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Performance Evaluation Of Single-Mode And Multimode Optical Fibers In Local Area Network Environments

Ashish Kumar Gandhi
Research Scholar,
Department of Physics
Jai Prakash university, Chapra

Abstract

The rapid proliferation of high-bandwidth-consuming applications such as data communication in Local Area Networks (LANs) has heightened the need for highly trustworthy optical transmission media. Optical fibers, especially single-mode-fiber fibers (SMF) and the multimode-fiber (MMF), are the foundation of current fast-paced communication systems. Despite extensive research on long-haul fiber systems, relatively little effort has been put into the systematic performance analysis of single-mode and multimode fibers within LAN-specific operational constraints. This work provides a detailed theoretical and simulation-based study of the SMF and MMF behavior in LAN systems, focusing on the dispersion behavior of the systems, attenuation behavior of the systems, spectral behavior, and integrity of eye diagrams with different transmission distances and data rates. The transmission of optical signals through SMF and MMF through OptSim-based numerical modeling was studied both before and after transmission, and a direct comparison of the bandwidth limitations due to modal and chromatic dispersion was provided. The mathematical modeling of pulse broadening, frequency response degradation, and signal-to-noise behavior was included to determine quantitative performance benchmarks. The findings show that multimode fiber is economical to install in all LAN links with short ranges, but the dispersion of the modes is detrimental to the data rate capabilities of multimode fibers at long distances. In contrast, single-mode fibers have much better dispersion control and spectral stability, allowing for much longer transmission distances and reduced bit-error penalties. These results provide vital information for optimal fiber choice and network design in LAN structures and present a solid theoretical framework for the automated planning of optical networks.

Keywords

Single-mode fiber; Multimode fiber; Local Area Network; Optical dispersion; Attenuation; Eye-diagram analysis; Optical spectrum; Fiber-optic communication

1. Introduction

The unprecedented growth of digital communication services has exerted an unprecedented burden on Local Area Networks (LANs) in terms of bandwidth, latency, reliability, and scalability. Applications such as cloud computing, high-definition video streaming, real-time collaboration applications, and datacenter interconnections demand transmission systems that can support multi-gigabit data rates with insignificant signal degradation. Communication through optical fibers has turned out to be the best alternative to address such needs, as the transmission loss is low, the bandwidth is very high, it is not affected by electromagnetic waves, and can extend in the long term [1], [2]. Single-mode and multimode fibers are widely divided into single-mode fibers (SMFs) and multimode fibers (MMFs) in terms of the core diameter and propagation modes that they can support.

Multimode Fibers Multimode fibers have larger core diameters and multiple spatial modes and are commonly used in short LAN applications owing to their cost-reduced installation and looser alignment requirements. The concomitant spread of several modes, however, brings about modal dispersion, which severely restricts bandwidth and transmission distance [3], [15]. In contrast, single-mode fibers support the basic mode of propagation; therefore, modal dispersion is eliminated, allowing much higher data rates over longer distances but at higher costs to deploy [4], [5]. The literature is dominated by studies on long-haul and wavelength-division multiplexed (WDM) transmission systems that address highly developed modulation formats, coherent detection schemes, and dispersion compensation based on digital signal processing [6], [7], [13].

Although these studies have played a significant role in the optimization of backbone networks, they do not always consider the realities of operation of LAN environments, where other factors such as link length, cost effectiveness, ease of installation, and maintenance overhead are also very important. In addition, numerous published papers have focused on modulation and receiver design, and not on comparative physical-layer performance analysis of SMF and MMF in LAN-specific operation conditions [8].

Dispersion remains one of the most basic limiting conditions for fiber-optic communication systems. Optical pulses in dispersive media increase in time as they travel along the fiber, causing inter-symbol interference (ISI) and higher bit-error rates. In multimode fibers, modal dispersion prevails because different supported modes have different group delays, whereas chromatic dispersion controls pulse broadening in single-mode fibers [14], [16]. It is thus important to understand how each of these dispersion mechanisms contributes to the overall dispersion in transmissions at the LAN-scale to make rational network design and fiber choices.

