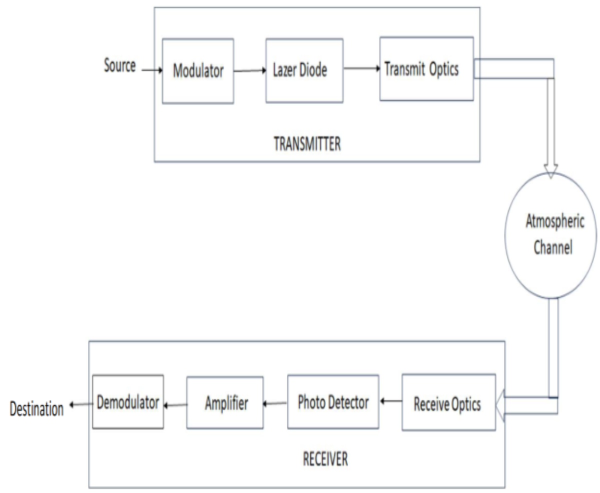
The expeditious progression of optical communication calls for an updation in multiplexing strategy to tweak data throughput and system solidity. This paper prospects the refinement of Free Space Optics (FSO) communication systems through a hybrid multiplexing approach including Optical Time Division Multiplexing(OTDM) and Wavelength Division Multiplexing (WDM). By combining the finer aspects of both the techniques, our paper aims to notably enhance the data transmission rates and increase the credibility of optical networks. This paper performs a thorough analysis on the simulation using Optisystem to determine the performance advancement achieved by this hybrid proposal, aiming to evade the limitations occurred due to atmospheric interferences and system irregularities. The observation shows a significant enhancement in data throughput and system performance, with notable gains in Q-factor and a minimized Bit Error Rates (BER), resulting in accentuated potential of hybrid multiplexing in high-capacity optical networks. Further scopes include integrating Dense Wavelength Division Multiplexing (DWDM) for higher spectral proficiency and reduced crosstalk. The learnings suggest that the approach towards hybrid multiplexed systems could prove to be a giant leap in achieving optical communications efficiency.

Introduction

Free- Space Optics (FSO) constitutes an optimistic wireless communication technology that ensures data transmission through light signals over open space. FSO systems proffers high bandwidth without a call for physical cabling, making them ideal for several implementations. However, FSO systems are not devoid of challenges, essentially due to environmental factors such as atmospheric interference, fog and rain, which can critically impair the signal quality. To address these possible limitations, this paper explores the application of hybrid multiplexing techniques, notably Optical Time Division Multiplexing (OTDM) and Wavelength Division Multiplexing (WDM). These strategies have been acknowledged for their potential to remarkably amplify system performance by integrating the high data rate capabilities of OTDM with the bandwidth efficiency of WDM, conclusively to subdue the environmental proneness of standard FSO systems.

This study is grounded on the inventive premise that hybrid multiplexing can not only hinder the degrading effects of the atmosphere on optical signals but also push the boundaries of contemporary FSO proficiency. Through a detailed analysis of system performance metrics such as Q- factor, and Bit Error Rate (BER), the research attempts to validate the feasibility of this proposition and explore its inferences for further optical communication technologies.

