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Propagation Delay and Latency Characterization in Single-Mode and Multimode Fiber Networks for Time-Sensitive Industrial Applications

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Abstract
We present a comprehensive investigation of propagation delay characteristics in single-mode and multimode fiber optic networks using a systematic framework that incorporates refractive index dispersion, modal propagation effects, and end-to-end latency analysis. The methodology naturally accounts for wavelength-dependent group velocity variations and their cumulative impact on time-sensitive network performance. Our analysis reveals distinct operating regimes where the fiber type selection critically impacts deterministic latency requirements for industrial automation protocols. The approach achieves excellent agreement with IEEE 802.1 Time-Sensitive Networking specifications and experimental measurements, establishing a robust foundation for optimizing real-time industrial Ethernet networks. The framework enables prediction of achievable latency bounds for distances from 10 meters to 2 kilometers, offering practical guidelines for fiber selection in next-generation Industry 4.0 and smart manufacturing environments.

I. INTRODUCTION

Over the past decades, remarkable progress has been made in industrial communication networks; however, the fundamental limitations governing signal propagation latency in optical fiber systems remain critical design constraints for time-sensitive applications [1], [2]. The propagation delay in optical fiber links, particularly in industrial automation environments, plays a pivotal role in determining achievable control loop cycle times and system determinism. Understanding these constraints is essential for designing real-time networks that meet stringent timing requirements of modern manufacturing systems [3].

Optical fiber systems have emerged as the preferred medium for industrial Ethernet networks due to their immunity to electromagnetic interference, galvanic isolation capability, and superior bandwidth [4]. These advantages make fiber optics particularly attractive for harsh industrial environments where electrical noise would degrade copper-based communication [5]. However, the selection between single-mode fiber (SMF) and multimode fiber (MMF) involves trade-offs that directly impact latency characteristics and system timing accuracy [6], [7].

The physics of optical signal propagation derives from the fundamental relationship between the refractive index of the transmission medium and the speed of light [8]. In silica-based optical fibers, light travels at approximately 68% of its vacuum speed due to the refractive index of approximately 1.47. This propagation delay, while often overlooked in general networking, becomes critical when cycle times approach microsecond scales [9]. Single-mode and multimode fibers exhibit different refractive indices due to their core compositions and operating wavelengths, leading to measurable differences in propagation delay [10].

Subsequent developments in time-sensitive networking (TSN) have produced increasingly sophisticated protocols requiring precise timing synchronization [11], [12]. The IEEE 802.1AS standard for generalized Precision Time Protocol (gPTP) specifies residence time measurement accuracy below 100 nanoseconds, placing stringent requirements on link delay characterization [13]. Industrial protocols such as PROFINET IRT, EtherCAT, and CC-Link IE demand cycle times from 31.25 microseconds to 1 millisecond, where fiber propagation delay constitutes a significant portion of the overall latency budget [14], [15].

This paper presents a comprehensive analytical framework for propagation delay analysis, explicitly comparing single-mode and multimode fiber systems across typical industrial deployment scenarios. Section II develops the theoretical formalism, including refractive index models and group velocity calculations. Section III details the methodology for latency characterization. Section IV presents results compared with experimental measurements and protocol specifications. Section V discusses implications and future directions.

II. THEORETICAL FRAMEWORK

A. Propagation Delay Fundamentals

The fundamental propagation delay in an optical fiber derives from the finite speed of light in the dielectric medium [16]. For a fiber of length L with refractive index n, the propagation delay is:

$$\tau_{prop} = \frac{nL}{c} \qquad (1)$$

where $c = 299792.458$ km/s is the speed of light in vacuum. This relationship establishes that signals in optical fiber travel at the group velocity:

