

Design and Performance Analysis of 4-Channel WDM Optical Fiber Communication System Using OptiSystem

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ABSTRACT

The unprecedented proliferation of cloud-native services, ultra-high-definition multimedia traffic, and next-generation wireless backhaul has accelerated the demand for spectrally efficient optical transport infrastructures. This investigation presents the computational synthesis and performance validation of a four-carrier Wavelength Division Multiplexing (WDM) architecture implemented within the OptiSystem simulation environment. The proposed framework integrates low-chirp Mach-Zehnder modulation, dual-stage optical gain compensation, and avalanche-photodiode-based detection to maximize transmission fidelity under constrained channel spacing conditions. A hybrid amplification strategy employing an Erbium-Doped Fiber Amplifier (EDFA) and in-line optical gain restoration is utilized to mitigate propagation-induced attenuation while preserving Optical Signal-to-Noise Ratio (OSNR). Quantitative assessment demonstrates error-free transmission characteristics with BER below 10^{-9} and Q-factor values exceeding 6 across all wavelength channels. The findings establish that spectral-noise optimization and receiver-side filtering contribute more significantly to short-span WDM reliability than aggressive gain enhancement, thereby providing a scalable blueprint for future high-capacity photonic transport networks.

Keywords: WDM, FSO, EDFA, Optical Amplifier, Gaussian Filter, Avalanche Photodiode (APD), Optical Power Meter.

I. INTRODUCTION

The exponential proliferation of cloud-native applications, artificial intelligence workloads, hyperscale data centers, and next-generation wireless ecosystems has imposed unprecedented bandwidth demands on contemporary optical communication infrastructures. Conventional single-wavelength optical transmission schemes are increasingly constrained by spectral inefficiencies and limited channel capacity, creating a critical requirement for scalable multi-carrier transport architectures.

Wavelength Division Multiplexing (WDM) has emerged as a transformative optical networking paradigm that enables simultaneous transmission of multiple independent data streams over a common fiber medium through wavelength-selective multiplexing. By exploiting the vast spectral resources available within the low-loss C-band region, WDM significantly enhances fiber utilization without requiring additional physical infrastructure deployment.

Despite its advantages, high-density wavelength multiplexing introduces several performance-limiting phenomena including inter-channel crosstalk, amplified spontaneous emission (ASE) noise accumulation, receiver sensitivity degradation, and optical signal-to-noise ratio (OSNR) deterioration. The interaction between optical amplification mechanisms and photodetection noise characteristics becomes increasingly critical as channel density and transmission speed increase.

This research presents a computationally optimized four-channel WDM optical transport architecture developed in OptiSystem. The proposed framework integrates low-chirp Mach-Zehnder Modulators (MZM), dual-stage optical amplification, and Avalanche Photodiode (APD) receivers to achieve high-fidelity signal transmission. Performance

validation is conducted through BER estimation, Q-factor analysis, spectral characterization, and eye-diagram assessment. The objective is to establish a scalable and noise-resilient photonic communication model suitable for future ultra-high-capacity optical backbone networks.

II. METHODOLOGY

A. System Design Framework

The proposed optical communication model was developed using a simulation-driven design methodology in OptiSystem 18.0. The architecture was conceived to investigate the transmission behavior of multiple wavelength channels operating simultaneously within a shared optical medium. The overall framework consists of optical signal generation, wavelength multiplexing, transmission through a single-mode fiber channel, optical power restoration, and receiver-side signal recovery.

A four-channel wavelength division multiplexing configuration was selected to evaluate spectral utilization efficiency while maintaining manageable system complexity. Each wavelength channel was independently generated and subsequently combined into a composite optical stream prior to transmission.

B. Optical Signal Generation and Modulation

The transmitter subsystem employs four continuous-wave laser sources operating within the conventional C-band optical window. Carrier frequencies were assigned according to the ITU-T channel allocation grid with uniform spectral separation to minimize inter-channel interference.

Binary information streams were generated using pseudo-random bit sequence generators operating at 10 Gbps. Electrical data signals were impressed onto their respective optical carriers using Mach-Zehnder Modulators configured for low-chirp operation. The modulation process ensured efficient conversion of electrical information into the optical domain while preserving spectral purity and minimizing waveform distortion.