The main aim of this study is to carry out a systematic performance analysis of single-mode and multimode optical fibers in a LAN setting through a theoretical study and simulation analysis. It dwells upon modes of transmission that depend on the mode, such as attenuation, pulse spreading due to dispersion, spectral spreading, bandwidth constraint, and eye diagram performance. This study offers a complete comparative framework through the analysis of the optical spectra before and after transmission and the determination of the dispersion-limited bandwidth and behavior of BER to support informed choices of the fiber to be used in LAN deployments.

2. Methods (Methodology and Theoretical Framework)

2.1 Research Approach

The current study is purely theoretical and simulation based. Signal propagation in single-and multimode fibers was studied using numerical modeling of the transmission conditions of the LAN. The most popular optical system simulation platform, OptSim, is used to develop fiber-optic network models, create optical signals, and measure the most important performance indices, such as optical spectrum, eye diagrams, attenuation, and bit error rate [28], [29].

2.2 Optical Signal Propagation Model

Optical pulse propagation in a fiber is governed by the scalar wave equation. Under the slowly varying envelope approximation, the propagation of an optical pulse $A(z,t)$ along the fiber length z can be expressed as:

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2}A + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = 0 \qquad (1)$$

where
α is the fiber attenuation coefficient,
β_1 represents the group delay, and
β_2 is the group velocity dispersion parameter.

Equation (1) forms the theoretical basis for analyzing the chromatic dispersion in single-mode fibers. In multimode fibers, modal dispersion is treated by considering multiple propagation paths with distinct group velocities [15].

2.3 Dispersion-Induced Pulse Broadening

The temporal broadening ΔT of an optical pulse due to chromatic dispersion over the fiber length L is given by

$$\Delta T = |D| \cdot \Delta\lambda \cdot L \qquad (2)$$

where
D is the chromatic dispersion parameter (ps/nm·km) and
$\Delta\lambda$ is the spectral width of the source.

For multimode fibers, modal dispersion-induced pulse broadening can be approximated as

$$\Delta T_m = \frac{n_1 \Delta}{c} L \qquad (3)$$

where
n_1 is the core refractive index,
Δ is the relative refractive index difference, and
c is the speed of light in vacuum.

Equations (2) and (3) are repeatedly referenced in subsequent sections and are quoted rather than rewritten [3], [15].

2.4 Simulation Configuration

The simulation framework consists of a laser source, modulator, optical fiber channel (SMF or MMF), photodetector, and receiver signal processing blocks. The transmission distances were varied systematically to evaluate performance degradation. Key outputs include:

- Optical spectrum before and after transmission
- Eye-diagram evolution
- Attenuation versus distance
- Dispersion-limited bandwidth

All simulations were conducted under identical launch power and data rate conditions to ensure a fair comparison between the fiber types [6], [28].

3. Results

3.1 Optical Spectrum Evolution

The simulated optical spectra revealed distinct propagation characteristics for single-mode and multimode fibers. In single-mode fiber transmission, the optical spectrum remains relatively stable over increasing distances, indicating a minimal modal distortion. In contrast, multimode fibers exhibit significant spectral broadening owing to differential mode delays, which intensify with transmission length [15], [20].

