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Design of 400 Gbps Dual-Polarisation QPSK Backhauling for Current and Future Mobile Networks: Practical Conditions, Applications, Challenges, and Research Directions

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Abstract

This study describes the design and analysis of a 400 Gbps dual-polarisation quadrature phase shift keying (DP-QPSK) backhaul system optimized for existing and future high-capacity mobile networks, such as 5G and 6G. To meet the growing demand for bandwidth-intensive applications such as AR, VR, and ultra-high-definition streaming, the system utilizes advanced optical transmission technologies, digital signal processing (DSP), and spectral efficiency techniques. The design uses Maxwell's equations and the nonlinear Schrödinger equation (NLSE) to simulate electromagnetic wave propagation and nonlinear impairments, including self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). Novel real-time, dynamic environmental modeling of fiber impairments, including temperature-dependent attenuation, dispersion, and polarisation mode dispersion (PMD), enables precise impairment mitigation, thereby enhancing signal integrity over extended distances. To achieve extremely low bit error rates, the system uses neural network-based equalizers, adaptive DSP, and unique impairment tracking. The challenges of nonlinear effects, fiber impairments, and integration with existing networks are examined, as well as potential solutions to improve resilience, scalability, and efficiency. The report also discusses future research topics, such as weather-resilient free-space optical communication, quantum-resistant security, and cost-effective deployment methods. Extensive simulation findings support the usefulness of the suggested technique, demonstrating near-error-free transmission capabilities, excellent spectrum efficiency, and durability under practical situations, thereby providing a potential foundation for next-generation high-capacity backhaul networks.

Keywords: *400 Gbps, Dual-Polarisation QPSK (DP-QPSK), Backhaul Network, Dense Wavelength Division Multiplexing (DWDM), 5G/6G Technology.*

1. Introduction

The rapid evolution of mobile networks has led to an unprecedented increase in data traffic, driven by the proliferation of bandwidth-intensive applications such as augmented reality (AR), virtual reality (VR), and ultra-high-definition video streaming [1]. As user demands escalate, the need for high-capacity, low-latency, and reliable backhaul solutions becomes critical. The design of a 400 Gbps Dual-Polarisation Quadrature Phase Shift Keying (DP-QPSK) backhauling system emerges as a viable solution to address these challenges, particularly in the context of current and future mobile networks, including the anticipated 6G technologies. The integration of DP-QPSK technology into backhaul networks offers significant advantages in terms of spectral efficiency and data transmission rates. However, implementing such high-speed communications presents several obstacles, including susceptibility to physical limitations such as chromatic dispersion, polarisation mode dispersion, and nonlinear effects [2]. These challenges are exacerbated at higher data rates, where even minor signal distortions can lead to substantial performance degradation. Therefore, developing effective compensating solutions that mitigate these limitations without increasing system complexity or cost is a significant concern [2]. The rapid evolution of mobile communication technologies has led to an unprecedented increase in data traffic, driven by the proliferation of bandwidth-intensive applications such as streaming services, online gaming, and real-time data analytics [2]. Additionally, the energy demands of high-capacity networks and the thermal output from associated equipment can limit adoption. Thus, achieving energy-efficient operation while maintaining optimal performance is crucial for addressing sustainability issues and reducing operational costs. This thesis aims to explore the design, simulation, and analysis of a 400 Gbps DP-QPSK backhauling system, focusing on its application in next-generation telecommunications networks. By employing advanced optical transmission technologies and digital signal processing techniques, this research seeks to provide a robust framework for future network architectures, ultimately contributing to the development of efficient and reliable backhaul solutions. Additionally, the energy demands of high-capacity networks and the thermal output from associated equipment can limit adoption [3]. Thus, achieving energy-efficient operation while maintaining optimal performance is crucial for addressing sustainability issues and reducing operational costs [4]. By employing advanced optical transmission technologies and digital signal processing (DSP) techniques [5], this research seeks to provide a robust framework for future network architectures, ultimately contributing to the development of efficient and reliable backhaul solutions. The rapid increase in mobile data traffic, driven by bandwidth-intensive applications, necessitates the development of high-capacity backhaul solutions to support these demands. As mobile networks transition to 5G and the anticipated 6G technologies, there is a critical need for ultra-high-capacity and low-latency solutions to accommodate advanced applications like augmented reality and ultra-high-definition video streaming [6; 7]. Additionally, the limitations of traditional backhaul methods highlight the importance of exploring optical fiber-based solutions, such as Dual-Polarisation Quadrature Phase Shift Keying (DP-QPSK), which offers increased data transmission capacity [8]. Addressing challenges related to signal impairments and ensuring energy efficiency and sustainability further motivates the research into effective backhaul solutions [9].

1.1 Objectives

This study sets out key objectives to explore and guide the design and deployment of 400 Gbps DP-QPSK backhaul systems:

1. To analyze the practical deployment conditions and transmission impairments that affect the performance of 400 Gbps DP-QPSK systems in mobile backhaul environments.
2. To evaluate and optimize digital signal processing (DSP) techniques for enhancing signal quality and mitigating impairments in 400 Gbps coherent optical links.
3. To investigate the cost, power consumption, and scalability trade-offs involved in deploying 400 Gbps DP-QPSK transceivers in 5G and 6G backhaul networks.
4. To assess how photonic integration improves the performance, size, and energy efficiency of 400 Gbps DP-QPSK transceivers.
5. To develop design frameworks and performance models that ensure 400 Gbps DP-QPSK systems are suitable for current 5G and future 6G mobile network backhaul requirements.

2. Related Works

Kachris and Tomkos [2] further explore the technical challenges of high-speed fiber transmission, noting that even minor signal distortions can lead to substantial performance degradation. Their findings underscore the necessity for effective compensation techniques to mitigate these impairments without adding complexity or cost to the system. This aligns with the objectives of the current study, which aims to develop advanced solutions for maintaining signal integrity in high-capacity modulation backhaul networks. The integration of 400 Gbps DP-QPSK backhaul solutions into existing network infrastructures is another critical area of research. The findings from the current study suggest that optimized routing and advanced techniques can effectively minimize latency, which is critical for real-time applications such as driverless vehicles and industrial automation [2]. This aligns with the broader literature that emphasizes the importance of low-latency communication in the context of emerging technologies. Security in backhaul networks has also garnered attention in recent research. The integration of quantum key distribution (QKD) and the development of quantum-resistant cryptographic methods are highlighted as necessary steps to enhance the security and resilience of high-capacity networks [4]. Research on a low-complexity digital signal processing solution for optical transmission that eliminates frequency offset compensation and carrier phase recovery using a self-coherent system. It uses an adaptive polarisation controller for MIMO-free operation and has successfully transmitted across 81 kilometers using 7-core fiber and ordinary single-mode fiber. The system achieves a capacity of 432 Gbps through space division multiplexing technology, demonstrating its potential for high-speed data transmission [10].

This adaptability is essential for optimizing network performance and ensuring efficient use of available spectrum. The performance metrics of DP-QPSK systems have also been a focal point of research. Studies have shown that integrating advanced digital signal processing (DSP) techniques can significantly improve the Bit Error Rate (BER) and Signal-to-Noise Ratio (SNR) in high-capacity networks [11]. These enhancements are vital for maintaining reliable

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data transmission in the presence of noise and dispersion, which are prevalent in long-haul optical communication. In terms of system robustness, the work of [12] highlights the resilience of DP-QPSK systems to fiber impairments such as chromatic dispersion and polarization mode dispersion. Their findings indicate that coherent detection combined with sophisticated DSP algorithms can effectively mitigate these impairments, ensuring signal integrity over extended distances.

