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Impact of Transmission Distance on Signal Quality in Multi-Channel Optical Fiber Networks Using WDM Technologies: A Comparative Performance Analysis of CWDM and DWDM

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Abstract

This paper presents a rigorous comparative evaluation of Coarse Wavelength Division Multiplexing (CWDM) and Dense Wavelength Division Multiplexing (DWDM) in multi-channel optical communication networks. The study systematic evaluates a 16-channel optical fiber infrastructure operating at 10 Gbps per channel under Non-Return-to-Zero (NRZ) modulation over standard single-mode optical fiber (ITU-T G.652) across transmission distances of 10 km, 50 km, 75 km, and 100 km. To strictly isolate the physical mechanics of transmission distance, linear attenuation, and chromatic dispersion, the baseline simulation model intentionally excludes optical amplifiers (EDFA) and dispersion compensation units (DCF). Key signal quality metrics—including Quality Factor (Q-Factor), Minimum Bit Error Rate (Min BER), and Eye Diagram opening—are quantitatively extracted using OptiSystem 7.0 simulation tools. Results demonstrate that CWDM exhibits superior numerical stability in unamplified links, achieving a peak Q-Factor of 80.0 (BER ≈ 0) at 10 km for the central channel (Ch8, 1411 nm), whereas DWDM yields an average Q-Factor of 11.48 (BER = 3.68 × 10^-31). At 75 km, both technologies enter a critical transition phase: CWDM drops to Q = 8.39 (Ch1), while DWDM degrades to Q = 3.46 (BER = 2.70 × 10^-4). At 100 km, DWDM suffers complete eye closure (Q = 0, BER = 1.0) due to severe attenuation and crosstalk noise, while CWDM maintains marginal un-uniform operation (Q = 3.19, BER = 6.30 × 10^-4). Methodological enhancements added in this edition provide explicit theoretical mathematical derivations for physical degradation bounds, compare empirical simulation data with international research standards, and establish a clear engineering deployment matrix.

Keywords: *Optical Communications, Wavelength Division Multiplexing (WDM), CWDM, DWDM, Quality Factor (Q-Factor), Bit Error Rate (BER), Eye Diagram, Chromatic Dispersion, Attenuation Limit, OptiSystem.*

1. Introduction and Theoretical Background

Modern optical fiber communications form the backbone of global telecommunication infrastructures, driven by an unprecedented demand for high-speed data transmission and bandwidth capacity. Wavelength Division Multiplexing (WDM) has emerged as the premier technological architecture, enabling the simultaneous transmission of multiple optical carrier signals over a single optical fiber waveguide by utilizing different optical wavelengths (Agrawal, 2021). The standard single-mode optical fiber (SMF), standardized under ITU-T Recommendation

G.652, serves as the global physical medium, characterized by zero-dispersion near 1310 nm and minimum attenuation (≈ 0.2 dB/km) in the 1550 nm C-band wavelength window.

1.1 WDM Technological Architectures: CWDM vs. DWDM

WDM technology is broadly categorized into two major architectures based on channel spacing and spectral efficiency:

- ***Coarse Wavelength Division Multiplexing (CWDM):*** *Governed by ITU-T Recommendation G.694.2, CWDM employs a wide channel spacing of 20 nm across the spectral range from 1271 nm to 1571 nm (supporting up to 18 channels). The wide channel spacing permits the use of uncooled DFB laser sources and wide-passband optical filters, significantly reducing thermal management requirements and system complexity (BlueOptics, 2024).*
- ***Dense Wavelength Division Multiplexing (DWDM):*** *Governed by ITU-T Recommendation G.694.1, DWDM utilizes a dense spectral grid with narrow channel spacings of 100 GHz (~0.8 nm) or 50 GHz (~0.4 nm) within the C-band (193.1 THz to 194.6 THz). While DWDM achieves massive spectral efficiency and multi-Terabit transmission capacity, it requires precision-thermostatted lasers and tight optical filter alignment to mitigate adjacent channel crosstalk (Kaeib et al., 2024).*

1.2 Physical Degradation Mechanisms & Theoretical Equations [Phase 1 Methodological Addition]

To establish rigorous scientific foundations, the mathematical expressions governing optical signal degradation during fiber propagation are explicitly formulated as follows:

1. Linear Attenuation Model: *The optical power received at distance L (km) decreases exponentially due to absorption and Rayleigh scattering, expressed in decibels as:*

$$P_{rx}\,(dBm) = P_{tx}\,(dBm) - \alpha \cdot L$$

where α represents the fiber attenuation coefficient (fixed at 0.2 dB/km in this study), and P_tx is the initial launch power (-3 dBm).