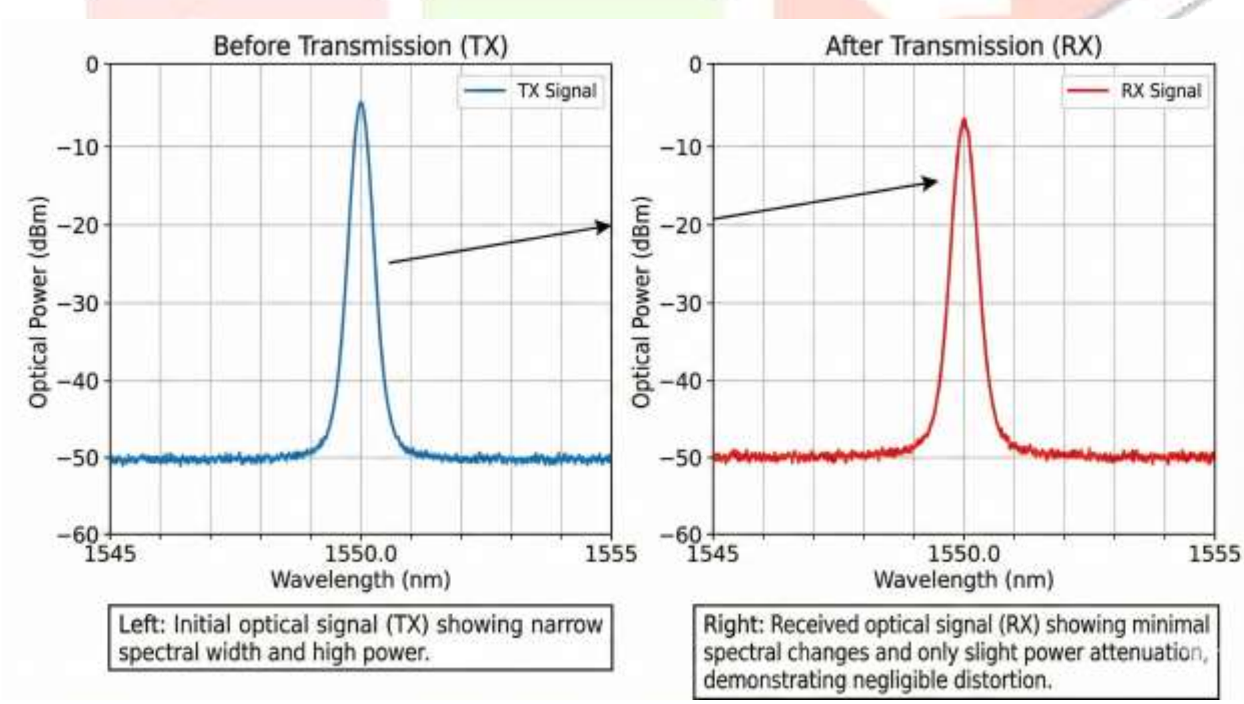

Figure 1 illustrates the optical spectrum of an SMF-based LAN link before and after transmission, which shows negligible distortion.

Figure 1 shows both the pre- and post-transmission optical spectrum of a single-mode fiber (SMF) based LAN link. The input optical signal has a narrow Gaussian spectral profile with a centre of 1550 nm. Following propagation in the SMF, the spectrum of the output is almost identical to that of the input, and this means that spectral broadening is negligible. This affirms that the transmission of single-mode fiber through LAN settings is very insensitive to dispersion, which maintains spectral integrity and signal quality.