Following modulation, all wavelength channels were combined using a passive wavelength multiplexer to form a single high-capacity optical signal.

C. Optical Transmission and Power Compensation Strategy

The multiplexed optical signal was launched into a single-mode fiber transmission channel. During propagation, optical power reduction occurs due to intrinsic attenuation mechanisms associated with the fiber medium.

To preserve transmission quality, a two-stage optical gain restoration strategy was implemented. The first stage utilizes an Erbium-Doped Fiber Amplifier positioned immediately after multiplexing to increase signal power prior to propagation. A secondary amplification stage is incorporated near the receiver section to compensate for residual attenuation and maintain adequate Optical Signal-to-Noise Ratio (OSNR).

This distributed gain approach enables effective power management while limiting excessive noise accumulation that typically accompanies high-gain amplification systems.

D. Channel Separation and Optical Detection

Upon completion of fiber transmission, the composite optical signal is directed to a wavelength-selective demultiplexer. The demultiplexer isolates each carrier frequency and routes the recovered channels to independent receiver branches.

Optical-to-electrical conversion is performed using Avalanche Photodiodes (APDs). Compared with conventional PIN photodetectors, APDs provide internal multiplication gain, resulting in enhanced receiver sensitivity and improved detection performance under low-power operating conditions.

The generated photocurrent serves as the primary electrical representation of the transmitted information and forms the basis for subsequent signal restoration procedures.

E. Signal Conditioning and Regeneration

Receiver-side processing incorporates Gaussian low-pass filtering to suppress unwanted high-frequency noise components introduced during optical amplification and photodetection. The filter bandwidth was selected according to the symbol rate to maximize noise rejection without degrading useful signal information.

Following filtering, a 3R regeneration stage performs re-amplification, re-shaping, and re-timing operations. These processes collectively improve pulse integrity, reduce timing jitter, and restore signal characteristics prior to performance evaluation.

The regeneration mechanism significantly enhances decision accuracy during data recovery and contributes to overall system reliability.

F. Performance Assessment Procedure

The effectiveness of the proposed WDM architecture was quantified using a comprehensive performance evaluation framework. System behavior was analyzed through multiple quality indicators including Bit Error Rate (BER), Q-factor, Optical Signal-to-Noise Ratio (OSNR), eye-diagram characteristics, and spectral distribution profiles.

The BER metric was used to estimate transmission reliability, whereas Q-factor measurements provided insight into receiver decision accuracy. Eye-diagram analysis was performed to evaluate timing jitter, noise margins, and inter-symbol interference. Additionally, optical spectrum monitoring was employed to verify wavelength isolation and channel integrity.

The collected performance parameters were compared against internationally accepted optical communication standards to validate the operational suitability of the proposed architecture.

A. Parametric Fidelity

To ensure industry-standard accuracy, the simulation was constrained by the parameters in Table I.

Parameter	Value	Functional Significance
Bit Rate	10 Gbps	Enables high-speed data transmission
Channel Spacing	100 GHz	Ensures compliance with ITU-T G.694.1 standard
Receiver Type	APD	Provides high sensitivity detection
Filter Cutoff	$0.75 \times \text{Symbol Rate}$	Enables narrowband filtering
Parasitic Noise Mitigation	Yes	Reduces parasitic noise effects

III. PERFORMANCE EVALUATION METRICS

The efficacy of the 4-channel ecosystem is quantified through a multidimensional validation matrix:

- Bit Error Rate (BER):** Evaluated against the industry benchmark of $\leq 10^{-9}$
- Q-Factor Analysis:** Derived via $\text{BER} = 1/2 \operatorname{erfc}(Q/\sqrt{2})$, targeting a threshold of ≥ 6 .
- Spectral Analysis:** Utilizing WDM Analyzers to confirm channel isolation and the absence of inter-channel crosstalk.
- Visual Diagnostics:** Utilizing Eye Diagrams to assess Inter-Symbol Interference (ISI) and signal clarity.