2. Chromatic Dispersion & Temporal Pulse Broadening: *The pulse spreading Δt caused by group velocity dispersion across fiber length L is given by:*

$$\Delta t = D \cdot \Delta\lambda \cdot L$$

where D is the chromatic dispersion coefficient (16.75 ps/nm/km for G.652 SMF at 1550 nm), and Δλ is the spectral width of the optical source. At a bit rate of 10 Gbps (bit period T_b = 100 ps), pulse broadening exceeding T_b / 2 induces severe Inter-Symbol Interference (ISI).

3. Mathematical Link Between Q-Factor and Bit Error Rate (BER): *The Quality Factor (Q-Factor) quantifies the electrical signal-to-noise ratio (SNR) at the optical receiver decision circuit:*

$$Q = (\mu_1 - \mu_0) / (\sigma_1 + \sigma_0)$$

where μ_1 and μ_0 are the mean signal levels for logic '1' and '0', and σ_1, σ_0 represent the noise standard deviations. The Minimum BER is mathematically linked to the Q-Factor via the complementary error function (erfc):

$$BER = 0.5 \cdot erfc(Q / \sqrt{2}) \approx (1 / (Q \sqrt{(2\pi)})) \cdot exp(-Q^2 / 2)$$

A standard telecommunication reliability threshold of BER ≤ 10^-9 corresponds to a minimum Q-Factor threshold of Q ≥ 6.0.

2. Research Methodology and System Architecture

This study adopts a controlled comparative simulation methodology executed in OptiSystem 7.0. The primary design objective is the controlled isolation of transmission distance (L = 10, 50, 75, 100 km) and multiplexing technique (CWDM vs. DWDM). All other system parameters are strictly held constant to eliminate confounding variables.

2.1 Global Simulation Setup and Fixed Parameters

Table 1 outlines the global parameters held constant across all eight simulation scenarios:

Parameter Name	***Value / Unit***	***Methodological Purpose***
Bit Rate (Per Channel)	*10 Gbps*	*Standard high-speed transmission rate; high sensitivity to dispersion*
Channel Count	*16 Channels*	*Provides representative optical spectrum loading*
Modulation Format	*NRZ (Non-Return-to-Zero)*	*Standard intensity modulation format*
Laser Transmit Power	*-3 dBm per channel*	*Fixed input launch power*
Optical Fiber Type	*SMF (ITU-T G.652)*	*Standard single-mode fiber waveguide*
Fiber Attenuation (α)	*0.2 dB/km*	*Fixed linear power loss coefficient*
Chromatic Dispersion (D)	*16.75 ps/nm/km*	*Fixed group velocity dispersion at C-band*
Sequence Length	*128 bits*	*Standard random binary sequence length*
Samples per Bit	*64*	*High resolution for eye diagram and BER calculation*
Optical Amplification / DCF	*Disabled (Unamplified)*	*Controlled isolation of pure distance physical effects*

Note. *Table 1 summarizes the baseline simulation parameters verified prior to running all 8 scenarios in OptiSystem 7.0.*

2.2 Spectral Allocation and Representative Sample Channels

To provide thorough spectral analysis without unnecessary data duplication, three key representative channels are evaluated across the 16-channel band:

- ***Channel 1 (Ch1):*** *Represents the lower band edge (1271 nm in CWDM; 193.1 THz in DWDM).*
- ***Channel 8 (Ch8):*** *Represents the central band region (1411 nm in CWDM; 193.8 THz in DWDM).*
- ***Channel 16 (Ch16):*** *Represents the upper band edge (1571 nm in CWDM; 194.6 THz in DWDM).*

3. Results and Quantitative Comparative Analysis

Simulation outputs were recorded using the OptiSystem BER Analyzer tool across eight distinct scenarios (S1–S8) covering transmission distances of 10 km, 50 km, 75 km, and 100 km for both CWDM and DWDM configurations.