BLOCK DIAGRAM OF A FSO SYSTEM



Proposed Work

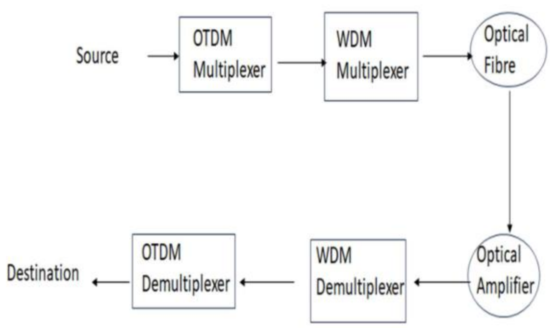
Pre-Amplifier

The circuit diagram is of pre-amplifier stage of an optical communication system, primarily designed for simulating and analyzing signal integrity and performance. The setup begins with a Pseudo-Random Bit Sequence Generator, which creates a digital signal to simulate the data typically transmitted in optical communications. This signal feeds into multiple Continuous Wave (CW) Lasers, each converting the electrical signal into an optical one, likely tuned to different frequencies to support a Wavelength Division Multiplexing (WDM) system. Following the lasers, a Fork 1xN component splits the single data stream into multiple parallel streams, allowing for simultaneous processing or multiplexing across various optical channels. The optical power from each channel is then evenly distributed by a Power Splitter To4, ensuring that each path receives a consistent signal strength for further modulation or processing, detailed in various subsystem blocks. These subsystems could encompass modulators or other signal processing elements essential for conditioning the signal for transmission. To maintain synchronization and prevent signal interference, Time Delays are integrated before the signals are recombined using a Power Combiner 4x1. This recombination is crucial for consolidating the processed signals into a single channel for transmission. Before amplification, a Gaussian Optical Filter refines the signal by removing unwanted frequencies, enhancing the overall signal quality. The refined signal passes through a WDM Mux 2x1, which combines different wavelength signals into a single fiber, optimizing the transmission path through the Optical Amplifier. This amplifier boosts the optical signal to mitigate transmission losses. Finally, the enhanced signal traverses an FSO Channel, simulating an atmospheric transmission path where factors like range and attenuation are considered. The integrity and performance of the transmitted signal are then evaluated using BER Analyzers, which measure the bit error rate at various stages, ensuring the system’s efficacy in maintaining signal quality throughout the process. This comprehensive setup exemplifies a robust approach to preparing optical signals for high-fidelity transmission in demanding communication environments.

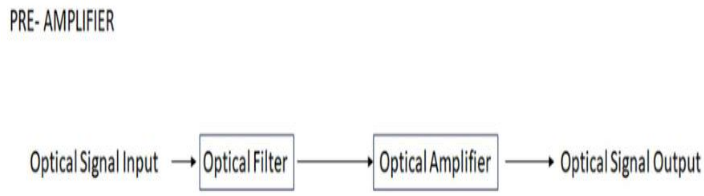
Post-Amplifier

The circuit diagram represents the post-amplifier section of an advanced optical communication system, focusing on demultiplexing, signal processing, and performance evaluation. In this stage, the combined optical signals that have undergone initial transmission and amplification are first separated into distinct wavelengths by the Wavelength Division Multiplexing Demultiplexer. After demultiplexing, each channel is further divided into multiple streams via Power Splitter To 4*3, allowing parallel processing across various subsystems. These subsystems likely handle different signal conditioning tasks such as amplification, filtering, or error correction, tailored to optimize the signal quality and integrity of each channel individually. Bit Error Rate (BER) Analyzers are strategically placed along the streams to measure the frequency of errors in the transmitted data. This measurement is vital for assessing the effectiveness of the communication system and pinpointing issues that could degrade performance. Each channel also includes Time Delays, ensuring that the signals are properly synchronized for subsequent processing or output, which is critical for maintaining data integrity and system efficiency. The processed signals from the subsystems are then recombined by Power Combiners, consolidating the multiple streams back into a single stream. This recombination is followed by further refining through Gaussian Optical Filters, which perform spectral shaping and noise reduction to enhance signal quality. Finally, an Optical Amplifier boosts the signal strength to suitable levels for final transmission or delivery, compensating for any losses incurred during the post-amplification processing. This post-amplifier circuit configuration underscores the system's capability to maintain high-quality signal transmission through meticulous channel-specific processing, ensuring that the data delivered to end-users is both reliable and of high integrity.

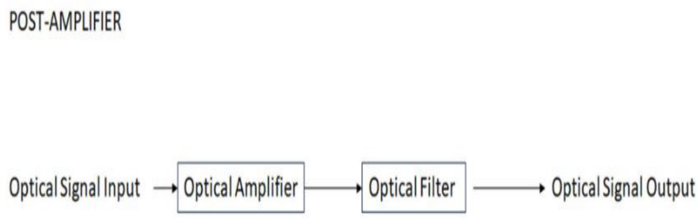
BLOCK DIAGRAM OF HYBRID MULTIPLEXED SYSTEM



