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Methodology Article

Single-mode and Multimode Optical Fibers: Theoretical Comparison and Performance Analysis

Randriana Heritiana Nambinina Erica*, **Ando Nirina Andriamanalina**

Telecommunications, Doctoral School of Engineering Sciences and Innovation, Antananarivo, Madagascar

Abstract

This research presents a theoretical and numerical comparison of single-mode and multimode optical fibers to evaluate their transmission performance under different operating conditions. The study is based on the fundamental equations of optical propagation, including numerical aperture, normalized frequency, number of guided modes, attenuation, dispersion, and maximum transmission distance. A MATLAB-based simulation is used to analyze a G.652 single-mode fiber operating at 1310 and 1550 nm and a 50/125 µm OM3 multimode fiber operating at 850 nm. The results show that, at a data rate of 10 Gb/s, the OM3 multimode fiber achieves a maximum transmission distance of approximately 0.28 km, compared with 31 km at 1310 nm and 36 km at 1550 nm for the single-mode fiber. The analysis also demonstrates that attenuation and dispersion play complementary roles in limiting transmission performance, depending on the operating wavelength and data rate. While single-mode fibers are better suited for long-distance and high-capacity communication systems, multimode fibers remain advantageous for short-distance links where installation cost and connection simplicity are important. These findings provide a quantitative basis for selecting the appropriate optical fiber architecture according to transmission requirements.

Keywords

Single-mode Fiber, Multimode Fiber, Optical Transmission, Numerical Aperture, Normalized Frequency

1. Introduction

Single-mode fiber can transmit signals over longer distances and at higher data rates than multimode fiber, whereas multimode fiber generally offers lower installation and operating costs for short-distance links [1-3]. This paper quantifies this difference using the fundamental equations of guided propagation and a MATLAB-based simulation. Optical fiber is now widely used in telecommunication networks, including intercontinental links, metropolitan networks, Fiber-to-the-Home (FTTH) access networks, as well as interconnections within data centers [1, 2, 4]. The signal is transmitted as a light wave guided through a silica core with a refractive index (n_1), surrounded by a cladding with a slightly lower refractive index (n_2). Within the framework of geometric optics, light guidance can be interpreted in terms of total internal reflection at the core-cladding interface [1]. More rigorously, the propagation characteristics and guided modes are obtained by solving Maxwell's equations for the cylindrical dielectric structure of the optical fiber [2, 6]. The number of propagation paths, known as modes, that light can follow within the core depends mainly on the fiber geometry, the refractive-index difference between the core and the cladding, and the operating wave-

*Correspondence: Randriana Heritiana Nambinina Erica (Erica_mada@hotmail.com)

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length [1, 6]. This fundamental property distinguishes two major families of optical fibers with different characteristics and application areas [2, 3]: single-mode fiber (SMF), whose core diameter is typically around 8-10 µm and which essentially supports the propagation of a single fundamental spatial mode at conventional telecommunication wavelengths [1, 2]; multimode fiber (MMF), whose core typically has a diameter of 50 or 62.5 µm and can support a large number of propagation modes [3, 7].

The difference in the number of modes directly affects transmission performance. In a multimode fiber, the different modes follow distinct propagation paths and may therefore reach the receiver at different times. This phenomenon results in modal dispersion, which is one of the main limitations on the bandwidth of multimode fibers, particularly as the transmission distance increases [3, 7]. In contrast, single-mode fiber practically eliminates this contribution to dispersion associated with different spatial modes, which explains its widespread use in long-distance and high-capacity transmission systems [1, 2]. However, the comparison between these two architectures should not be limited to the number of modes. The core diameter, numerical aperture, normalized frequency (V), field distribution, guided power, dispersion, and propagation losses are also essential parameters for characterizing their performance [1, 6, 7]. A combined analysis of these parameters therefore makes it possible to establish a quantitative comparison between single-mode and multimode fibers and to determine their respective fields of application. In this context, the present work proposes a theoretical and numerical comparative study of single-mode and multimode optical fibers. The analysis is based on the fundamental equations of guided propagation and a numerical simulation developed in MATLAB. The performance of both fiber architectures is evaluated using characteristic parameters such as the number of guided modes, numerical aperture, normalized frequency (V), power propagation, and guiding characteristics. This approach provides a quantitative assessment of the advantages and limitations of each type of fiber under different transmission conditions.