3.1 CWDM System Performance Across Transmission Distances

Table 2 summarizes the measured Q-Factor, Minimum BER, Eye Height, and Eye Status for the representative CWDM channels:

Distance	***Channel***	***Q-Factor***	***Min BER***	***Eye Height (a.u.)***	***Eye Diagram Status***
10 km	*Ch1 (1271 nm)*	*41.13*	*0.00 (< 10^-50)*	*4.63 × 10^-4*	*Fully Open & Clear*
10 km	*Ch8 (1411 nm)*	*80.00*	*0.00 (< 10^-50)*	*5.10 × 10^-4*	*Optimal Eye Opening*
10 km	*Ch16 (1571 nm)*	*43.12*	*0.00 (< 10^-50)*	*4.71 × 10^-4*	*Fully Open & Clear*
50 km	*Ch1*	*11.37*	*2.94 × 10^-30*	*3.67 × 10^-4*	*Open (Slight Jitter)*
50 km	*Ch8*	*36.12*	*1.12 × 10^-45*	*4.15 × 10^-4*	*Open & Stable*
50 km	*Ch16*	*12.05*	*1.05 × 10^-33*	*3.72 × 10^-4*	*Open (Slight Jitter)*
75 km	*Ch1*	*8.39*	*2.34 × 10^-17*	*2.76 × 10^-4*	*Partially Constricted*
75 km	*Ch8*	*19.51*	*4.21 × 10^-28*	*3.20 × 10^-4*	*Open & Acceptable*
75 km	*Ch16*	*8.82*	*5.12 × 10^-19*	*2.81 × 10^-4*	*Partially Constricted*
100 km	*Ch1*	*3.19*	*6.30 × 10^-4*	*2.95 × 10^-5*	*Severely Constricted*
100 km	*Ch8*	*13.82*	*1.02 × 10^-22*	*2.10 × 10^-4*	*Moderately Open*
100 km	*Ch16*	*3.41*	*3.25 × 10^-4*	*3.12 × 10^-5*	*Severely Constricted*

3.2 DWDM System Performance Across Transmission Distances

Table 3 summarizes the measured Q-Factor, Minimum BER, Eye Height, and Eye Status for the representative DWDM channels:

Distance	***Channel***	***Q-Factor***	***Min BER***	***Eye Height (a.u.)***	***Eye Diagram Status***
10 km	*Ch1 (193.1 THz)*	*11.53*	*3.68 × 10^-31*	*2.09 × 10^-4*	*Open & Highly Uniform*
10 km	*Ch8 (193.8 THz)*	*11.48*	*4.12 × 10^-31*	*2.08 × 10^-4*	*Open & Highly Uniform*
10 km	*Ch16 (194.6 THz)*	*11.42*	*5.01 × 10^-31*	*2.06 × 10^-4*	*Open & Highly Uniform*
50 km	*Ch1*	*7.61*	*1.33 × 10^-14*	*2.59 × 10^-5*	*Open (Degraded SNR)*
50 km	*Ch8*	*7.55*	*1.82 × 10^-14*	*2.55 × 10^-5*	*Open (Degraded SNR)*
50 km	*Ch16*	*7.48*	*2.11 × 10^-14*	*2.51 × 10^-5*	*Open (Degraded SNR)*
75 km	*Ch1*	*3.46*	*2.70 × 10^-4*	*1.65 × 10^-6*	*Critical / Near-Closure*
75 km	*Ch8*	*3.41*	*3.12 × 10^-4*	*1.60 × 10^-6*	*Critical / Near-Closure*
75 km	*Ch16*	*3.35*	*4.01 × 10^-4*	*1.52 × 10^-6*	*Critical / Near-Closure*
100 km	*Ch1*	*0.00*	*1.00*	*0.00*	*Complete Eye Closure*
100 km	*Ch8*	*0.00*	*1.00*	*0.00*	*Complete Eye Closure*
100 km	*Ch16*	*0.00*	*1.00*	*0.00*	*Complete Eye Closure*

3.3 Comparative Average Q-Factor Summary

Table 4 presents a comparative breakdown of average Q-Factor values across all distances:

Distance	***CWDM Average Q***	***DWDM Average Q***	***Numerical Difference***	***Engineering Assessment***
10 km	*54.75 (Peak Ch8: 80.0)*	*11.48 (Highly Uniform)*	*+43.27 (CWDM higher)*	*CWDM excels in short unamplified links*
50 km	*19.85 (Peak Ch8: 36.12)*	*7.55 (Uniform)*	*+12.30 (CWDM higher)*	*Both operate reliably above Q=6 threshold*
75 km	*12.24 (Ch8: 19.51)*	*3.41 (Sub-threshold)*	*+8.83 (CWDM higher)*	*DWDM requires EDFA amplfication*
100 km	*6.81 (Ch8: 13.82)*	*0.00 (Total Breakdown)*	*DWDM Failure*	*DWDM completely collapses without active support*

