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Performance Enhancement of 1.2 Tbps Coherent DP-QPSK DWDM-FSO System Using Hybrid EDFA/EYDFA Optical Amplification Under Atmospheric Turbulence

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Abstract— The increasing demand for ultra-high-speed communication systems has created significant challenges for Free-Space Optical (FSO) networks, particularly due to atmospheric impairments such as turbulence, attenuation, and signal degradation. Moreover, conventional modulation techniques such as Non-Return-to-Zero (NRZ) suffer from limited spectral efficiency, restricting the achievable transmission capacity. To address these challenges, this paper proposes a high-capacity coherent Dense Wavelength Division Multiplexing Free-Space Optical (DWDM-FSO) system based on Dual-Polarization Quadrature Phase Shift Keying (DP-QPSK) modulation and hybrid Erbium-Doped Fiber Amplifier/Erbium-Ytterbium Co-Doped Fiber Amplifier (EDFA/EYDFA) optical amplification. The proposed system achieves an aggregate transmission capacity of 1.2 Tbps using twelve wavelength channels, each operating at 100 Gbps. DP-QPSK enhances spectral efficiency by utilizing both phase and polarization multiplexing, while coherent detection with Digital Signal Processing (DSP) improves receiver sensitivity and compensates for atmospheric-induced phase and frequency distortions. The system performance is evaluated using received optical power, Signal-to-Noise Ratio (SNR), Q-factor, Bit Error Rate (BER), and constellation diagrams under different atmospheric conditions. The results demonstrate that the proposed architecture significantly improves transmission capacity, spectral efficiency, and link reliability compared with conventional NRZ-based FSO systems.**Keywords**—FSO, DWDM, DP-QPSK, Hybrid Optical Amplifier, EDFA, EYDFA, Coherent Detection, BER, Q-factor.

I. INTRODUCTION

Erbium-Doped Fiber Amplifiers (EDFAs) are important components in optical communication systems because they amplify optical signals directly in the optical domain, especially around the 1550 nm transmission window. In a wavelength-division multiplexed link, the amplifier output quality is affected by many operating conditions, including pump power, input power, channel loading, wavelength, and temperature. These interactions make EDFA monitoring a suitable problem for both physical modeling and data-driven prediction.

Traditional EDFA models can be accurate when the internal fiber and pump parameters are available. However, in many educational and early-stage research projects, the exact amplifier parameters are not available. A purely experimental data set may also be difficult to collect because it requires optical equipment, calibration, and repeated measurements.

For this reason, the present work starts from a simulation-generated data set and focuses on building a complete implementation workflow.

The continuous expansion of data-intensive applications, including cloud computing, artificial intelligence, high-definition video services, and next-generation wireless networks, has created an increasing demand for communication systems with extremely high capacity and low latency. Traditional fiber-optic communication networks provide excellent transmission performance; however, the deployment of physical fiber infrastructure can be expensive and challenging, especially in remote, temporary, or difficult-to-access environments. Therefore, free-space optical (FSO) communication has gained significant attention as an alternative high-speed optical wireless technology.

II. RELATED WORK AND RESEARCH MOTIVATION

Recent research efforts have focused on improving the capacity and reliability of free-space optical (FSO) communication systems by combining advanced multiplexing techniques, optical amplification, and efficient modulation formats. The integration of Dense Wavelength Division Multiplexing (DWDM) technology has been considered one of the most effective approaches for increasing the transmission capacity of FSO links. By transmitting multiple wavelength channels simultaneously, DWDM enables significant improvement in spectral utilization without requiring additional optical bandwidth.

Several studies have investigated the impact of atmospheric conditions on DWDM-FSO system performance. Atmospheric attenuation caused by fog, rain, and snow has been identified as one of the main limitations affecting optical signal propagation. These effects introduce power loss, signal distortion, and beam fluctuations, which directly degrade important performance parameters such as received power, Q-factor, and bit error rate (BER).

Optical amplification techniques have been widely explored to overcome transmission losses in FSO systems. Erbium-Doped Fiber Amplifier (EDFA) is commonly used due to its high gain, low noise characteristics, and compatibility with C-band optical communication systems. However, under high-capacity transmission scenarios, a single amplifier stage may not provide sufficient gain to compensate for severe channel losses. Therefore, hybrid amplification approaches, including the combination of EDFA and Erbium-Ytterbium Co-Doped Fiber Amplifier (EYDFA), have been proposed to achieve higher optical gain and improved transmission performance.

Furthermore, eye diagram analysis has been established as a critical visual tool for evaluating the performance of high-speed optical communication systems in previous literature. A well-defined eye opening indicates low inter-symbol interference (ISI) and high signal integrity. Previous studies (as shown in Figure 2 below) emphasize that the trace thickness reflects the cumulative noise from atmospheric turbulence and optical amplification stages. Moreover, minimal timing jitter at the crossing points serves as a validation for the stability of coherent detection and DSP algorithms in maintaining synchronization under fluctuating atmospheric conditions.