2. Mathematical Modeling of the Comparison

2.1. Problem Statement

The choice between the two fiber families involves a trade-off between three main parameters: the distance over which the signal can travel, the data rate it can carry, and the overall system cost [1-3]. In principle, single-mode fiber offers advantages in terms of the first two parameters. Multimode fiber, with its larger core, allows more tolerant connections and can operate with relatively low-cost light sources, such as light-emitting diodes (LEDs) and 850 nm vertical-cavity surface-emitting lasers (VCSELs) [3, 7, 8].

The question addressed in this study is therefore: At what distance and data rate do dispersion and attenuation cause the performance advantage to shift from one fiber family to the other?

2.2. Objectives

This work pursues three main objectives:

1) To establish the fundamental equations governing the operation of the two types of optical fibers, including normalized frequency, number of modes, attenuation, modal and chromatic dispersion, and bandwidth [1, 3, 6];
2) To define a realistic set of parameters for a G.652 single-mode fiber and a 50/125 µm OM3-type multimode fiber [9, 10];
3) To simulate, using MATLAB, the normalized frequency, power budget, and maximum transmission distance as a function of data rate, and then compare the resulting curves.

3. Materials and Methods

The comparison is based on six fundamental relationships describing numerical aperture, normalized frequency, number of guided modes, attenuation, dispersion, and bandwidth. These relationships are applied to two representative fiber types and evaluated numerically using MATLAB [1, 3, 6].

3.1. Fiber Structure and Geometrical Parameters

A step-index optical fiber is characterized by the core radius (a), the core refractive index (n_1), and the cladding refractive index (n_2), with ($n_1 > n_2$). The numerical aperture (NA) and relative refractive-index difference (Δ) are expressed as follows [1, 6]:

$$NA = \sqrt{n_1^2 - n_2^2}, \tag{1}$$

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \approx \frac{n_1 - n_2}{n_1} \tag{2}$$

The normalized frequency (V) summarizes the ability of the fiber core to guide light at a given wavelength (\lambda) [1, 6]:

$$V = \frac{2\pi}{\lambda} NA \tag{3}$$

The criterion separating the two propagation regimes is the value of (V). A step-index fiber supports only the fundamental mode $LP01$ when ($V < 2.405$), where 2.405 corresponds to the first zero of the zeroth-order Bessel function ($J0$) [1, 6]:

$$\lambda_c = \frac{2\pi a NA}{2.405} \tag{4}$$

The cutoff wavelength can therefore be derived as:

$$M \approx \frac{V^2}{2} \quad (5)$$

$$M \approx \frac{V^2}{4} \quad (6)$$

3.2. Attenuation and Power Budget

The optical power decreases exponentially with propagation distance. In decibels, the linear attenuation coefficient ($\boldsymbol{\alpha}$) ($\boldsymbol{dB/km}$) is given by [1, 9]:

$$\alpha = \frac{10}{L} log_{10} \frac{P_0}{P(L)} \quad (7)$$

$$P(L)_{dBm} = P_{0,dBm} - \alpha L \quad (8)$$

The link operates as long as the received power exceeds the receiver sensitivity (S) plus a system margin (M). The attenuation-limited transmission distance is therefore:

$$L_{att} = \frac{P_0 - (S+M)}{\alpha} \quad (9)$$

Attenuation depends strongly on wavelength. Rayleigh scattering, which varies approximately as ($\frac{\mathbf{1}}{\boldsymbol{\lambda^4}}$, dominates at shorter wavelengths, whereas infrared absorption of silica becomes increasingly significant at longer wavelengths [1, 9]. The commonly used transmission windows are 850 nm and 1300 nm for multimode systems, and 1310 nm and 1550 nm for single-mode systems [9, 10].