This robustness is particularly important for long-haul communication, where maintaining signal quality is critical for operational reliability. The integration of 400 Gbps DP-QPSK backhaul solutions into existing network infrastructures presents several challenges. As noted by Cisco [13], the transition from legacy systems to high-capacity networks requires careful planning to ensure interoperability and scalability. The high costs associated with upgrading or replacing outdated infrastructure can pose significant barriers to adoption. Therefore, developing standardized interfaces and protocols is essential for facilitating a smooth transition and minimizing operational disruptions. Study a novel approach to free space optical communication (FSOC) by proposing a system that utilizes optical angular momentum (OAM) multiplexing combined with polarisation division multiplexed (PDM) quadrature phase shift keying (QPSK) and digital signal processing (DSP) at the receiver. The authors investigate the system's performance under various weather conditions, including clear weather, rain, and fog, to assess the impact of these conditions on the system's bit error rate (BER). The study employs Laguerre Gaussian (LG) beams, specifically LG0,0, LG0,13, LG0,40, and LG0,80, to facilitate a four-channel FSOC system through OAM multiplexing [2]. The paper investigates the impact of IQ and XY power imbalances in dual-polarisation quadrature amplitude modulation (DP-QAM) optical transmitters, proposing an optical interference-based pre-calibration method for effectively detecting and compensating these imbalances, thereby improving performance for high-speed transmission applications above 400 Gb/s [14]. In summary, recent studies on 400Gbps DP-QPSK backhaul systems emphasize DSP-based signal integrity solutions and novel approaches like self-coherent transmission and OAM multiplexing. While these demonstrate improved performance and capacity, key gaps remain in cost-effective deployment, real-world validation, legacy network integration, and energy efficiency. Research also highlights growing needs for quantum-resistant security and weather-resilient free-space optics, though practical implementation challenges persist. These findings collectively underscore the need for balanced solutions addressing both technical performance and operational feasibility in next-generation optical networks.

3. Methodology

This study uses a mixed modeling and simulation technique to create a 400 Gbps Dual-Polarisation Quadrature Phase Shift Keying (DP-QPSK) optical backhaul system optimized for next-generation mobile networks. The methodology combines theoretical optical communication models with powerful digital signal processing (DSP) and machine learning (ML) tools to assess and improve system performance under real-world physical-layer impairments. The system architecture is designed as an end-to-end coherent optical communication link that includes a DP-QPSK transmitter, a standard single-mode fiber

(SSMF) channel with inline erbium-doped fiber amplifiers (EDFAs), and a coherent receiver. The optical channel is thoroughly simulated for both linear and nonlinear impairments, such as chromatic dispersion (CD), polarisation mode dispersion (PMD), self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). The simulation is based on theoretical formulations based on the Nonlinear Schrödinger Equation (NLSE), Manakov system, and Gaussian noise models, with analytical formulas utilized to produce performance measures such as bit error rate (BER), optical signal-to-noise ratio (OSNR), and Q-factor. The simulation framework, developed using MATLAB, employs a modular design methodology that includes signal creation, modulation, optical propagation, detection, and performance evaluation. The DSP layer uses ML-based equalization and compensating techniques. Deep neural networks (DNNs) and convolutional neural networks (CNNs) are taught to detect distortion patterns and forecast optimal signal recovery parameters, whilst reinforcement learning (RL) agents adjust launch power and DSP configurations depending on real-time performance feedback. BER, OSNR, Q-factor, and constellation clarity are used to measure system performance under different link situations. Verification is accomplished by comparing simulated outcomes to theoretical models and literature benchmarks. Validation comprises sensitivity analysis and cross-validation of machine learning models to ensure their robustness. The key assumptions include optimal temporal synchronization, fixed laser linewidths, and statistical emodeling of amplifier and dispersion impairments. The limits of synthetic training data and ambient heterogeneity are recognized, especially for ML generalization and physical hardware variations. This methodological framework offers a scalable, intelligent platform for simulating and optimizing high-capacity optical backhaul systems in constantly changing mobile network settings. It also establishes the groundwork for future hardware development and experimental validation.

4. Methods

This study creates and tests a 400 Gbps DP-QPSK optical backhaul system with a hybrid simulation technique that combines physical-layer models, nonlinear fiber propagation theory, and machine learning-enhanced DSP. The MATLAB-based model simulates a fully coherent connection with fiber impairments and adaptive ML-driven optimization, with performance validated by analytical comparisons and key metrics including BER, OSNR, and Q-factor.

Table 1: Summary of methods used (Source: Field Data)

Step	Method Description
1. System Design	Define the architecture using a 400 Gbps DP-QPSK modulation format with coherent optics.
2. Parameter Setup	Configure critical parameters: symbol rate, fiber length, OSNR, dispersion, attenuation, and polarization effects.
3. Signal Generation	Generate pseudo-random binary sequences (PRBS), apply QPSK modulation, and shape pulses using RRC filters.
4. Channel Modeling	Simulate standard single-mode fiber (SSMF) characteristics with impairments like CD, PMD, attenuation, and nonlinearity.
5. Optical Amplification	Include EDFAs in the link and model ASE noise based on typical gain and noise figure parameters.
6. Coherent Detection & DSP	Apply DSP at the receiver, including polarization demultiplexing, dispersion compensation, carrier recovery, and clock recovery.
7. FEC Integration	Implement LDPC or BCH codes to correct bit errors and enhance transmission performance.
8. Performance Evaluation	Evaluate the system using BER, Q-factor, OSNR, and visual diagnostics like eye and constellation diagrams.
9. Simulation Tool	Use MATLAB to simulate system components, channel behavior, and signal processing algorithms.
10. Validation	Compare results with theoretical expectations and existing literature to validate design accuracy.

5. Problem Formulation

The 400 Gbps DP-QPSK backhaul system was designed using a mixed-method approach that integrates theory, modeling, and validation to address the high-capacity, low-latency, and spectrum efficiency requirements of 5G/6G networks. DP-QPSK was chosen because of its durability and coherence compatibility.

$$\nabla x E = -\frac{\partial B}{\partial t}, \nabla x H = J + \frac{\partial D}{\partial t}$$

(1)

Where:

E: Electric field vector (units: V/m). **B**: Magnetic flux density (also called magnetic induction) (units: Tesla, T). **H**: Magnetic field intensity (units: A/m). **J**: Current density vector (units: A/m²). **D**: Electric displacement field (units: C/m²). ∇ X: The Curl operator measures the rotation of a vector field. $\frac{\partial}{\partial t}$ Partial derivative with respect to time.

$\nabla x E = -\frac{\partial B}{\partial t}$ A time-varying magnetic field induces a circulating electric field (Faraday's law of electromagnetic induction).

$\nabla x H = J + \frac{\partial D}{\partial t}$ A circulating magnetic field is produced by an electric current J and a time-varying electric displacement field D (Ampère-Maxwell law).

The Nonlinear Schrödinger Equation (NLSE) is applied in the 400 Gbps DP-QPSK backhaul to model and mitigate dispersion and nonlinearities, enabling reliable ultra-high-capacity long-haul transmission. $\frac{\partial A}{\partial z} + \frac{\alpha}{2} A + \beta_1 \frac{\partial A}{\partial t} - j \frac{\beta_2}{2} \frac{\alpha^2 A}{\partial t^2} + Y |A|^2 A = 0$
(2)

Where:

A (z, T) = Complex envelope of the optical pulse. α = Fiber attenuation (dB/km). β2 = Group Velocity Dispersion (GVD, ps^2/km). β3 = Third-order dispersion (ps^3/km). γ = Nonlinear coefficient ($W^{-1} \cdot km^{-1}$). = Kerr nonlinearity (self-phase modulation, SPM).