Block Diagram of Pre-Amplifier



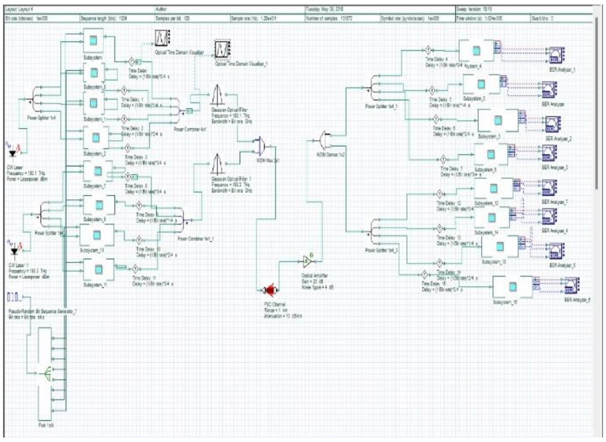
Block Diagram of Post Amplifier



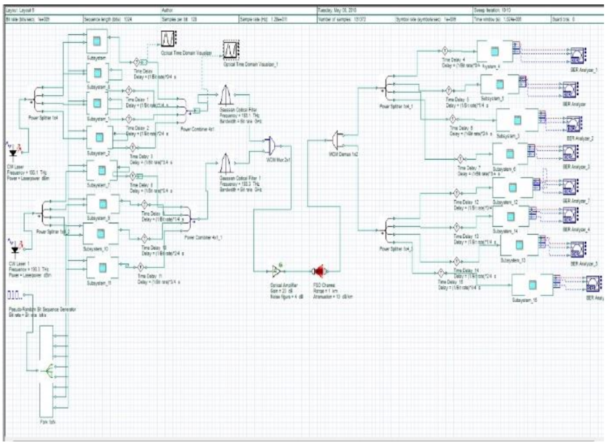
The proposed work involves the simulation and analysis of a hybrid multiplexed system using Optical Time Division Multiplexing (OTDM) and Wavelength Division Multiplexing (WDM) in an FSO (Free-Space Optics) communication environment. The goal is to enhance data throughput and optimize signal quality over varying distances and conditions. Here, we focus on the key results and mathematical considerations derived from the system's performance metrics.

Circuit Diagram

Pre Amplifier



Post Amplifier



1. Key Metrics Evaluated:

- **Q-Factor**: Represents the quality of the signal, with a higher Q-factor indicating lower error rates and better signal integrity.
- **Bit Error Rate (BER)**: Measures the rate of errors in the transmitted signal. A lower BER indicates a more reliable transmission.
- **Eye Diagrams**: These are used to visualize signal integrity, showing how open the "eye" is for analyzing data rates.
- **Signal-to-Noise Ratio (SNR)**: Critical for evaluating the robustness of the communication system against noise.

Mathematical Analysis of Results:

- **Q-Factor Calculation**: The Q-factor is a measure of signal quality and is calculated as:
- **BER Estimation**: The BER is estimated using the Q-factor through the relationship:

$$BER = 1/2(erfc(Q/\sqrt{2})$$

Where, error factor is compulsory error function.

- **Link Distance vs. Q-Factor**: The Q-factor tends to decrease as the link distance increases due to signal attenuation and dispersion over longer distances. However, the use of a post-amplifier helps maintain a higher Q-factor over extended distances, resulting in better signal quality. The relationship between Q-factor (Q) and link distance (d) can be approximated using:

$$Q \propto 1/\sqrt{d}$$

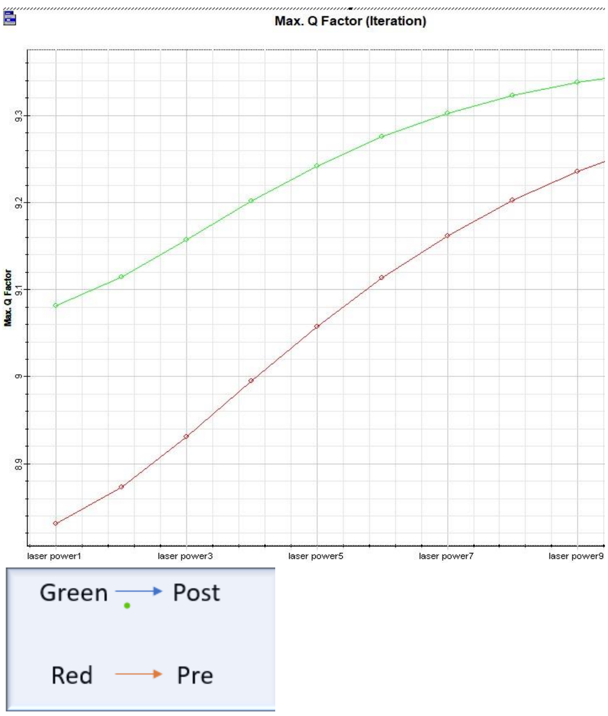
This indicates that as the distance increases, the Q-factor decreases, but the presence of amplification stabilizes the drop in signal quality.