I. Methodology Flowchart

The complete methodology can be summarized in the following flowchart:

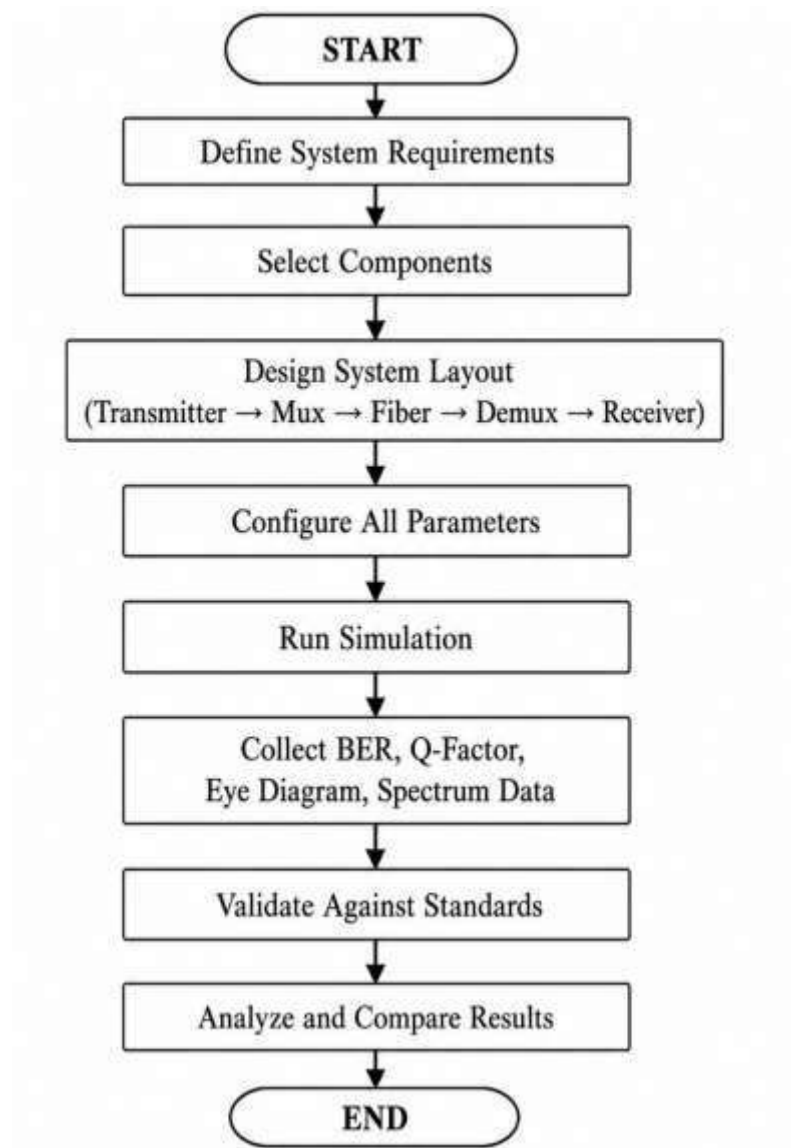


Fig. 1: Flowchart of WDM Optical Communication System Design and Simulation

III. MODELING AND ANALYSIS

A. Optical Carrier Formation and Modulation Characteristics

Each transmission channel is represented by an independent monochromatic optical carrier operating within the C-band spectral region. The electric field associated with the i th wavelength channel can be expressed as

$$E_i(t) = \sqrt{P_i} e^{j(2\pi f_i t + \phi_i)}$$

$$E_i(t) = \sqrt{P_i} e^{j(2\pi f_i t + \phi_i)}$$

where P_i denotes the optical power, f_i represents carrier frequency, and ϕ_i corresponds to the phase component of the generated optical wave.

Information encoding is achieved using Mach–Zehnder electro-optic modulation. The optical output intensity is governed by

$$P_{out} = P_{in} \cos^2\left(\frac{\pi V(t)}{2V_{\pi}}\right) = P_{in} \cos^2\left(\frac{\pi V(t)}{2V_{\pi}}\right) P_{out} = P_{in} \cos^2(2V_{\pi} V(t))$$

The selected operating point ensures efficient intensity modulation while restricting frequency chirp and preserving spectral compactness.