In DP-QPSK, the coupled NLSE models PMD and XPM between polarisation states, predicting dispersion and nonlinear effects like SPM and XPM.

Manakov Equation (S. V. Minkov) extends the NLSE for dual-polarisation systems:

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A + \beta_1 \frac{\partial^2 A_x}{\partial t} - j \frac{\beta_2}{2} \frac{\alpha^2 A}{\partial t^2} = jy(|A_x|^2 + |A_y|^2) A_x$$
(3)

The coupled NLSE models DP-QPSK nonlinear interactions (XPolM), while Jones Calculus manages polarisation states for multiplexing, PMD compensation, and coherent detection in 400 Gbps backhauling. Polarisation states are represented as. $E = \begin{bmatrix} E_x \\ E_Y \end{bmatrix} = \begin{bmatrix} A_x e^{j\phi z} \\ E_Y e^{j\phi y} \end{bmatrix}$
(4)

The Shannon-Hartley theorem defines the capacity limits of 400G DP-QPSK backhauling, where bandwidth and OSNR set performance ceilings, guiding modulation efficiency and impairment compensation. $C = B.\log_2\left(1 + \frac{S}{N}\right)$
(5)

Where:

C = Channel capacity (bits per second). B = Channel bandwidth (Hz). S/N = Signal-to-noise power ratio (linear scale).

The Wiener-Khinchin theorem relates autocorrelation to PSD, enabling OSNR estimation and DSP filtering in 400G DP-QPSK backhauling.:

$S_X(f) = \int_{-\infty}^{\infty} R_X(\tau) e^{-2\pi f \tau j\phi z} d\tau$
(6)

Where: $S_X(f)$ is the power spectral density (PSD) of the random process $X_{(t)}$). $R_X(\tau)$ is the autocorrelation function. $X_{(t)}$ f is the frequency and τ Is there a time delay?

Lyapunov's Stability Theorem ensures CMA equalizer convergence in 400G DP-QPSK backhauling, reducing impairments and maintaining reliable low-BER transmission.

$V(w) > 0, \forall w \neq w^*$ and
(7)

$\Delta V(w) = V(w(k+1) - V(w(k) < 0$
(8)

Where: V(w) is the Lyapunov (cost) function, positive-definite. w(k) is the equalizer tap weights at iteration k. ΔV(w) represents the change in the function over iterations. For CMA, a common cost function (Lyapunov candidate) is (9):

The candidate is: $J(w) = E\left[(|y(k)|^2 - R)^2 \right]$
(9)

Where: y(k) is the equalizer output at iteration k. R is the constant modulus (expected signal power for QPSK). E [·] is the expectation operator. If this cost function continuously decreases with each iteration, per Lyapunov's theorem, the system is stable and will converge.

Cramer-Rao Lower Bound (CRLB) (Harald Cramér, Calyampudi Rao) equation in optical communication is used to limit phase noise estimation accuracy [27].

$Var(\phi) \geq \frac{1}{N.SNR}$
(10)

The impact on the design is to guide carrier recovery DSP algorithms. The Volterra Series Equation provides nonlinear system emodeling (an alternative to NN-DSP).[20]

$y(t) = \frac{\infty}{n=1} \int \ldots \int h_n(\tau_1, \ldots, \tau_n) \prod_{i=1}^{n} x(t-\tau_1) d\tau_i$ [20]
(11)

The neural network-augmented Minkov equation adaptively compensates for nonlinearities and polarization effects in 400G DP-QPSK, improving accuracy, reach, and spectral efficiency beyond DBP.

Standard Manakov Equation: $\frac{\partial u}{\partial z} + \frac{\alpha}{2} u + i \frac{\beta_2}{2} \frac{\partial^2 u}{\partial \mathrm{T}^2} = i\Upsilon(|u|^2 u)$
(12)

Where: $u = [u_x, u_y]$ Represents the two polarisation components.

The SDE models random polarization drift in 400G DP-QPSK, enhancing PMD robustness, DSP equalizers, and adaptive ML-based compensation for dynamic networks.

$$du(t) = A(u,t)dt + B(u,t)dW(t)$$
(13)

Where: $u(t) = [u_x, u_y]^{T}$ Is the Jones vector of the optical field. A is Deterministic drift fiber nonlinearity.

The RL-optimized GNLSE model adaptively corrects nonlinearities in 400G DP-QPSK, enabling real-time impairment mitigation, reduced complexity, and improved BER under dynamic conditions.[30]. $$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A + i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial \mathrm{T}^2} - \frac{\beta_3}{6}\frac{\partial^3 A}{\partial \mathrm{T}^3} = i\Upsilon |A|^2 A + R_\theta(A, z, t, \Omega)$$
(14)

Where: $A = [x, \mathrm{T}] = [A_x, A_y]^{T}$ Is the Jones vector representing both polarisation components, and α Is the attenuation coefficient (dB/km). β_2 β_3 Are the group velocity dispersion parameters (ps²/km and ps³/km). Υ Is the nonlinear coefficient ($W^{-1}km^{-1}$). R_θ Represents the RL policy network with the input current field envelope. An RL-based correction term augments the Minkov equation, where parameters θ are updated via policy gradients to learn optimal nonlinear compensation in 400G DP-QPSK backhaul systems. In this design, signals are represented using this model.

For DP-QPSK**:** $E(t) = E_x(t)\hat{x} + E_y(t)\hat{y}$
(15)

Where: $E(t)$ Is the total **electric field vector** a function of time? $E_x(t)$ Is the **electric field component along the x-axis** at time t? $E_y(t)$ Is the electric field component along the y-axis at time t? $\hat{x}$ Is the Unit vector in the

x-direction and $\hat{y}$ Unit vector in the y-direction.

Symbol Mapping (QPSK) utilized the equation below.

Each QPSK symbol maps 2 bits**:** $S_k = A_x e^{j\left(\frac{\pi}{2}mk\right)}$
(16)

Where: mk = {0, 1, 2, 3}

Power is controlled by using Launch Power Optimization, which sets the Nonlinear Threshold.

This equation was to maximize OSNR while minimizing nonlinear effects:

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$$P_{opt} = \sqrt{\frac{\alpha}{2}\gamma^{L_{eff}}}$$

(17)

Where: α Is the attenuation coefficient (dB/km). γ Is the nonlinear coefficient ($W^{-1}km^{-1}$).

$$L_{eff} = \frac{1-e^{-\alpha L}}{\alpha}$$

The OSNR and BER Relation is presented using the model below.

Approximate BER for DP-QPSK with SD-FEC: $BER = \frac{1}{2} erfc\left(\sqrt{\frac{OSNRxB}{2R_b}}\right)$

(18)

Where: OSNR: Optical Signal-to-Noise Ratio. B: noise bandwidth. R_b Is the bit rate.

First-order PMD: $\Delta\tau = D_{pmd}\sqrt{L}$, where D_{pmd} Is the PMD coefficient $(ps/\sqrt{km})$.

The equation supports 400G DP-QPSK backhauling while introducing adaptive ML equalization, time-variant NLPN models, and 3D constellation monitoring for next-generation optical networks.