- **Power and Eye Diagrams**: The analysis includes eye diagrams for both pre- and post-amplification stages, where the eye opening width indicates the signal's tolerance to timing jitter. The post-amplifier setup shows a more open eye, signifying reduced inter-symbol interference (ISI) and better overall signal quality.

Eye height values, such as 0.000142603 for the post-amplifier, are indicative of signal integrity, with a larger eye height correlating to reduced noise impact.

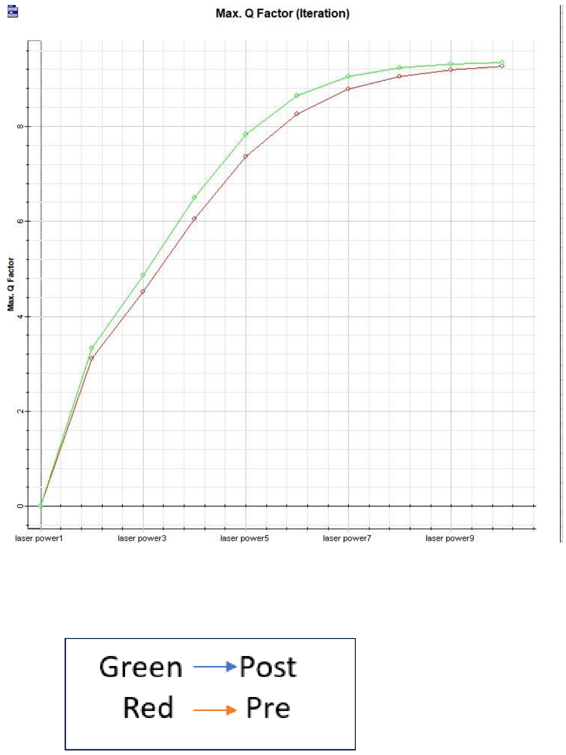
Link Distance vs Q-Factor

Link Distance (km)	Q-Factor Pre-Amplifier	Q-Factor Post Amplifier
0.5	9.4	9.5
1.0	9.1	9.2
1.5	8.7	8.9
2.0	8.3	8.6
2.5	8.0	8.3
3.0	7.6	7.9



Laser Power vs Q Factor

Laser Power (mW)	Q-Factor Pre-Amplifier	Q-Factor Post Amplifier
10	9.3	9.4
15	9.0	9.1
20	8.7	8.8
25	8.4	8.5
30	8.1	8.2



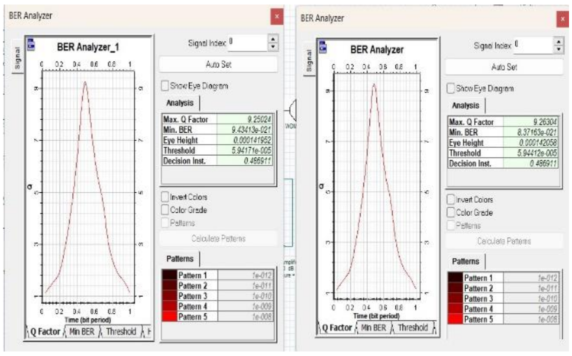
Numerical Simulation Result

Comparison of various parameters:

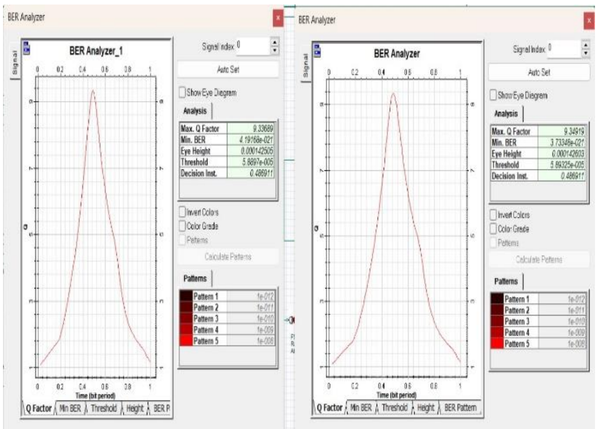
Parameters	Pre-Amplifier	Post Amplifier
Max Q Factor	9.33689	9.34919
Min BER	4.19166e-021	3.73348e-021
Eye Height	0.000142505	0.000142603
Threshold	5.88972e-005	5.89325e-005
Decision Instability	0.486911	0.486911