3.3. Dispersion

The optical pulse broadens as it propagates through the fiber, thereby limiting the achievable data rate [1, 5, 6, 13, 14]. Two main mechanisms are considered in this study.

Intermodal dispersion. Each guided mode follows a different propagation path and consequently has a different propagation time. For a step-index fiber of length (L), the time difference between the fastest and slowest modes is approximately given by [1, 6]:

$$\Delta_{\tau_{mod}} = \frac{Ln_1\Delta}{c} \quad (10)$$

For a graded-index fiber, the propagation times of the different modes become more similar, reducing the theoretical modal delay by a factor proportional to $\frac{8}{\Delta}$:

$$\Delta\tau_{mod}^{grad} = \frac{Ln_1\Delta^2}{8c} \quad (11)$$

In a practical fiber, imperfections in the refractive-index profile limit this theoretical improvement. The effective modal bandwidth specified by the manufacturer is therefore used. In this study, a value of $(2000\ \ MHz.km)$ is retained for an OM3 fiber at 850 nm [10].

Chromatic dispersion. Chromatic dispersion affects both fiber families because the refractive index of silica depends on wavelength and the optical source has a finite spectral width $(\Delta\lambda)$ [1, 5, 9, 13, 14].

$$\Delta_{\tau_{chrom}} = |D(\lambda)|L\Delta\lambda, \quad (12)$$

For G.652 single-mode fiber, (D) approaches zero around (λ_0), with a dispersion slope of approximately $(S0 = 0.092\ \ ps/nm^2/km)$ [9]. At 1550 nm, the chromatic dispersion is approximately $17ps/nm/km$.

3.4. Bandwidth and Maximum Data Rate

The bandwidth associated with a pulse broadening (Δ_τ) is approximated by $B \approx 0.44/\Delta_\tau$ [1, 6]:

$$\frac{1}{B_{tot}^2} = \sum_i \frac{1}{B_i^2} \quad (13)$$

$$B_{tot} \geq 0.7R \quad (14)$$

$$L_{disp} = \frac{(B.L)_{tot}}{0.7R} \quad (15)$$

Independent dispersion contributions are combined in quadrature. For an NRZ signal with data rate (R), a minimum bandwidth of approximately (0.7R) is required [6]:

$$L_{max} = \min(L_{att}, L_{disp}) \quad (16)$$

The actual transmission distance is determined by the most restrictive of the two limitations, attenuation and dispersion:

$$L_{max} = \min(L_{att,} L_{disp}) \quad (17)$$

3.5. Selected Parameters

Table 1. Selected Parameters in the simulation.

Parameter	Single-mode G.652	Multimode OM3 50/125
Core radius (a) (µm)	4.0	25
Core refractive index (n_1)	1.468	1.480
Cladding refractive index (n_2)	1.4631	1.4664
Numerical aperture (NA)	0.12	0.20
Refractive-index difference (Δ) (%)	0.33	0.91
Simulated windows (nm)	1310; 1550	850
Attenuation (α) (dB/km)	0.35 (1310); 0.20 (1550)	3.0 (850)
Source	DFB laser, $\frac{\Delta}{\lambda} = 0.1$ nm	VCSEL, $\frac{\Delta}{\lambda} = 0.45\ nm$
Chromatic dispersion (D) ($ps/nm/km$)	$-0.2\ at\ 1310$ (floor 0.5); 17.3 at 1550	$-\ 97\ at\ 850$
Modal bandwidth ($MHz.km$)	Not applicable	2000
Transmitted power (P_0) (dBm)	0	0
Sensitivity (S) (dBm) / margin (M) (dB)	$-14\ /\ 3$	$-14\ /\ 3$

The attenuation and dispersion values are representative orders of magnitude derived from ITU-T G.652 recommendations and typical manufacturer specifications; they are not measurement results [9-12]. The power budget, corresponding to 11 dB of available margin, is kept identical for all links in order to compare the fiber types rather than the transmitters.