In 400G DP-QPSK backhauling, the Kalman filter enables real-time recursive estimation and correction of PMD and nonlinear phase noise for stable DSP performance.

$$X_{(k)} = AX_{k-1}(t) + W_{k-1}$$

(19) $x_{(k)} = Hx_k + v_k$

(20) Where: x_k It is the state vector for PMD parameters and nonlinear phase noise estimates. A is the state transition matrix. z_k These include the observation vector, received signal statistics, and constellation point deviations. W_{k-1} Is the process noise typically modeled as a zero-mean Gaussian with covariance Q? H is the observation matrix mapping state to measurement space. v_k Is the measurement noise zero-mean Gaussian with covariance R?

Dynamic Impairment is used to determine the Temperature-Dependent Attenuation and is modeled as:

$$\alpha(T) = \alpha_0(1 + k_T(T - T_0)$$

(21)

where α0 is baseline fiber attenuation at reference temperature T0, and kT is a temperature sensitivity constant (0.002–0.005 dB/km/°C.

The Temperature-Dependent Chromatic Dispersion is modeled as: $D(T) = D_0 + \frac{Dd}{dT}(T - T_0)$

(22)

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With $\frac{Dd}{d\mathrm{T}}$ = 0.003- 0.005 ps/nm/km/^{0}C

The PMD Variability is Modeled as: $PMD(\mathrm{T})\alpha\sqrt{L\chi}(1+\in_{\mathrm{T}}(\mathrm{T}-\mathrm{T}_0))$ (23)

Capturing rapid environmental birefringence shifts is $\phi nl(t)=\gamma\int_0^L P(t,z)dz$ (24)

Where instantaneous power $P(t,z)$ It is varied according to simulated traffic profiles.

The design used five important equations that represent the innovative contributions to coherent detection and noise modeling in 400Gbps DP-QPSK systems:

The Non-Gaussian Noise Statistics Model is used in the simulation to take out the noise in the design, as shown in the equation below.

$$p(\phi NL)=\frac{1}{2\sqrt{2\pi\sigma_\phi}}e^{-\frac{\phi NL}{2\sigma_\phi^2}}+\lambda\phi^4 NL^{e-k\phi^2}NL$$

(25)

where ϕ_{NL} is the nonlinear phase noise, σ_ϕ the Gaussian component, and λ, κ characterize the non-Gaussian tail.

The Correlated ASE Noise in EDFA Chains is modeled as:

$$R_{ASR}(z_1,z_2)=N_{sp}hvG(z_1)G(z_2)\sqrt{\alpha(z_1)\alpha(z_2)}e^{-\int_{z_1}^{z_2}\alpha(\varsigma)d\varsigma}$$

(26)

with Nsp spontaneous emission factor, G(z) gain profile, and α(z) attenuation.

Polarisation-Mode Coupled Noise is also modeled as:

$$n_{PM}(t)=J(t)n_{ASR}(t)+\beta\frac{dJ(t)}{dt}n_{ASR}(t)$$

(27)

where J(t) is the random Jones matrix evolution and β is the coupling coefficient.

Quantum-Limited SNR Bound is presented in the form:

$$SNR_{QL}=\frac{nP_{LO}}{2hvB}\left(1+\frac{4\sigma^2_{th}}{R^2\eta^2P^2_{LO}}\right)^{-1}$$

(28)

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With η detector efficacy, $P^2{}_{LO}$ Power and, $\sigma^2{}_{th}$ Thermal noise.

The Monte Carlo model was used to determine the BER Validation. Monte Carlo also gives the confidence interval equation for BER estimation. For M simulated symbols:

$$BER_{MC} = \frac{ErrorCount}{2M} \quad (29)$$

With a 95% confidence interval:

$$CI = BER_{MC} \pm 1.96\sqrt{\frac{BER_{MC}(1-BER_{MC})}{2M}} \quad (30)$$

Where CI Is Confidence Interval. BER_{MC} It is the Monte Carlo Bit Error Rate. The simulated BER value is calculated as the ratio of erroneous bits to total transmitted bits in the simulation. 1.96 is the Z-score for a 95% Confidence Level. A constant from the normal distribution representing the 95% confidence bounds (±1.96 standard deviations).

M is the Number of Simulated Symbols:

The term under the square root $\sqrt{\frac{BER_{MC}(1-BER_{MC})}{2M}}$ Is the standard error.

6. Flow Chart for Dual-Polarisation QPSK Backhauling Design.

The system implementation flowchart outlines the end-to-end design of the 400 Gbps DP-QPSK optical backhaul, covering data generation, modulation, fiber transmission with impairments, coherent detection, DSP-based compensation, and performance evaluation. It also integrates ANN modules for adaptive optimization, ensuring accurate simulation, scalability, and readiness for 5G/6G backhaul networks.

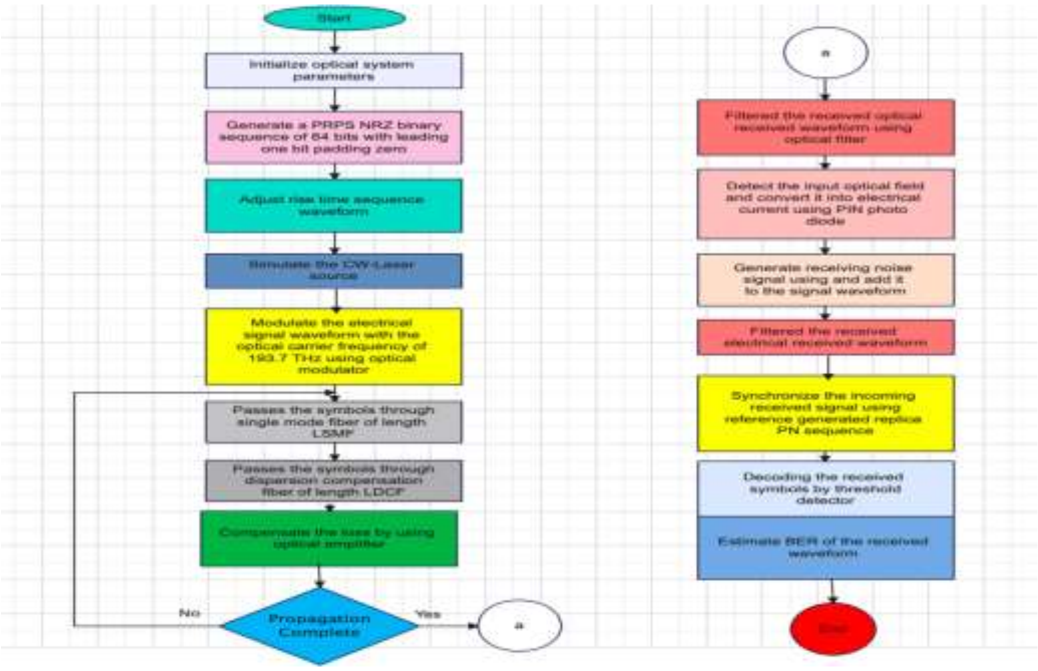

Figure 1 The Flow Chart of the Design (Source: Field Data)

6.1 D-P QPSK Backhauling Block Diagram

The 400 Gbps DP-QPSK backhaul system is modeled as a complete end-to-end block diagram including a high-speed transmitter, realistic fiber channel with impairments, and a coherent receiver with advanced DSP. Using MATLAB/Simulink, the design integrates PRBS generation, DP-QPSK modulation, fiber effects (CD, PMD, nonlinearities, ASE), and DSP compensation (equalization, phase recovery, filtering), enabling accurate performance evaluation for 5G/6G backhaul applications**.**