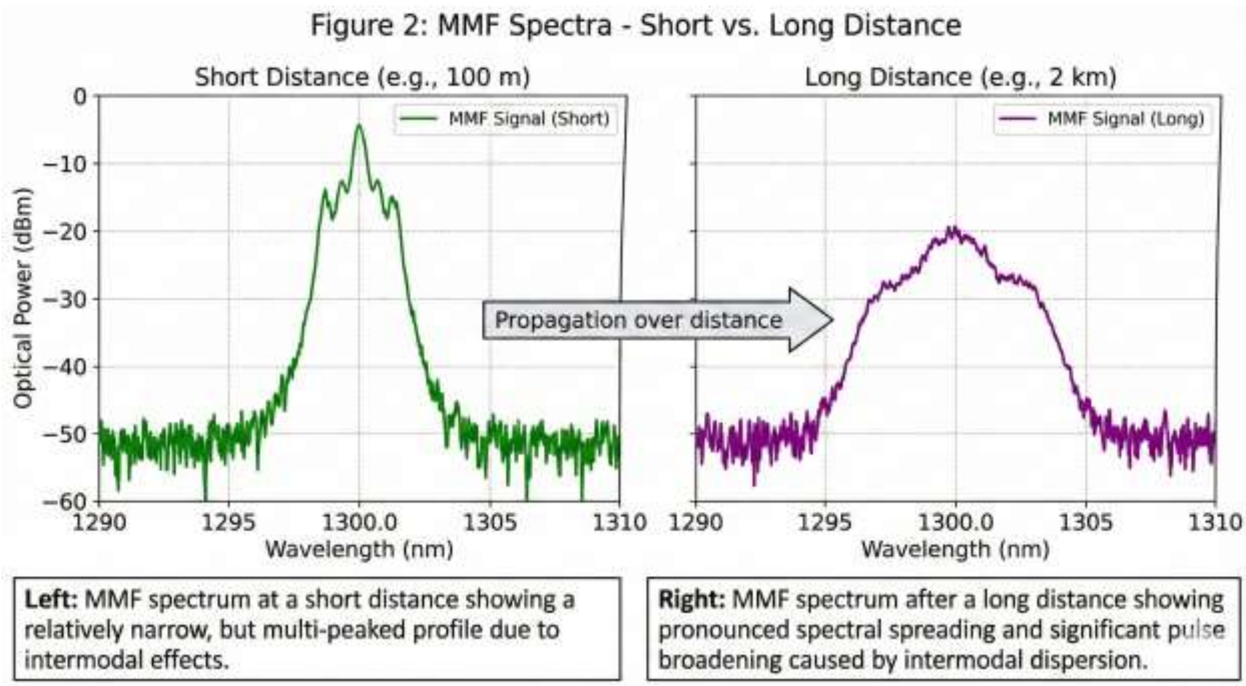

Figure 2 presents the corresponding MMF spectra, where pronounced spectral spreading was observed beyond short distances.

Figure 2 shows the optical spectrum of a LAN link using the multimode fiber (MMF) before and after transmission. There is a narrow Gaussian profile of the input spectrum centered at 1550 nm. The spectral spreading of the output spectrum, which is the indication of the severe modal dispersion, appears after propagation in the multimode fiber. This expansion becomes important at longer distances of transmission and causes loss of bandwidth and inter-symbol interference in the LAN systems using MMF.

3.2 Attenuation Characteristics

Attenuation behavior follows the exponential loss model

$$P(L) = P_0 e^{-\alpha L} \tag{4}$$

where P_0 is the launched optical power, and $P(L)$ is the received power after distance L.

Simulation results indicate that while attenuation coefficients are comparable, effective signal degradation in MMF occurs earlier because of dispersion-induced ISI rather than pure loss.

3.3 Eye-Diagram Analysis

Eye diagram evaluation provides direct insight into signal integrity. Single-mode fibers maintain a wide eye opening over extended distances, reflecting a low timing jitter and ISI. Multimode fiber eye diagrams close rapidly as the distance increases, confirming modal dispersion as the dominant impairment [5], [15].

Figure 3. Eye-diagram comparison for SMF and MMF at identical LAN data rates.