3.6. Simulation Method

The calculations are performed in MATLAB using the Optical Design and Simulation library. Three simulations are conducted:

$V(\lambda)$: the normalized frequency is evaluated from 0.60 to 1.70 µm with a step of 0.05 µm for both fibers and compared with the single-mode threshold ($V = 2.405$);

$P(L)$: the received optical power is calculated from 0 to 10 km with a step of 0.5 km for three links: single-mode at 1310 nm, single-mode at 1550 nm, and multimode at 850 nm;

$L_{max}(R)$: the data rate (R) varies from 0.1 to 100 Gb/s over 19 logarithmically spaced values. For each link, the maximum transmission distance is determined as the minimum of (L_{att} and (L_{disp}).

The plots presented in Section 3 are generated directly from the result tables produced by the simulation.

4. Results

At 10 Gb/s, the OM3 multimode fiber is limited to 0.28 km, whereas the single-mode fiber reaches 36 km at 1550 nm and 31 km at 1310 nm. This difference is primarily due to intermodal dispersion, followed by attenuation at 850 nm.

4.1. Normalized Frequency and Number of Modes

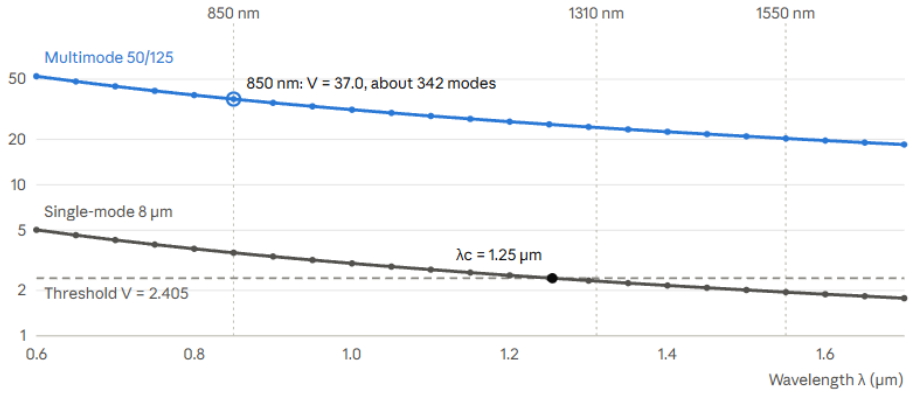


Figure 1. Normalized Frequency and Number of Modes.

At 1310 nm, (V) is 2.30 for the single-mode fiber, and 1.95 at 1550 nm. Both operating windows remain below the cutoff value of 2.405, with a cutoff wavelength of 1.254 µm. Below this wavelength, the fiber no longer operates in the single-mode regime: at 850 nm, (V) reaches 3.55 and several modes are guided.

The 50/125 µm multimode fiber remains well above the cutoff threshold over the entire wavelength range considered: ($V = 37.0$) at 850 nm and ($V = 24.2$) at 1300 nm. This corresponds to approximately 342 modes at 850 nm and 146 modes at 1300 nm for a parabolic refractive-index profile, and approximately twice as many modes for a step-index profile, reaching 683 modes at 850 nm.

4.2. Power Budget

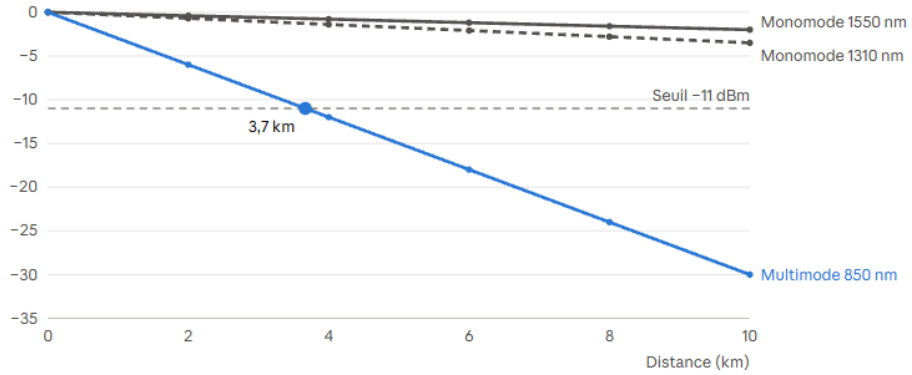


Figure 2. Power Budget.