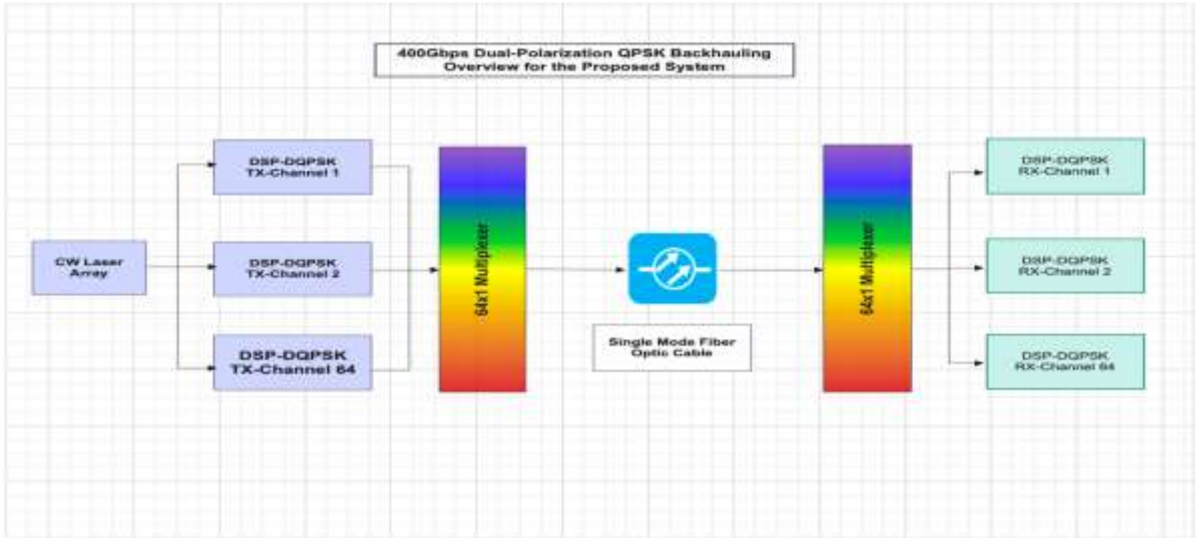

Figure 2 An overarching schematic of the proposed system (Source: Field Data)

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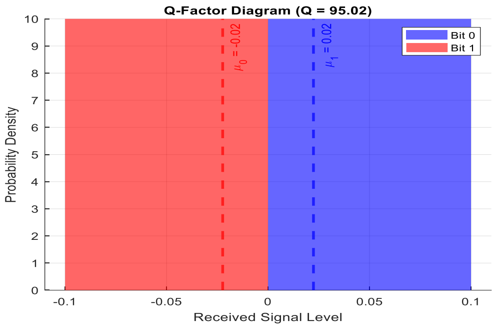
7.1 Simulation

The 64-channel 400 Gbps backhaul system employs DRZ, QPSK, and DP-QPSK modulation over SSMF with EDFA and DCF for dispersion management, while OptiSystem 22 and MATLAB 21 simulations validate performance through demultiplexing, detection, and BER analysis. The system aims for a Q-factor > 92.05 (BER ≤ 10^{-12}) for an ideal 400 Gbps transmission.

7.2 Results

The Q-factor diagram evaluates signal quality by clustering received symbols, where a higher Q indicates lower BER; the system achieves Q > 6, ensuring error-free FEC for 400 Gbps long-haul backhauling, as shown in Figure 3 below.



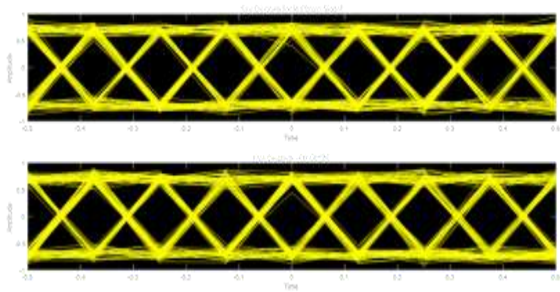
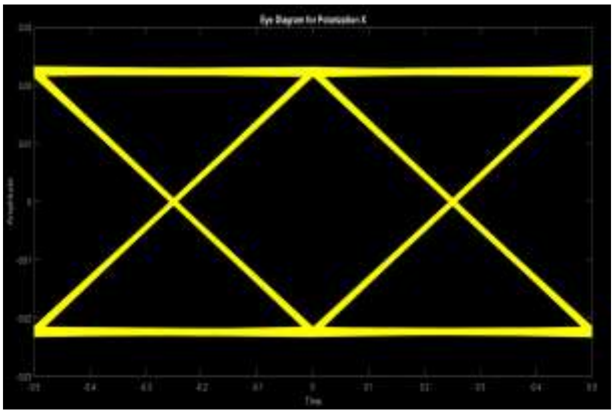


Figure 3(a) The Q-factor diagram (Source: Field Data) Figure 3(b) Eye Diagram with Noise (Source: Field Data)

The eye diagram visualizes signal impairments in 400G DP-QPSK backhauling, showing noise, dispersion, and nonlinear effects, and is used to optimize launch power and predict Q-factor for real-time performance monitoring.

An eye diagram in 400G DP-QPSK backhauling visualizes signal quality by overlapping successive bits, forming an eye-shaped pattern that reveals impairments.



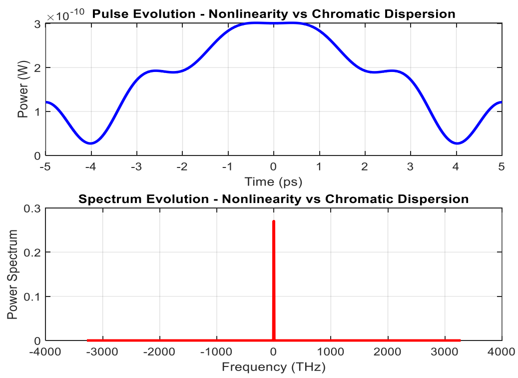


Figure 4(a) Eye Diagram without Noise (Source: Field Data) Figure 4(b) Effect of Pulse Evolution Nonlinearity and Chromatic Dispersion (Source: Field Data)

Chromatic dispersion and fiber nonlinearities (SPM, XPM, FWM) degrade 400G DP-QPSK signals, requiring optimized power, fiber, and DSP, with SSFM simulations guiding system design. The BER vs. SNR graph shows that soft-decision FEC greatly improves 400G DP-QPSK performance, enabling lower OSNR, longer reach, and near error-free transmission.

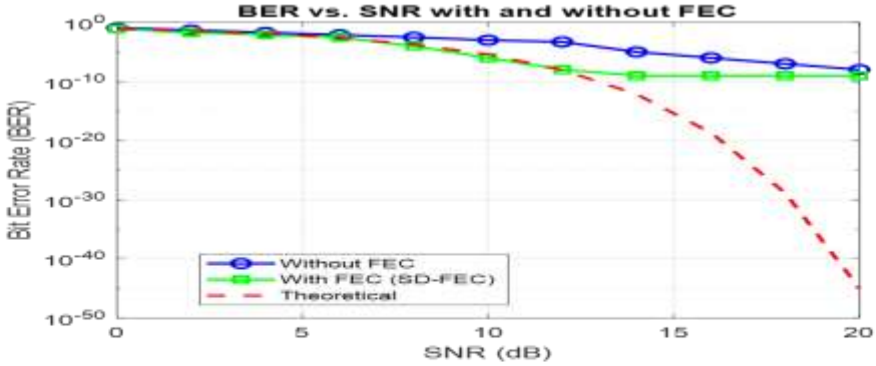


Figure 5 The BER vs SNR with and without FEC (Source: Field Data)

Constellation diagrams reveal how dispersion, nonlinearity, and noise distort DP-QPSK signals, helping optimize equalization, polarization control, and BER performance.