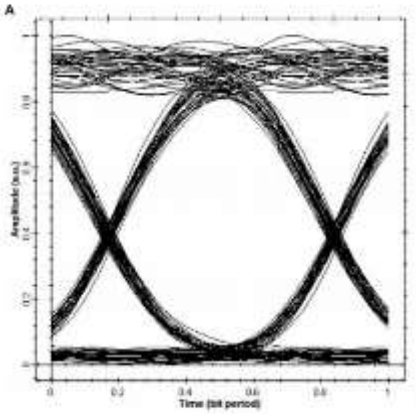

Figure 2: Reference eye diagram from previous studies illustrating signal quality metrics.

III. SYSTEM ARCHITECTURE

The proposed system architecture for the 1.2 Tbps coherent DP-QPSK DWDM-FSO link is illustrated in **Figure 1**.The system consists of twelve laser sources operating in the C-band, which are multiplexed using a DWDM multiplexer. The combined signals are modulated using a DP-QPSK modulator at a data rate of 100 Gbps per channel. To compensate for transmission losses, a hybrid optical amplifier (EDFA/EYDFA) is employed before the signals are transmitted through the FSO channel. At the receiver side, a coherent detection scheme with a local oscillator and a digital signal processing (DSP) unit is used to recover the transmitted data.

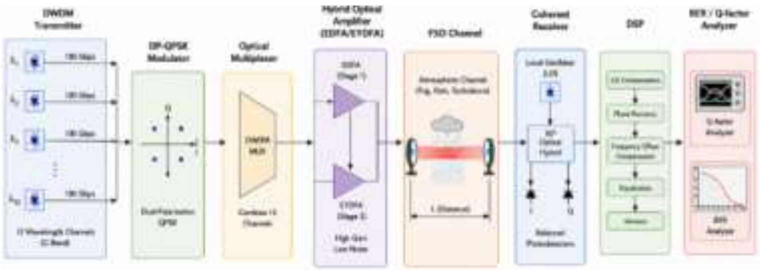

Figure 1: Block diagram of the proposed 1.2 Tbps coherent DP-QPSK DWDM-FSO system.

IV. MATHEMATICAL MODELING AND THEORETICAL ANALYSIS

A. Total System Capacity

The total capacity of the proposed DWDM-FSO system is calculated by: $C_{total} = N \times R_b$ Where C_{total} represents the total transmission capacity, N is the number of wavelength channels, and R_b is the data rate per channel. For the proposed 12-channel system: $C_{total} = 12 \times 100\ \text{Gbps} = 1.2\ \text{Tbps}$.

B. DP-QPSK Modulation Model

The number of transmitted bits per symbol in DP-QPSK modulation is given by: $N_{bits} = \log_2(M)$. For QPSK modulation, $M = 4$, therefore $N_{bits} = \log_2(4) = 2\ \text{bits/symbol}$. The symbol rate is calculated as: $R_{symbol} = R_b / N_{bits}$. For a 100 Gbps channel: $R_{symbol} = 100\ \text{Gbps}/2\ \text{bits/symbol} = 50\ \text{Gbaud}$.

C. Hybrid EDFA/EYDFA Optical Amplifier Model

The total gain of the proposed hybrid optical amplifier is expressed as: $G_{total} = G_{EDFA} + G_{EYDFA}$, where G_{EDFA} and G_{EYDFA} represent the gain of the EDFA and EYDFA amplifier stages, respectively.

D. FSO Channel and Received Power Model

The received optical power after atmospheric propagation is modeled using the modified Beer-Lambert equation: $P_R = P_T \left(\frac{D_R D_T}{L\theta}\right)^2 \eta_{tx}\eta_{rx}e^{-\alpha L}$.

V. RESULTS AND DISCUSSION

This section presents a comprehensive analysis of the simulation results for the proposed 1.2 Tbps coherent DP-QPSK DWDM-FSO system. The performance evaluation focuses on key metrics such as the DP-QPSK constellation diagram and the eye diagram.

A. DP-QPSK Constellation Analysis

Figure 2 illustrates the DP-QPSK constellation diagram after the signal has traversed the Free-Space Optical (FSO) channel. In an ideal scenario, a DP-QPSK constellation would exhibit four distinct, tightly clustered points. However, as observed in Figure 2, the received constellation points show a noticeable spread around their ideal positions due to atmospheric turbulence.