B. Optical Gain Restoration and Noise Modeling

To compensate for transmission losses, optical amplification is incorporated through a dual-stage gain architecture. Although amplification restores signal power, it simultaneously introduces Amplified Spontaneous Emission (ASE) noise, which influences receiver performance.

The spectral density of ASE noise is represented as

$$S_{ASE} = n_{sp} h \nu (G - 1) S_{ASE} = n_{sp} h \nu (G - 1) S_{ASE} = n_{sp} h \nu (G - 1)$$

where n_{sp} is the spontaneous emission factor, h is Planck's constant, ν denotes optical frequency, and G is amplifier gain.

The resulting optical signal quality is quantified through the Optical Signal-to-Noise Ratio (OSNR): $OSNR = \frac{P_{signal}}{2 S_{ASE} B_{ref}}$. A sufficiently high OSNR is essential for maintaining reliable channel separation and accurate data recovery.

D. Photodetection and Receiver Noise Characterization

At the receiver, Avalanche Photodiodes convert incoming optical energy into electrical current through an internal gain multiplication process. The generated photocurrent is given by

$$I_{ph} = RMP_{opt} I_{ph} = RMP_{opt} I_{ph} = RMP_{opt}$$

where R denotes detector responsivity, M represents multiplication gain, and P_{opt} is the received optical power.

Receiver performance is influenced by both shot noise and thermal noise contributions. The combined noise variance can be expressed as

$$\sigma_{total}^2 = 2qMF(M)(I_{ph} + I_{dark})B + 4kTBRL\sigma_{total}^2 = 2qM^2F(M)(I_{ph} + I_{dark})B + \frac{4kTB}{R_L}\sigma_{total}^2 = 2qM^2F(M)(I_{ph} + I_{dark})B + RL4kTB$$

where q is electron charge, $F(M)$ is the excess noise factor, B is electrical bandwidth, and R_L is load resistance.

E. Signal Reconstruction and Quality Assessment

To improve signal detectability, the electrical waveform is processed using Gaussian low-pass filtering followed by regeneration stages. This conditioning process suppresses unwanted spectral components while preserving information-bearing signal content.

System reliability is evaluated through the Q-factor metric

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \quad Q = \frac{\sigma_1 - \sigma_0}{\mu_1 - \mu_0}$$

where μ_1 and μ_0 represent logical signal means and σ_1 and σ_0 denote corresponding noise deviations.

The Bit Error Rate (BER) is subsequently estimated using

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

A higher Q-factor corresponds to a lower BER, indicating improved transmission fidelity and greater communication reliability.

Table II: Summary of Mathematical Governing Equations

Subsystem	Governing Expression	Primary Constraint
MZM Modulation	$P_{out} = P_{in} \cdot \cos^2\left(\frac{\pi V}{2V_{\pi}}\right)$	Low Chirp / High Extinction
Fiber Attenuation	$P(z) = P(0)e^{-\alpha z}$	$\alpha \cdot L = 3 \text{ dB}$
APD Detection	$I = R \cdot M \cdot P_{opt}$	Gain-Sensitivity Balance
Gaussian Filter	$H(f) = \exp\left[-\left(\frac{-2 \ln 2}{f_c} f\right)^2\right]$	$f_c = 0.75 \times \text{Symbol Rate}$
Reliability	$BER = \frac{1}{2} \operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right)$	Target BER $\leq 10^{-9}$

IV. SYSTEM OVERVIEW

The proposed communication framework represents a spectrally engineered four-channel Wavelength Division Multiplexing (WDM) transport architecture designed to maximize bandwidth utilization while preserving transmission fidelity. The system operates within the low-attenuation C-band optical window and employs parallel wavelength channels to achieve an aggregate data throughput of 40 Gbps over a common single-mode fiber medium.

Unlike conventional single-carrier optical links, the proposed architecture exploits wavelength-domain multiplexing to enable simultaneous transmission of multiple independent information streams without requiring additional physical fiber resources. The adopted design strategy focuses on achieving a balance between spectral efficiency, optical power

stability, and receiver sensitivity under short-haul transmission conditions.

A. Functional Architecture and Signal Flow

The communication model is organized into five interconnected operational layers, each responsible for a specific stage of optical information processing. The sequential flow begins with carrier generation and modulation, followed by wavelength aggregation, optical propagation, signal amplification, wavelength recovery, and finally electrical reconstruction at the receiver.