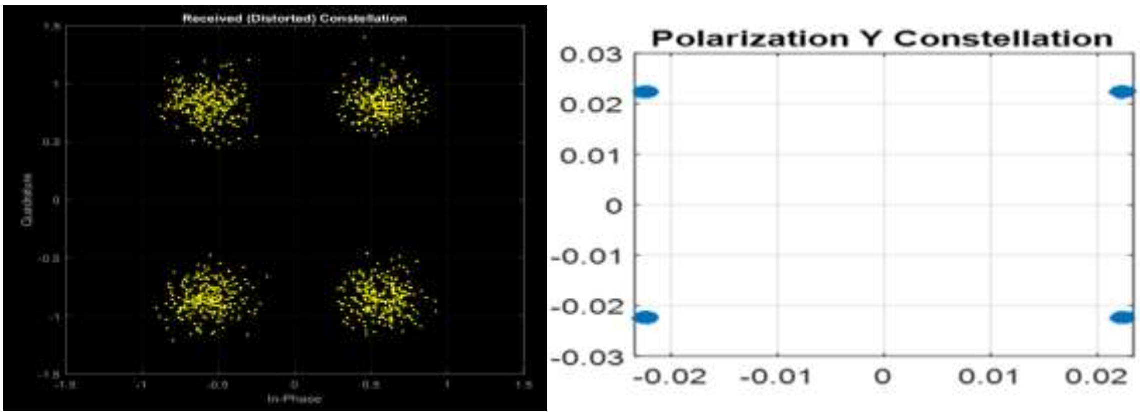
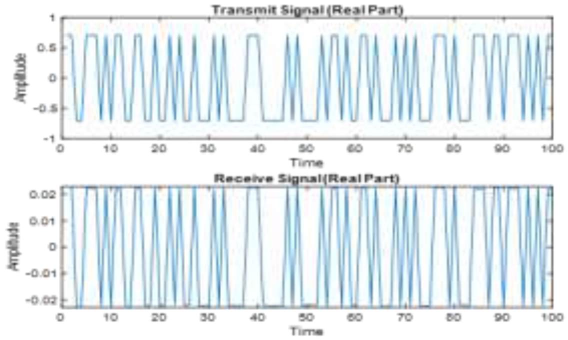


Figure 6 (a) Received Distorted (Source: Field Data) Figure 8(b) Polarisation Constellations (Source: Field Data)

Transmit and receive real-part signal graphs show waveform degradation from fiber impairments, aiding dispersion compensation validation and DSP optimization for reliable DP-QPSK transmission.



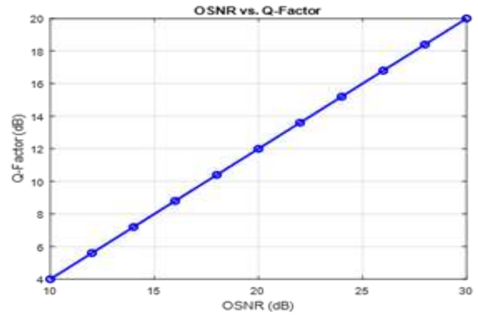
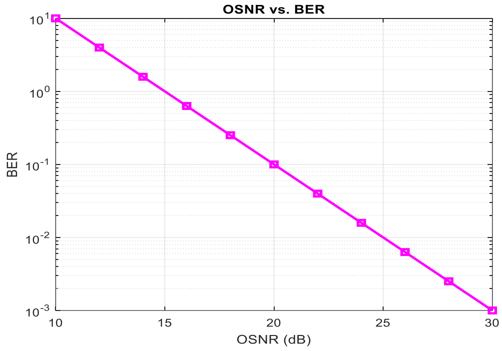


Figure 7(a) The Transmit and Received Signal (Source: Field Data). Figure 7(b) OSNR vs. Q-Factor Analysis (Source: Field Data)

The OSNR vs. Q-Factor graph shows that higher OSNR improves signal quality up to a limit set by nonlinearities, guiding optimal power and amplifier settings in DP-QPSK systems. The OSNR vs. BER graph shows that BER decreases as OSNR increases, but improvements slow beyond a threshold due to fiber nonlinearities. This defines the OSNR needed for acceptable BER and guides system design in high-speed optical networks.



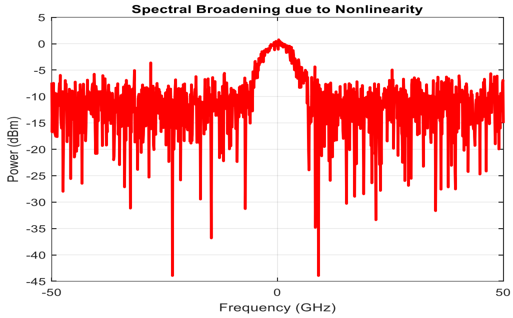
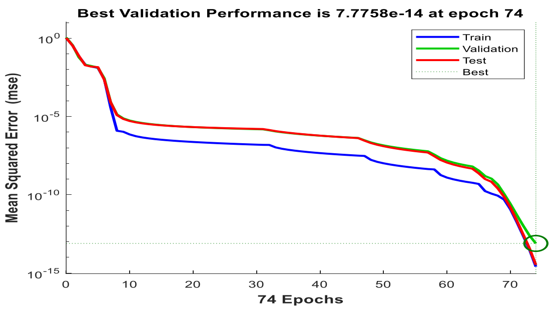


Figure 8(a) OSNR vs. BER Analysis (Source: Field Data) Figure Spectral Broadening (Source: Field Data)

The Spectral Broadening graph shows that higher launch power widens the signal spectrum through nonlinear effects, guiding optimization of power, filters, and spacing for reliable high-capacity transmission. Neural network training in a 400 Gbps DP-QPSK system enhances adaptive equalization and reliability, with the validation performance graph identifying the optimal training point to avoid overfitting and ensure accurate symbol correction.



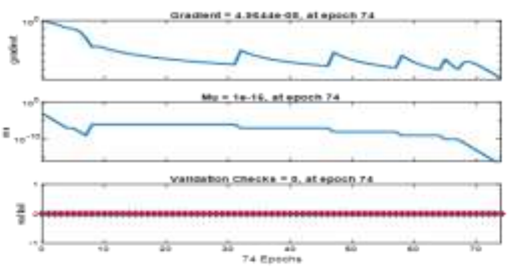


Figure 9(a) NN Best Validation (Source: Field Data) Figure 9(b) Training State graph (Source: Field Data)

The Neural Network Training State and Error Histogram graphs help optimize DP-QPSK system equalizers by ensuring stable convergence and accurate signal recovery, where a well-centered, narrow error distribution indicates low BER, high reliability, and strong system performance.