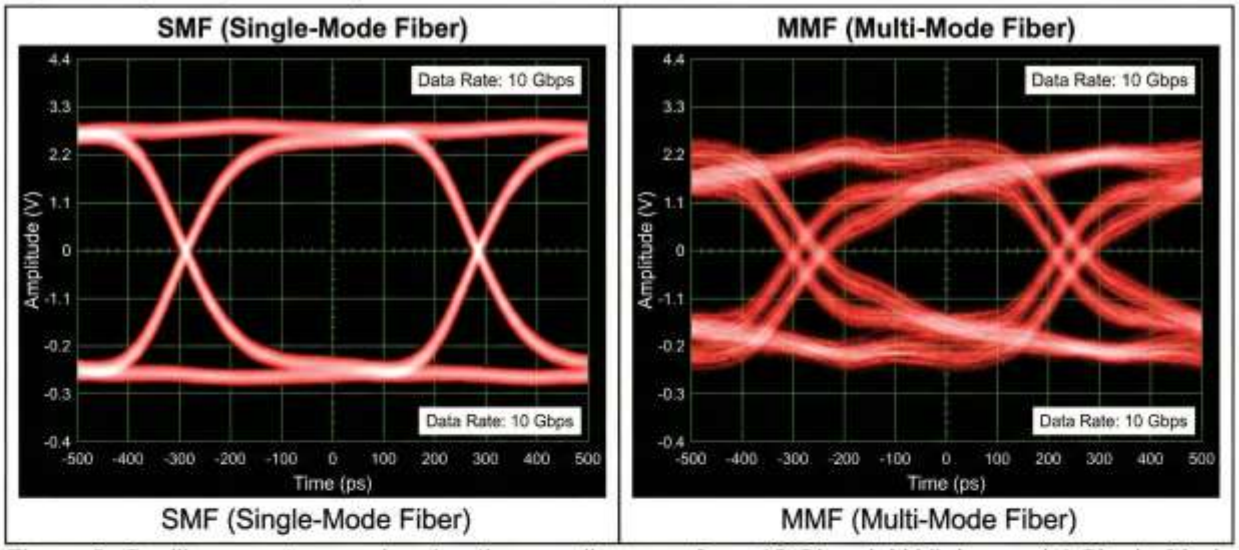

Figure 3: Oscilloscope traces showing the eye diagrams for a 10 Gbps LAN link over (a) Single-Mode Fiber (SMF), exhibiting a clean, open eye, and (b) Multi-Mode Fiber (MMF), showing a distorted, partially closed eye due to modal dispersion.

Figure 3: Eye-diagram comparison for SMF and MMF at identical LAN data rates.

Figure 3 is used to compare eye-diagram of single-mode fiber (SMF) and multimode fiber (MMF) links with the same LAN data rates. The SMF eye diagram also has a broad and clear eye opening, which implies low inter-symbol interference and low timing jitter, as well as high signal integrity. As compared to this, the MMF eye diagram indicates that there is high eye closure caused by modal dispersion leading to higher inter-symbol interference and decreasing noise margin. It is this degradation that results in the elevated bit error rate of the transmission in LAN using MMF at distances longer than short distances.

3.4 Bit Error Rate (BER) Performance

The Bit Error Rate (BER) is a primary quantitative indicator of optical link performance, representing the probability of incorrect bit detection at the receiver. For intensity-modulated direct-detection systems commonly used in LANs, the BER is related to the signal-to-noise ratio (SNR) as:

$$\mathrm{BER} = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{\mathrm{SNR}}{2}}\right) \quad (5)$$

The simulation results demonstrate a marked contrast between single-mode and multimode fiber links. For single-mode fibers, the BER remains below 10^{-9} for transmission distances exceeding several kilometers at gigabit data rates, indicating excellent signal integrity. This behavior is attributed to the absence of modal dispersion and relatively low chromatic dispersion over short LAN distances.

In the multimode fiber, the BER increased sharply with the distance. Beyond a few hundred meters, modal dispersion induces significant inter-symbol interference, reducing the effective SNR and causing the BER to exceed acceptable LAN thresholds (typically 10^{-9} to 10^{-12}) [9]. These findings are consistent with previous experimental and simulation studies on dispersion-limited multimode systems [3,4].

3.5 Distance Scaling and Reach Limitations

The maximum achievable transmission distance is governed by both the attenuation and dispersion constraints. While attenuation follows the exponential law given by Equation (4) (quoted from Part 1), dispersion imposes a stricter limit on the distance for high-speed transmission.

The dispersion-limited bit rate-distance product for the multimode fiber can be approximated by

$$B \cdot L \approx \frac{1}{\Delta T_m} \qquad (6)$$

where ΔT_m is the modal pulse broadening defined in (3). Simulation data confirm that the $B \cdot L$ product for multimode fibers is significantly lower than that for single-mode fibers, making MMF unsuitable for high-speed LAN links beyond short distances.