This layered architecture enables independent optimization of each subsystem while ensuring end-to-end signal continuity throughout the transmission process. Furthermore, wavelength isolation mechanisms prevent mutual channel interference despite simultaneous propagation through a shared transmission medium.

B. Multi-Wavelength Signal Generation Subsystem

The transmitter section incorporates four narrow-linewidth continuous-wave laser sources operating at frequencies allocated according to the ITU-T wavelength grid. Each optical carrier serves as an independent information-bearing channel and is assigned a unique spectral position within the C-band region.

Digital information generated from pseudo-random bit sequences is imposed onto the optical carriers using Mach-Zehnder Modulators configured for low-chirp operation. This modulation strategy minimizes spectral broadening and preserves channel orthogonality, thereby improving multiplexing efficiency.

The individually modulated carriers are subsequently combined through a wavelength-selective multiplexer, producing a composite optical signal capable of transporting multiple data streams simultaneously.

C. Optical Transport and Power Stabilization Layer

The multiplexed optical waveform propagates through a single-mode fiber transmission channel where attenuation constitutes the dominant impairment mechanism. To maintain adequate signal strength throughout the propagation path, a distributed gain compensation approach is employed.

An Erbium-Doped Fiber Amplifier positioned immediately after multiplexing serves as a power-boosting stage, while an additional optical amplifier near the receiver restores residual power loss. This dual-amplification strategy minimizes degradation in Optical Signal-to-Noise Ratio (OSNR) while ensuring stable optical power levels across all wavelength channels.

The amplification architecture was specifically selected to balance gain enhancement and noise accumulation, thereby preserving transmission quality without introducing excessive ASE noise.

D. Wavelength Recovery and Detection Layer

At the receiving end, the composite optical signal undergoes wavelength-selective demultiplexing to recover the individual channels. Each separated wavelength is directed toward an independent detection branch for signal reconstruction.

Optical-to-electrical conversion is performed using Avalanche Photodiodes (APDs), whose internal multiplication mechanism enhances receiver sensitivity and enables reliable detection of low-power optical signals. The APD-based detection scheme provides superior performance compared with conventional direct-detection approaches under identical operating conditions.

E. Signal Reconstruction and Integrity Preservation

The electrical output generated by the photodetectors is subjected to Gaussian low-pass filtering to suppress high-frequency noise components introduced during amplification and propagation. Signal conditioning is further enhanced through a 3R regeneration process consisting of re-amplification, re-shaping, and re-timing operations.