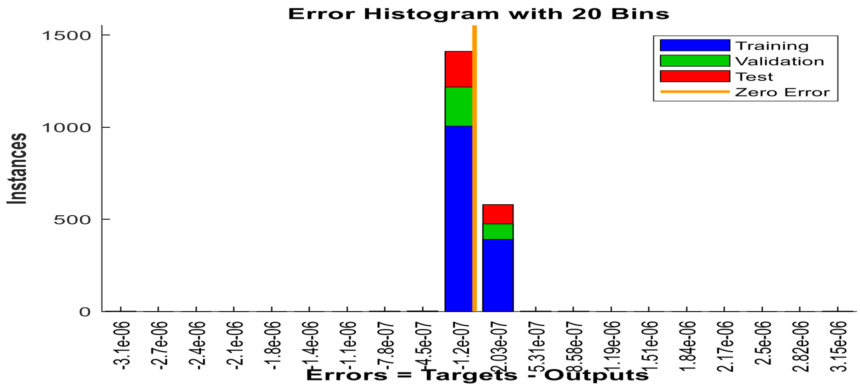


Figure 10 The Neural Network (NN) Error Histogram graph (Source: Field Data)

The NN training regression graph evaluates prediction accuracy, where a well-aligned diagonal line indicates precise signal recovery, reduced BER, and improved reliability in DP-QPSK backhauling systems.

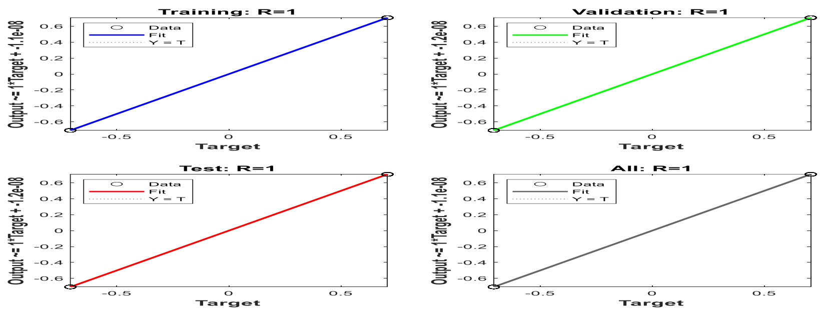


Figure 11 The Neural Network (NN) Regression graph (Source: Field Data)

Monte Carlo simulation graphs for 400 Gbps DP-QPSK systems assess impairments, DSP effectiveness, and design trade-offs, using BER, OSNR, error histograms, constellations, Q-factors, and confidence bands to guide reliable network optimization.

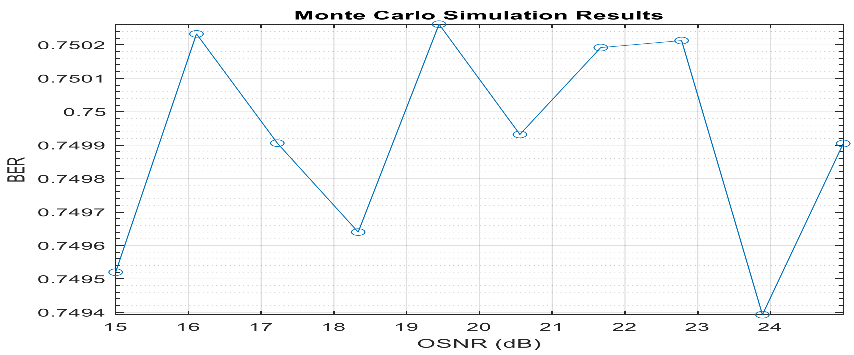


Figure 12 Monte Carlo simulation graphs (Source: Field Data)

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4.2.1 Comparison of Modulation Schemes in the Design

Choosing a modulation scheme in high-speed backhauling balances data rate, noise resilience, and complexity: QPSK offers robust long-haul reliability, while higher-order QAM (16–128) increases capacity but demands higher SNR, stronger error correction, and cleaner channels, making them suitable for shorter or high-quality links.

Table 2: Comparison of various modulation techniques (Source: Field Data)

Modulation	Bits/Symbol	Required SNR (for BER = 1e-3)	Relative Complexity
QPSK	2	~7 dB	Low
16QAM	4	~15 dB	Moderate
32QAM	5	~19 dB	High
64QAM	6	~22 dB	Higher
128QAM	7	~26 dB	Very High

Figures 13(a) and 13(b) show that QPSK ensures robust long-range performance, 16-QAM balances rate and resilience, while higher-order QAM boosts throughput but needs high SNR and advanced correction for short-range links.

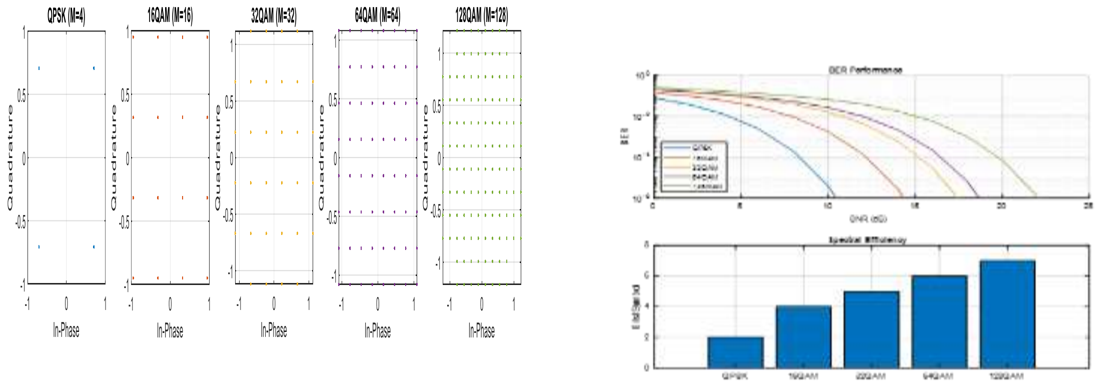

Figure 13(a) Modulation Constellation Graphs (Source: Field Data*)* Figure 13(b) Modulation BER and Spectral Efficiency (Source: Field Data)

Nonlinear effects in 400 Gbps DP-QPSK—SPM, XPM, and FWM—distort pulses, broaden spectra, and cause crosstalk, with visualizations (spectral, time-domain, and constellation plots) highlighting their impact and guiding mitigation through power control, channel spacing, and compensation.

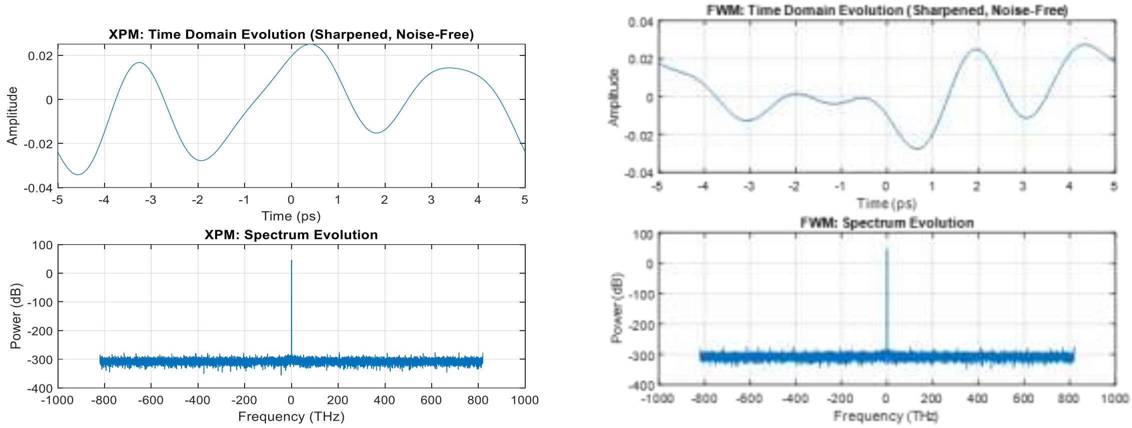

Figure 14(a) XPM Time Domain and Spectrum Evolution (Source: Field Data) Figure 14(b) FWM Time Domain and Spectrum Evolution (Source: Field Data)