With 11 dB of available power budget, corresponding to 0 dBm transmitted power, a receiver sensitivity of −14 dBm, and a 3 dB system margin, the attenuation-limited transmission distance is 55 km at 1550 nm, 31.4 km at 1310 nm, and 3.7 km at 850 nm. The factor-of-15 difference between the best-performing single-mode configuration and the multimode configuration results from the linear attenuation coefficient (0.20 versus 3.0 dB/km), rather than from the number of modes.

The choice of operating window is therefore as important as the fiber type itself. A multimode fiber operated at 1300 nm, with an attenuation of approximately 1 dB/km (typical value, not simulated in this study), would reach approximately 11 km based solely on the attenuation criterion.

4.3. Maximum Transmission Distance as a Function of Data Rate

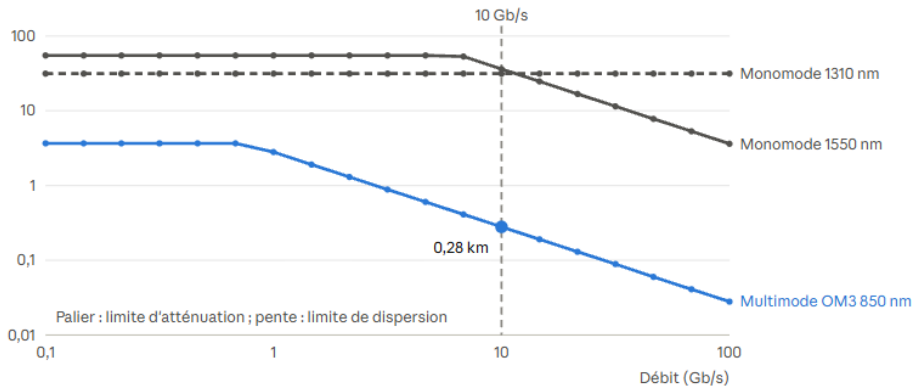


Figure 3. Maximum Transmission Distance.

Each curve exhibits a plateau, where attenuation determines the maximum transmission distance, followed by a decreasing region in which dispersion becomes the dominant limitation. The plateau of the 1550 nm single-mode link ends at approximately 6.6 Gb/s, whereas that of the OM3 multimode link ends as early as 0.76 Gb/s. Above 11.5 Gb/s, the 1310 nm link, for which chromatic dispersion is nearly zero, provides a longer transmission distance than the 1550 nm link despite its higher attenuation (31 versus 55 km).

Table 2. Maximum Transmission Distance.

Link	$(B.L)$ total $(GHz.km)$	Range at 1 Gb/s	Range at 10 Gb/s	Range at 100 Gb/s
Single-mode 1310 nm	850 nm step-index multimode			
Single-mode 1550 nm	254	55km	36.2km	3.6km
OM3 multimode 850 nm	1.96	2.80km	0.28km	0.028km
850 nm step-index multimode	0.0098	14m	1.4m	0.14m

For the OM3 fiber, the chromatic-dispersion contribution associated with the VCSEL (approximately 10 GHz km) has little effect compared with the modal bandwidth (2 $GHz.km$): the combined bandwidth-distance product decreases only from 2.00 to 1.96 $GHz.km$. For the step-index fiber, the modal broadening of 45 ns/km results in a bandwidth-distance product of only 9.8 $MHz.km$, restricting this type of fiber to very short links at low data rates.

5. Discussion

Three main limitations should be considered when interpreting these results. First, the criterion is an approximation. Ethernet standards specify shorter practical transmission distances than those predicted by this low-data-rate model, typically around 550 m at 1 Gb/s over 50/125 µm multimode fiber, because they account for additional penalties that are not included in the present model. At 10 Gb/s, however, the simulated distance of 0.28 km is close to the commonly specified 300 m range for OM3 fiber.