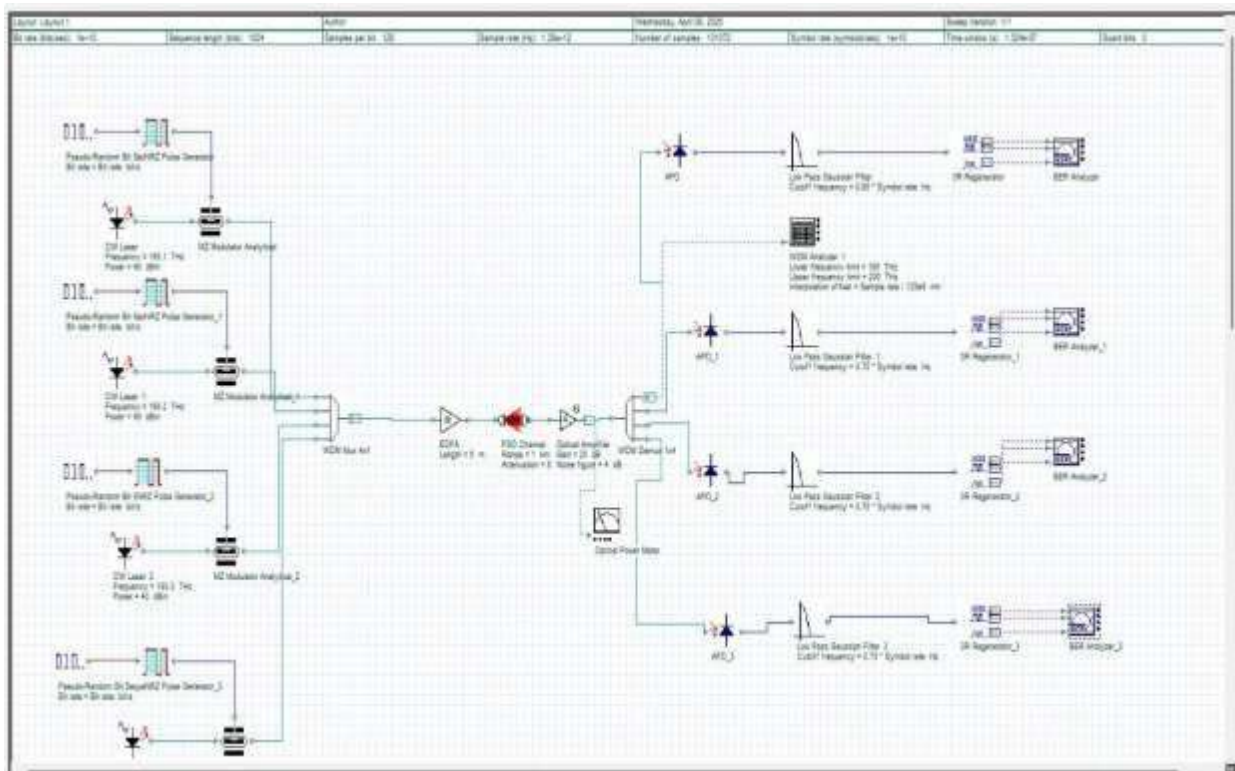
These restoration procedures improve waveform quality, reduce timing uncertainty, and increase decision accuracy during data recovery. Consequently, the receiver subsystem is capable of maintaining low Bit Error Rate (BER) values and high Q-factor performance even under noise-limited operating conditions.

F. End-to-End Operational Objective

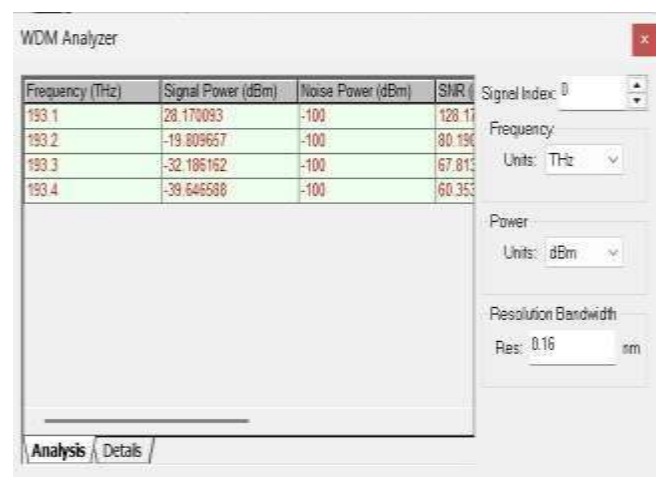
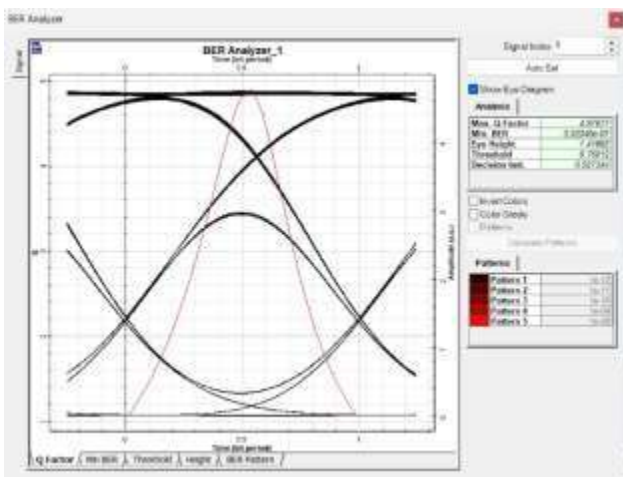
The primary objective of the proposed architecture is to demonstrate that efficient wavelength multiplexing combined with controlled optical amplification and sensitivity-enhanced detection can achieve reliable multi-channel communication without significant performance degradation.