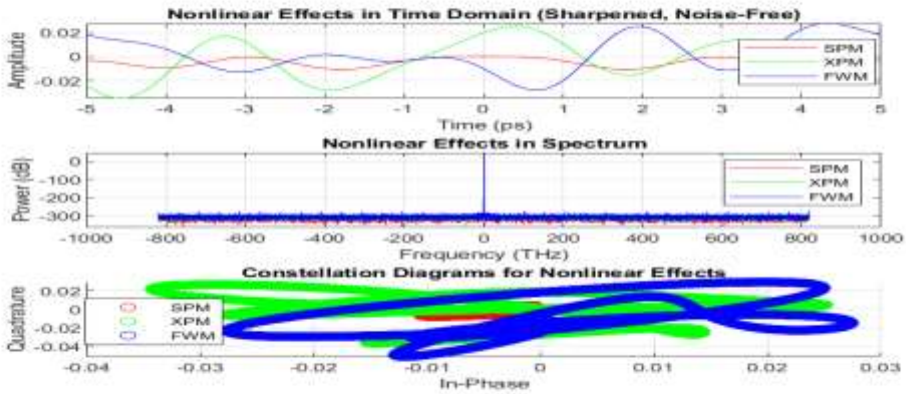

Figure 15 Nonlinear effect in Time Domain, Spectrum, and Constellation Diagram (Source: Field Data)

7.3 Discussions

The design of the 400 Gbps DP-QPSK mobile backhaul system is fundamentally anchored in a set of theoretical equations that provide both physical insight and mathematical precision for system modeling and optimization. Maxwell's equations form the foundation for understanding electromagnetic wave propagation in optical fibers, dictating design decisions related to modulation, polarization management, and light–matter interactions. The nonlinear Schrödinger equation (NLSE) serves as the principal framework for describing nonlinear effects such as self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). These impairments, especially at high launch powers, are mitigated through optimized fiber selection, launch power control, and dispersion management.

To accommodate the dual-polarization nature of the system, Minkov's equation extends these models, while stochastic differential equations (SDEs) capture random perturbations in polarization and birefringence caused by environmental fluctuations. A key innovation in this design is the integration of machine learning (ML) with digital signal processing (DSP). Neural network–augmented models enhance traditional approaches by adaptively compensating for residual nonlinearities and polarization drifts in real time. DSP techniques such as digital backpropagation, polarization demultiplexing, and frequency-domain chromatic dispersion compensation are directly influenced by these mathematical frameworks. Neural equalizers further refine performance by dynamically learning correction strategies under time-varying channel conditions. Real-time power optimization and adaptive channel spacing strategies are also employed to minimize nonlinear penalties such as FWM, while advanced dispersion compensation supported by ML reduces inter-symbol interference. These combined approaches allow reliable, ultrahigh-speed, and power-efficient data transmission at 400 Gbps, even in dense wavelength division multiplexing environments. The overall findings demonstrate that physics-informed modeling, combined with adaptive DSP and ML, ensures robustness, low bit error rates, and high system capacity for next-generation optical backhaul networks.

7.3.1 Findings

The findings of this study are consistent with earlier research that identified the nonlinear Schrödinger equation as the central model for optical transmission and confirmed the importance of digital backpropagation in compensating nonlinear phase distortions. However, this work extends beyond those studies by demonstrating that DBP, when enhanced with neural-network-based correction, achieves superior performance while reducing computational complexity. The observed nonlinear impairments, including SPM, XPM, and FWM, align with prior studies that reported their critical impact on high-capacity links. The present findings corroborate these results but further show that a physics-informed AI approach provides effective real-time mitigation, leading to improved signal integrity and extended reach in 400 Gbps DP-QPSK systems. In the case of dispersion management, previous works emphasized the role of frequency-domain compensation and polarization demultiplexing in coherent systems. The current design validates these techniques while introducing adaptive compensation through ML-assisted equalizers, ensuring improved resilience under varying network conditions. Overall, the present study agrees with foundational research on the significance of nonlinear effects and DSP but diverges from traditional approaches by introducing neural network augmentation and real-time adaptive optimization. This advancement demonstrates a clear progression toward intelligent, high-capacity, and power-efficient optical backhaul networks for 5G and beyond.

7.3.2 Contributions

This study proposes a novel 400 Gbps DP-QPSK optical backhaul system tailored for 5G and 6G networks, distinguished by its integration of real-time environmental modeling, machine learning (ML)-enhanced digital signal processing (DSP), and detailed physical-layer impairment simulation. The design adaptively compensates for dynamic factors such as temperature-dependent attenuation, chromatic dispersion, PMD, and weather effects on fiber and FSO links, ensuring robust operation under diverse conditions. Advanced ML techniques—including deep neural networks for nonlinear equalization, CNNs for distortion recognition, and reinforcement learning for real-time parameter tuning—enable self-optimization under time-varying impairments. Enhanced amplifier noise modeling accounts for inter-stage correlations in EDFA chains, while nonlinear effects like SPM, XPM, and FWM are mitigated through optimized launch power, wavelength spacing, and filtering. Adaptive dispersion management, predictive analytics, and intelligent monitoring (BER, Q-factor, constellation, eye diagrams) further strengthen resilience and fault detection. Additionally, a software-defined backhaul layer supports AI-driven traffic prediction, dynamic routing, and energy-aware power regulation, aligning performance gains with sustainability goals. Collectively, this system offers a scientifically rigorous and practically deployable solution that overcomes limitations of prior research, setting a new benchmark for high-capacity, intelligent, and energy-efficient optical backhaul networks

7.4 Conclusion

This study introduces a 400 Gbps DP-QPSK optical backhaul system for 5G and 6G networks that surpasses earlier research by integrating real-time environmental modeling, machine learning-driven DSP, and comprehensive simulations of nonlinear and noise impairments. Unlike prior works that relied on static fiber models, Gaussian noise assumptions, or fixed DSP structures, this design employs adaptive equalization, predictive analytics, and correlated amplifier noise modeling to achieve more realistic and resilient performance. Neural networks, CNNs, and reinforcement learning enhance nonlinear compensation and adaptive parameter tuning, extending capabilities beyond traditional digital backpropagation and polarization demultiplexing methods. Moreover, while previous studies often neglected dynamic environmental impacts or power optimization, this system incorporates adaptive dispersion control, energy-aware processing, and AI-based backhaul management, aligning with emerging green networking goals. Overall, the findings not only corroborate established theories of fiber nonlinearity and dispersion mitigation but also expand on them by offering a robust, intelligent, and practically deployable framework that sets a new benchmark for high-capacity optical backhaul.

7.4.1 Recommendations

The study recommends adopting real-time impairment modeling, machine learning-based equalization, optimized launch power and wavelength spacing, and AI-driven adaptive compensation to enhance resilience, mitigate nonlinear effects, and ensure reliable high-capacity backhaul performance.

7.4.2 Research Directions

The key research directions are the development of AI-driven real-time impairment compensation, comprehensive physics-based modeling of nonlinear fiber behavior, and field validation of adaptive systems to ensure resilience, scalability, and efficiency in practical deployments.

7.4.3 Acknowledgements

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7.4.4 Conflicts of Interest

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

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