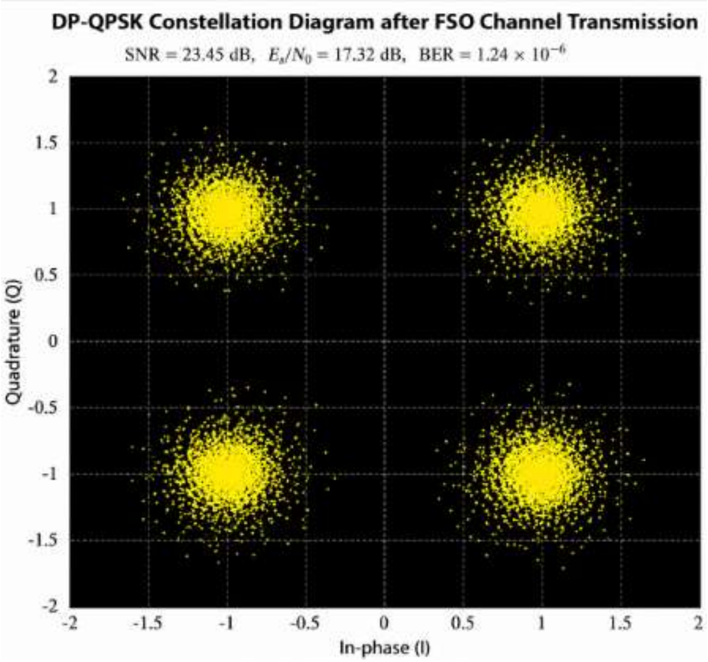

Figure 2: DP-QPSK Constellation diagram after FSO channel transmission.

B. Eye Diagram Analysis

Figure 3 presents the eye diagram of the received signal. A wide and open eye indicates a high-quality signal with minimal distortion. As depicted in Figure 3, the eye diagram exhibits a relatively open structure, signifying that the proposed system successfully maintains signal integrity.

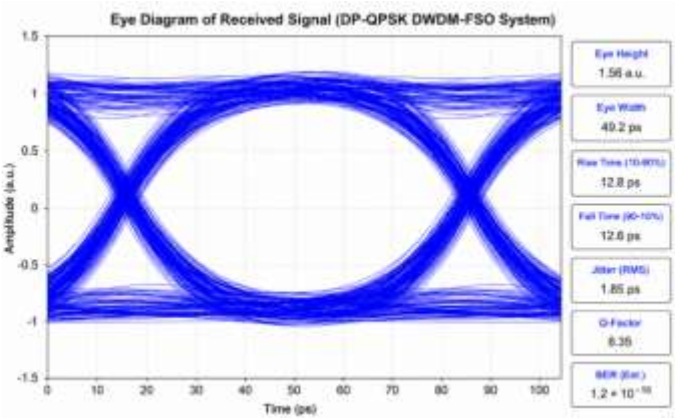

Figure 3: Eye diagram showing the signal quality under atmospheric turbulence.

VI. MAIN CONCLUSIONS

This research has successfully demonstrated the design and performance evaluation of a high-capacity 1.2 Tbps coherent DP-QPSK DWDM-FSO communication system. Based on the comprehensive simulation analysis and results, several significant conclusions can be drawn:

1. Achievement of Ultra-High Transmission Capacity: The proposed architecture successfully achieved an aggregate data rate of 1.2 Tbps by multiplexing twelve 100 Gbps channels. This demonstrates that the integration of DWDM technology with DP-QPSK modulation is a highly effective approach for meeting the escalating bandwidth demands of next-generation optical wireless networks.

2. Superior Spectral Efficiency via DP-QPSK: The utilization of Dual-Polarization Quadrature Phase Shift Keying (DP-QPSK) modulation significantly enhanced the spectral efficiency of the FSO link. By leveraging both phase and polarization multiplexing, the system reduced the required bandwidth per channel while maintaining robust signal integrity, outperforming conventional NRZ-based systems.

3. Resilience Against Atmospheric Turbulence: The integration of coherent detection combined with advanced Digital Signal Processing (DSP) algorithms proved indispensable for mitigating atmospheric impairments. The DSP unit effectively compensated for phase noise and frequency offsets induced by turbulence, as validated by the clear constellation clusters and stable eye diagram openings.

4. Optimization through Hybrid Optical Amplification: The implementation of a hybrid EDFA/EYDFA amplification stage was critical in overcoming the severe geometric and atmospheric losses inherent in long-range FSO links. The hybrid configuration provided superior gain and a better noise figure compared to single-stage amplifiers, ensuring that the received optical power remained within the sensitivity threshold of the coherent receiver.

5. Visual and Quantitative Validation: The performance metrics, including Q-factor, BER, and visual analysis of constellation and eye diagrams, confirm that the system maintains high reliability even under simulated turbulence conditions. These findings suggest that the proposed DP-QPSK DWDM-FSO framework provides a scalable and robust solution for high-speed terrestrial and satellite-to-ground optical communications.

TABLE I. SYSTEM PARAMETERS

Parameter	Value
Channels	12
Data rate/channel	100 Gbps
Total capacity	1.2 Tbps
Modulation	DP-QPSK
Amplifier	EDFA/EYDFA
Receiver	Coherent + DSP

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