4. Discussion and Engineering Interpretation

4.1 Physical Explanation of CWDM Superiority in Unamplified Links

The numerical superiority of CWDM in the unamplified simulation model stems directly from its wide 20 nm channel spacing. This wide spectral separation virtually eliminates inter-channel crosstalk and linear filter passband distortion. Furthermore, the central channel (Ch8 at 1411 nm) benefits from an optimal trade-off: it avoids the higher attenuation near the E-band water-peak regions while experiencing lower cumulative dispersion than channels located further up at 1571 nm.

4.2 Mechanics of DWDM Complete Breakdown at 100 km

At 100 km, cumulative fiber loss reaches 20 dB (100 km × 0.2 dB/km). In a 100 GHz DWDM grid, receiver power falls close to the PIN photodiode thermal noise floor. Because the channels are densely spaced (~0.8 nm), small amounts of dispersion-induced temporal broadening cause

optical power to overlap into adjacent channel time slots and frequency passbands, triggering severe Inter-Symbol Interference (ISI) and inter-channel crosstalk. Without Erbium-Doped Fiber Amplifiers (EDFA) and Dispersion Compensating Fiber (DCF), the SNR drops below the receiver decision threshold, resulting in complete eye closure (Q = 0, BER = 1.0).

4.3 Comparison with Published Literature [Phase 1 Methodological Benchmark]

The empirical findings of this research align precisely with established optical telecommunications literature:

- ***Kaeib et al. (2024):*** *Demonstrated in 'Al-Mukhtar Journal of Engineering Research' that uncompensated DWDM systems undergo severe performance degradation beyond 50 km, confirming that symmetric dispersion compensation and inline EDFA amplification are mandatory for long-haul DWDM.*
- ***Ivaniga & Ivaniga (2019):*** *Proved in the 'Journal of Engineering Science and Technology' that inline placement of EDFA amplifiers is the key determinant for maintaining BER < 10^-9 in DWDM systems operating across long transmission distances.*
- ***Middle Technical University (2024):*** *Published in 'Journal of Techniques' that 10 Gbps and 40 Gbps DWDM links require active laser power management (0 to 5 dBm) and DCF modules to achieve link distances of 240–300 km without signal collapse.*

5. Engineering Applications and Deployment Matrix

Based on the quantitative findings, an engineering deployment matrix is established to guide optical network planners:

1. Short-Haul & Metro Access (< 50 km): *CWDM is the optimal selection. It provides excellent signal quality (Q > 36), lower capital expenditure (CAPEX) due to uncooled lasers, and operational simplicity without optical amplifiers.*

2. Medium-Range Metropolitan Links (50–75 km): *CWDM remains feasible without amplification (Q = 12.24). DWDM can be deployed if high channel density is required, but requires precise OSNR monitoring and inline amplification near 75 km.*

3. Long-Haul Core Backbones (> 75 km to 100+ km): *DWDM is the mandatory technological choice, provided that inline EDFA amplifiers and DCF modules are integrated. Unamplified deployment at 100 km is unviable.*

6. Conclusion and Future Research Directions

This study rigorously quantified the impact of transmission distance on signal quality in multi-channel CWDM and DWDM systems. The primary conclusions are:

- ***1. Distance Control:*** *Transmission distance is the decisive physical governor of signal degradation in unamplified WDM links.*
- ***2. CWDM Robustness:*** *CWDM demonstrates high immunity to linear attenuation up to 75 km due to its 20 nm wide channel spacing.*
- ***3. DWDM Amplification Requirement:*** *DWDM collapses completely at 100 km in unamplified links (Q = 0, BER = 1.0), establishing that DWDM is an architecture inherently dependent on active optical amplification and dispersion compensation.*

6.1 Future Work Recommendations

Future research will explore hybrid EDFA-Raman optical amplification, advanced phase-shift keying modulation (DP-QPSK, 16-QAM), and Flex-Grid dynamic spectrum allocation to extend DWDM link distances beyond 200 km.

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