Second, polarization-mode dispersion, nonlinear effects, and connector losses are not included in the model. These effects mainly reduce the transmission distance of single-mode systems at high data rates and over very long links.

Finally, the cost of transmitters, connectors, and installation is not included in the simulation. Nevertheless, these economic factors are important in explaining the widespread use of multimode fiber in data centers, where link distances generally remain below approximately 300 m.

6. Conclusion

Single-mode fiber remains the only fiber architecture capable of supporting high data rates over distances exceeding one kilometer, whereas OM3 multimode fiber is generally limited

to links of a few hundred meters at 10 Gb/s. The equations and numerical simulations converge toward this conclusion through three complementary aspects.

Guidance. The single-mode fiber, with an 8 µm core and ($NA = 0.12$), operates in the single-mode regime only above 1.254 µm, with ($V = 2.30$) at 1310 nm. The 50/125 µm multimode fiber, with ($NA = 0.20$), guides approximately 342 modes at 850 nm, resulting in significant intermodal dispersion.

Attenuation. With an available power budget of 11 dB, the transmission distance reaches 55 km at 1550 nm, 31 km at 1310 nm, and 3.7 km at 850 nm. This difference is mainly associated with the operating wavelength window and the corresponding attenuation coefficients (0.20 versus 3.0 dB/km).

Dispersion. At 10 Gb/s, the 2 $GHz.km$ modal bandwidth of OM3 limits the transmission distance to approximately 0.28 km. For single-mode fiber, chromatic dispersion becomes significant at 1550 nm above approximately 6.6 Gb/s, whereas at 1310 nm it remains negligible up to 100 Gb/s under the assumptions of the present model.

The practical result is therefore a clear division of applications: multimode fiber is well suited to short-distance, cost-sensitive cabling, whereas single-mode fiber is preferred for access, metropolitan, and long-distance networks, as well as for future migration toward data rates above 10 Gb/s over distances of several hundred meters.

This study is based on a simplified model that does not include polarization-mode dispersion, nonlinear effects, or connector losses and uses representative fiber parameters. Further work should therefore include experimental measurements on real optical links, a comprehensive cost assessment of both solutions, and an extension of the analysis to OM4 and OM5 multimode fibers as well as multilevel modulation formats such as PAM4.

Abbreviations

CMT	Coupled-mode Theory
DC	Dual-core
EM	Electromagnetic
FEM	Finite Element Method
Lc	Coupling Length
LP	Linearly Polarized Mode
MATLAB	Matrix Laboratory
MMF	Multimode Fiber
NA	Numerical Aperture
SNR	Signal-to-noise Ratio
SMF	Single-mode Fiber
TE	Transverse Electric
TM	Transverse Magnetic
V	Normalized Frequency
WDM	Wavelength-division Multiplexing
κ	Coupling Coefficient
$\Delta n12$	Core-to-core Refractive-index Difference
Δn^c	Core-to-cladding Refractive-index Difference

Author Contributions

Randriana Heritiana Nambinina Erica: Conceptualization, Investigation, Methodology, Writing – original draft

Ando Nirina Andriamanalina: Methodology, Supervision, Validation

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



Randriana Heritiana Nambinina Erica is a lecturer and researcher at the University of Antananarivo and a faculty member at the École Supérieure Polytechnique d'Antananarivo. He is also a doctoral candidate within the EDSTII doctoral school, specializing in telecommunications. His research focuses primarily on optical fiber technologies, including performance optimization, signal propagation, and applications in high-speed communication systems. He has contributed to several academic and applied research projects related to broadband network development and emerging communication infrastructures in Madagascar. His work reflects a strong commitment to advancing optical communication solutions adapted to local and regional technological needs. He actively participates in scientific activities through teaching, research supervision, and conference contributions.

Research Field

Randriana Heritiana Nambinina Erica: Telecommunication, Transmission, Optical Fiber, Optical Communication, Signal Processing

Ando Nirina Andriamanalina: Telecommunications, Control Systems, Signal Processin