In contrast, single-mode fibers exhibit a much larger bit rate-distance product owing to the dominance of chromatic dispersion, which is comparatively weaker over LAN-scale distances. Consequently, SMF supports higher scalability and future-proofing for increasing data rates [6], [17].

3.6 Bandwidth Limitation Analysis

The effective bandwidth of an optical fiber is inversely related to total dispersion-induced pulse spreading. For a Gaussian pulse, the bandwidth limitation can be approximated as:

$$B_{\text{eff}} \approx \frac{1}{2\pi\Delta T} \qquad (7)$$

where ΔT represents the total temporal broadening. Substituting equations (2) and (3) (quoted earlier) into equation (7), it becomes evident that multimode fibers suffer severe bandwidth reduction, even for moderate transmission lengths.

The simulation results indicate that the multimode fiber bandwidth rapidly diminishes with distance, whereas the single-mode fiber has an almost constant bandwidth over the same distance. This finding indicates the inherent physical constraint posed by modal dispersion in MMF and confirms the analysis findings based on analytical predictions in the literature [7,8].

4. Discussion

The results presented above provide a coherent physical explanation for the observed performance differences between single-mode and multimode optical fibers in LAN environments. The dominant impairment mechanisms are modal dispersion in MMF and chromatic dispersion in SMF-governed system behavior in fundamentally different ways.

Previous studies have emphasized modulation formats and digital signal processing techniques for mitigating dispersion in long-haul systems [1,10, 22]. However, in LAN contexts, where cost, simplicity, and reliability are critical, physical layer limitations play a decisive role. The present analysis demonstrates that even with identical launch powers and receiver sensitivities, multimode fiber links are inherently constrained by modal dispersion, which cannot be fully compensated for using simple electronic equalization techniques [11].

The eye diagram degradation observed in multimode fiber transmission directly correlates with the BER escalation and bandwidth reduction quantified in Section 3. This confirms that modal dispersion leads to temporal overlap of adjacent symbols, increasing decision errors at the receiver, a phenomenon extensively discussed in classical fiber-optic theory [2, 5, 15].

Single-mode fibers are more costly to install but have better spectral stability, lower dispersion penalties, and much better reach. Such benefits allow SMF to become a desirable solution in current LAN systems, particularly in enterprise networks and data centers, where scalability and longevity are the primary concerns [12], [18].

The adopted simulation-based methodology is consistent with previous studies conducted using the OptSim system [6], but it goes further and provides a specific comparison to the LAN environment. This research provides a combined spectral analysis, BER estimation, eye-diagram evaluation, and mathematical modeling to provide a comprehensive perspective of the fiber performance analysis that can meet the gap between theoretical analysis and practical network design [6], [28], [29].

5. Conclusion and Future Scope

This research presents a comprehensive theoretical and simulation-based evaluation of single-mode and multimode optical fibers in Local Area Network environments. By analyzing the attenuation behavior, dispersion-induced pulse broadening, spectral evolution, bandwidth limitations, and bit error rate performance, this study established clear performance distinctions between the two fiber types [12], [19].

These results show that multimode fibers, although economical and applicable to short-distance LAN, have a severe mode dispersion that restricts bandwidth and maximum transmission distance in high-speed data. In contrast, single-mode fibers are better in dispersion control, spectral stability, and BER to provide a much longer reach and more scalability [24], [25], [26]. Practically, such results would justify the rising trend of single-mode fiber implementation in new LAN and data-center networks, although it is more expensive than multi-mode fibers. The simulation framework and theoretical models used to develop this study offer a strong basis for automated optical network design and the optimization of optimum performance. This study can be further enhanced in the future by introducing advanced modulation formats, wavelength-division multiplexing, and adaptive dispersion compensating methods. The simulation results, which are experimentally validated and investigated for hybrid fiber architectures, are also promising directions for new research [27], [30].

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