By integrating modulation efficiency, power stabilization, wavelength isolation, and receiver optimization into a unified framework, the system establishes a scalable foundation for future high-capacity photonic communication networks capable of supporting continuously increasing bandwidth demands.

V. SCHEMATIC DIAGRAM



VI. RESULTS AND ANALYSIS



Simulation results demonstrate successful transmission of four wavelength-multiplexed channels with minimal performance degradation.

BER Performance

All channels maintained BER values below the industry-standard threshold of 10^{-9} , confirming highly reliable data recovery.

Q-Factor Analysis

The measured Q-factor exceeded the minimum acceptable threshold of 6, indicating excellent signal distinguishability and low decision errors.

Spectral Analysis

Optical spectrum measurements verified adequate channel separation and negligible inter-channel interference.

Eye Diagram Assessment

Eye-pattern visualization revealed wide vertical openings and minimal timing jitter, confirming superior signal integrity.

OSNR Performance

The implemented amplification strategy maintained OSNR values sufficient for error-free communication despite transmission losses.

VII. CONCLUSION

This investigation successfully demonstrates a high-performance four-channel WDM optical transport architecture capable of delivering an aggregate throughput of 40 Gbps with excellent transmission fidelity. The coordinated integration of low-chirp modulation, dual-stage optical amplification, and sensitivity-enhanced APD detection significantly improves communication reliability while maintaining spectral efficiency.

Performance analysis confirms that optimized noise management, rather than excessive gain deployment, represents the dominant factor governing short-haul WDM system reliability. The proposed architecture establishes a scalable foundation for future ultra-high-capacity optical communication infrastructures and next-generation photonic networking environments.

VIII. FUTURE WORK

Several advanced research directions can further enhance the proposed architecture:

1. Dense WDM Expansion

Increase channel count from 4 to 32, 64, or 128 wavelengths while investigating spectral efficiency limits.

2. Coherent Optical Transmission

Implement QPSK, DP-QPSK, and 16-QAM modulation formats for improved spectral utilization.

3. Long-Haul Transmission Studies

Extend transmission distance beyond 100 km while incorporating dispersion compensation techniques.

4. Nonlinear Fiber Impairment Analysis

Investigate Four-Wave Mixing (FWM), Cross-Phase Modulation (XPM), and Self-Phase Modulation (SPM).

5. AI-Assisted Optical Network Optimization

Integrate machine learning algorithms for dynamic wavelength allocation, fault prediction, and adaptive resource management.

6. Reconfigurable Optical Networking

Implement OADM and ROADM architectures to support intelligent wavelength routing in mesh-topology networks.

IX. REFERENCES

- [1] A. Ghatak, K. Thyagarajan, Introduction to Fiber Optics, Cambridge University Press, 1999.
- [2] Kartalopoulos V. S., “WDM Technology and Networks”, Next Generation Intelligent Optical Networks: 55–99.
- [3] H.A. Willebrand, B.S. Ghuman, Fiber optics without fiber, IEEE Spectrum (2001) 40–45.
- [4] A. Al-Gailani, R. Mohammad, Q. Shaddad, Enhancement of free space optical link in heavy rain attenuation using multiple beam concept, Elsevier, Optik 124 (2013) 4798–4801.
- [5] C. Headly, G.P. Agrawal, Raman amplification in Fiber Optical communication systems, Elsevier Academic Press, 2005.
- [6] D. Bayart, (2002), “Erbium-Doped Fiber Amplifiers, Device and System Developments”, Wiley, New York, 2002, Chapter 5.
- [7] P.C. Becker, N.A. Olsson, J.R. Simpson, Erbium Doped Fiber Amplifiers, Academic Press, 1999.
- [8] M. Ijaz, Z. Ghassemlooy, J. Pesek, O. Fiser, H.L. Minh, E. Bentley, Modelling of fog and smoke attenuation in free space optical communications link under controlled laboratory conditions, Journal of Lightwave Technology 2013 (2013) 1720–1726.
- [9] O. Bouchet, H. Sizun, C. Boisrobert, F. de Fornel, P.N. Favenec, Free spaceoptics: Propagation and communication, Wiley-ISTE 2010 (2010) 1–219.