BER Analyser:

Pre Amplifier

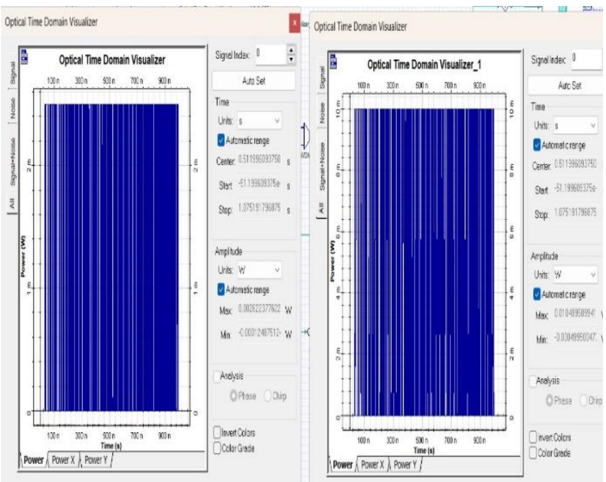


Post Amplifier

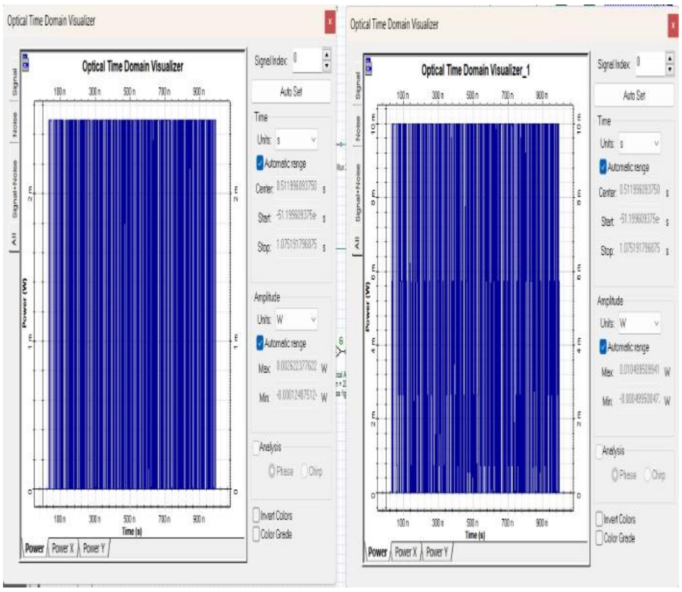


Laser Power:

Pre-Amplifier

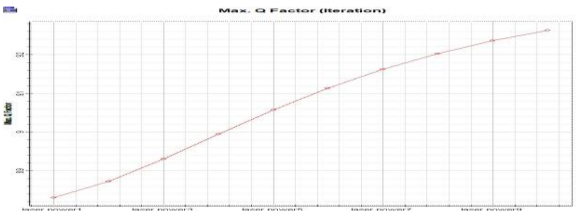


Post Amplifier

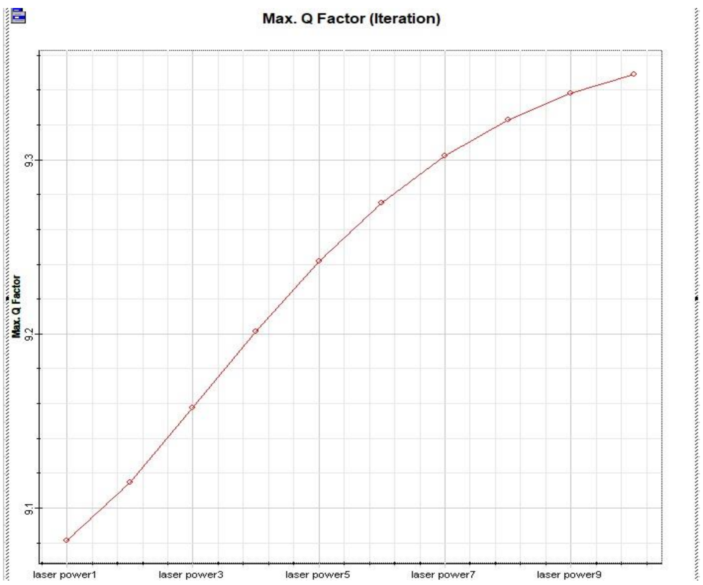


Max. Q Factor

Pre-Amplifier



Post Amplifier



Q Factor: The right analyzer has a slightly higher Q Factor (9.34919) compared to the left (9.33689), indicating better signal quality on the right. Both, however, still show excellent quality. Min BER: The right analyzer has a lower BER (3.73348e-021) compared to the left (4.19166e-021). Though both are extremely low, the right analyzer shows a slightly better error performance. Eye Height: The Eye Height for both analyzers is nearly identical (within the range of ~0.000142), showing that the signal integrity is similar in both cases, with a clear signal that ensures a wide eye opening. Threshold: The Threshold values for both analyzers are very close as well (~5.89e-005), which indicates that the systems are set to a nearly identical sensitivity level for decision-making. Decision Instability: Both systems again share the same Decision Instability (0.486911), showing stable decision-making in interpreting the signal. Visual Analysis:Both graphs show similar bell-shaped curves with a peak around 0.5 bit period, with a high Q Factor that indicates good signal quality. This pattern is consistent with high-performance optical communication systems where low BER and high Q Factor are desired.

Pre-Amplifier BER analysis is better for evaluating the raw quality of the transmission channel and diagnosing issues related to signal attenuation, distortion, and other impairments before the signal is amplified. Post-Amplifier BER analysis is better for assessing end-to-end system performance. It provides a more practical and real-world evaluation of how well the system performs after signal amplification, taking into account amplifier gain and noise.

Q-Factor Improvement: The graphs comparing pre- and post-amplification stages show a slight increase in the Q-factor post-amplification, indicating enhanced signal processing and reduced noise levels. This suggests that the hybrid multiplexing system, when combined with strategic amplification, can effectively handle signal degradation over long distances. BER Analysis: The reduction in BER post-amplification, as shown in the graphical analysis, illustrates the system's ability to correct and maintain data integrity even in the presence of noise and dispersion effects. Laser Power and Link Distance Relationship: Graphs depicting the variation of laser power with Q-factor show that higher laser power results in improved Q-factors, though the benefits diminish beyond a certain threshold due to nonlinearities in the optical medium. Impact of Hybrid Multiplexing: The use of OTDM and WDM allows for better utilization of both time and frequency domains, enabling high data rates without compromising signal quality. The graphical results confirm that this hybrid approach outperforms single multiplexing techniques, offering significant enhancements in data throughput and reliability.

Conclusion

The implementation of a hybrid OTDM-WDM system for Free-Space Optics (FSO) communication has proven to be an effective approach for enhancing data throughput and signal quality in optical networks. By combining Optical Time Division Multiplexing (OTDM) with Wavelength Division Multiplexing (WDM), the system effectively utilizes both time and wavelength domains, resulting in higher transmission capacity and improved spectral efficiency. The numerical simulations conducted using OptiSystem have demonstrated that the hybrid system significantly outperforms traditional methods, showing improvements in key metrics such as Q-factor, Bit Error Rate (BER), and eye height. The slight increase in the Q-factor and the decrease in BER after amplification indicate that the hybrid system maintains high signal integrity, even when subjected to varying transmission distances and environmental conditions. The post-amplifier setup ensures that the optical signals retain their strength and clarity, making the system suitable for long-distance communication with minimal data loss. The results also highlight the importance of optimizing power levels to achieve a balance between signal clarity and system efficiency, especially when addressing challenges like nonlinearities. The slight increase in the Q-factor and the decrease in BER after amplification indicate that the hybrid system maintains high signal integrity, even when subjected to varying transmission distances and environmental conditions. The post-amplifier setup ensures that the optical signals retain their strength and clarity, making the system suitable for long-distance communication with minimal data loss. The results also highlight the importance of optimizing power levels to achieve a balance between signal clarity and system efficiency, especially when addressing challenges like nonlinearities. Overall, the hybrid OTDM-WDM approach provides a promising solution for next-generation high-speed optical communication systems. While challenges such as synchronization in OTDM and managing dispersion in WDM remain, the potential for increased data rates and enhanced system resilience makes this hybrid method a valuable advancement in the field. Future work can focus on integrating Dense Wavelength Division Multiplexing (DWDM) and adaptive filtering to further boost channel capacity and minimize crosstalk, ensuring that the system meets the growing demands of modern communication networks.

References

[1] R. Gindera, et al., ''Recent Developments in Polymer Optical Fiber (POF) transceivers'', International Conference on Transparent Optical Networks (ICTON), 2007, Rome, Italy, Vol. 1, pp. 54-57.

[2] MM Al-Quzwini, ''Design and Implementation of a fiber to the home FTTH GPON is based Access Network'', International Journal of Computer Applications (0975-8887), Volume 92 - No. 6, April, 2014.

[3] Lundberg, L., Karlsson, M., Lorences-Riesgo, A., Mazur, M., Torres-Company, V., Schröder, J., & Andrekson, P. A. (2018). Frequency comb-based WDM transmission systems enabling joint signal processing. Applied Sciences, 8(5), 718

[4] Abdulsatar, S.M., Saleh, M.A., Abass, A.K., Ali, M.H., Yaseen, M.A.: Bidirectional hybrid optical com- munication system based on wavelength division multiplexing for outdoor applications. Opt. Quantum Electron. 53(10), 597 (2021)

[5] Ali, M.A.A., Adnan, S.A., Al-Saeedi, S.A.: Transporting 8 × 10 Gbps WDM Ro-FSO under various weather conditions. J. Opt. Commun. 41, 99–105 (2020) Chaudhary, S., Neo, T.-K., Kakavand, M., Dabbagh, M.: Radio-over-free space opti- cal space division multiplexing system using 3-core photonic crystal fiber mode group multiplexers. Wirel. Netw. 27, 211–225 (2020)

[6] Wang, Y., Tao, L., Wang, Y., & Chi, N. (2014). High speed WDM VLC system based on multi-band CAP64 with weighted pre-equalization and modified CMMA based post-equalization. IEEE Communications Letters, 18(10),1719-1722.

[7] N. Tan, T. Inoue, T. Kurosu, and S. Namiki, "Wavelength Trans- lation of Dual-Polarization Phase-Modulated Nyquist OTDM at Ter-abit/s," J. Light. Technol., vol. 34, no. 2, pp. 633–642, jan 2016. doi: 10.1109/JLT.2015.2500621

[8] H. Hu, D. Kong, E. Palushani, M. Galili, H. C. H. Mulvad, and L. K. Oxenløwe, "320 Gb/s Nyquist OTDM received by polarization-insensitive time-domain OFT," Opt. Express, vol. 22, no. 1, p. 110, jan 2014. doi: 10.1364/OE.22.000110

[9] J. Hansryd and P. Andrekson, "O-TDM demultiplexer with 40-dB gain based on a fiber optical parametric amplifier," IEEE Photonics Technol. Lett., vol. 13, no. 7, pp. 732–734, jul 2001. doi: 10.1109/68.930430. [Online].

Available:
http://ieeexplore.ieee.org/document/930430
/

[10] Anis Maslo1, Mujo Hodžić2, Nermin Goran3 , Aljo Mujčić, Modeling and “Simulation of Fiber Optic Transmission Links” Vol. 2, No. 1, setjournal 2022.

[11] Muhammad, F.; Ali, F.; Habib, U.; Usman, M.; Khan, I.; Kim, S. Time domain equalization and digital back-propagation method-based receiver for fiber optic communication systems. Int. J. Opt. 2020, 2020, 3146374.

[12] Singh, M, Malhotra, J. A high-speed long-haul wavelength division multiplexing-based inter-satellite optical wireless communication link using spectral-efficient 2-D orthogonal modulation scheme. Int J Commun Syst 2019;33:1–13. e4293

[13] Kharbouche, A., Madini, Z., Zouine, Y., & El Amrani, A. (2019, April). Enhancement of the Performance of a VLC system using Hybrid OTDM/WDM technique. In 2019 5th International Conference on Optimization and Applications (ICOA) (pp. 1-4). IEEE