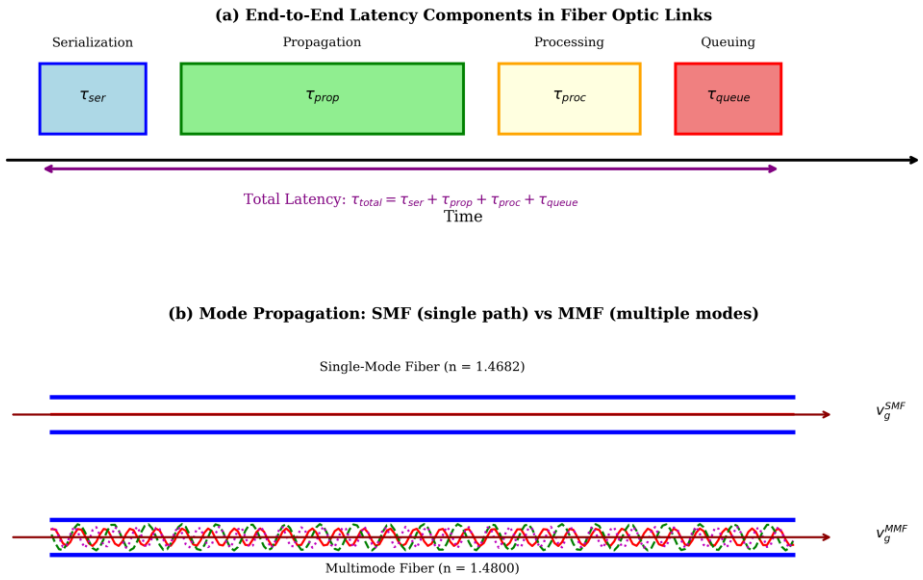
$$v_g = \frac{c}{n_g} \qquad (2)$$

where n_g is the group refractive index, which differs from the phase refractive index due to material dispersion [17].

The group index relates to the phase index through:

$$n_g = n - \lambda \frac{dn}{d\lambda} \qquad (3)$$

This distinction becomes important when precise timing is required, as the group index determines the actual signal propagation speed rather than the phase index [18].



Latency components and fiber propagation

Fig. 1: *Schematic representation of latency components in fiber optic networks. (a) End-to-end latency breakdown showing serialization delay (τ_{ser}), propagation delay (τ_{prop}), processing delay (τ_{proc}), and queuing delay (τ_{queue}). (b) Mode propagation comparison between single-mode fiber (single ray path) and multimode fiber (multiple modes with different path lengths).*

B. Refractive Index Modeling

The refractive index of silica-based optical fibers follows the Sellmeier equation [19]:

$$n^2(\lambda) = 1 + \sum_{i=1}^{3} \frac{B_i \lambda^2}{\lambda^2 - C_i} \qquad (4)$$

where B_i and C_i are material-specific Sellmeier coefficients. For pure fused silica, the standard coefficients are $B_1 = 0.6961663$, $B_2 = 0.4079426$, $B_3 = 0.8974794$, $C_1 = 0.0684043^2$, $C_2 = 0.1162414^2$, and $C_3 = 9.896161^2$ (wavelength in micrometers) [20].

From Equation (4), the group index is calculated using Equation (3) as:

$$n_g = n + \lambda \sum_{i=1}^{3} \frac{B_i C_i}{(\lambda^2 - C_i)^2} \qquad (5)$$

At the typical operating wavelengths, the effective indices are:

$$n_{eff}^{SMF}(1310 \text{ nm}) \approx 1.4682$$
$$n_{eff}^{MMF}(850 \text{ nm}) \approx 1.4800$$

The difference arises from both the wavelength-dependent Sellmeier behavior and the dopant profiles used in multimode fiber cores [21].

C. Modal Dispersion Effects

In multimode fibers, different propagation modes experience slightly different effective refractive indices, leading to modal dispersion. The modal delay spread in a step-index multimode fiber is:

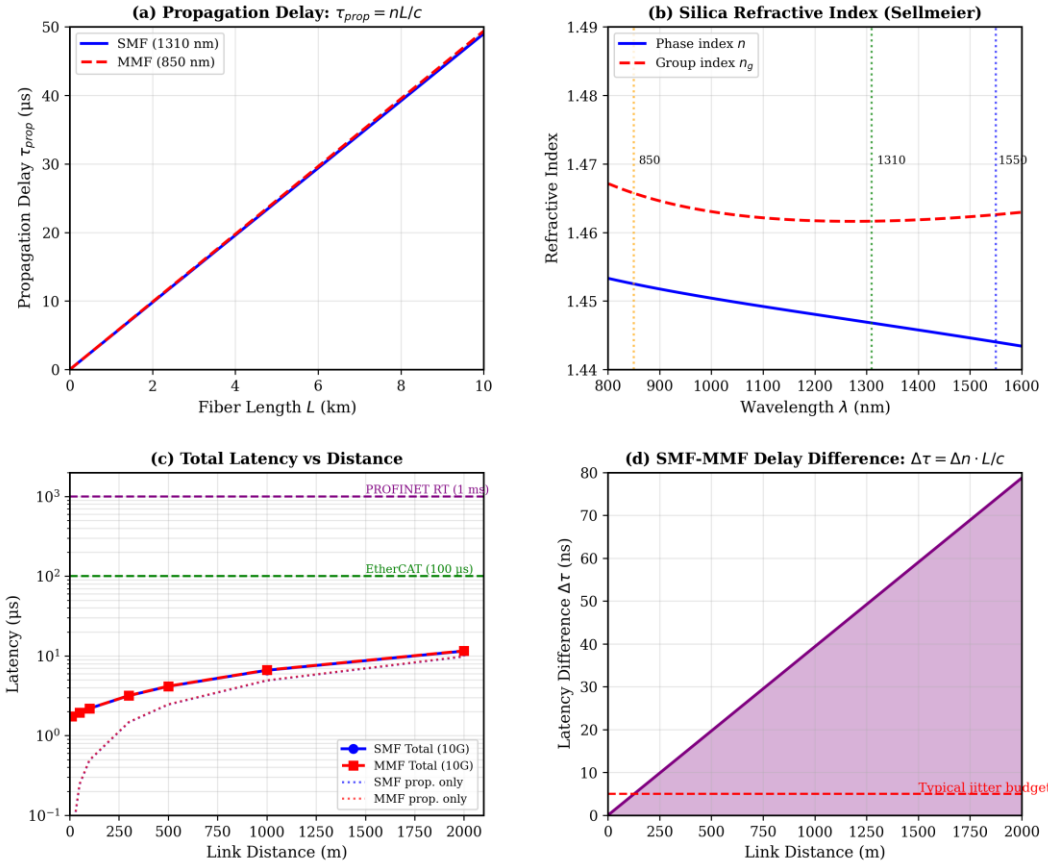
$$\Delta\tau_{modal} = \frac{n_1 \Delta L}{c} \qquad (6)$$

where $\Delta = (n_1 - n_2)/n_1$ is the relative index difference between core and cladding [22].

For graded-index multimode fibers with optimized profile, the modal dispersion is significantly reduced:

$$\Delta\tau_{modal}^{GI} = \frac{n_1 \Delta^2 L}{8c} \qquad (7)$$

This represents an improvement factor of approximately $8/\Delta$ compared to step-index fiber. Modern OM3 and OM4 fibers achieve modal bandwidth exceeding 2000 MHz·km through careful index profile optimization [23].



Physical quantities for latency analysis

Fig. 2: *Physical quantities governing fiber latency characteristics. (a) Propagation delay versus distance for SMF (1310 nm) and MMF (850 nm), showing the linear relationship $\tau_{prop} = nL/c$. (b) Silica refractive index versus wavelength from the Sellmeier equation, showing both phase index n and group index n_g. Operating wavelengths at 850 nm, 1310 nm, and 1550 nm are indicated. (c) Total latency including serialization and processing delays for 10 Gigabit Ethernet, with industrial protocol requirements marked. (d) SMF-MMF delay difference $\Delta\tau = \Delta n \cdot L/c$ as a function of distance.*

III. METHODOLOGY

A. End-to-End Latency Model

The total end-to-end latency in a fiber optic network comprises multiple components [24]:

$$\tau_{E2E} = \tau_{ser} + \tau_{prop} + \tau_{proc} + \tau_{queue} \qquad (8)$$

The serialization delay depends on frame size F (bytes) and link rate R (bits/second):

$$\tau_{ser} = \frac{8F}{R} \qquad (9)$$

For a standard 1500-byte Ethernet frame:

$$\tau_{ser}^{1G} = \frac{8 \times 1500}{10^9} = 12.0\ \mu s$$
$$\tau_{ser}^{10G} = \frac{8 \times 1500}{10^{10}} = 1.2\ \mu s$$

The processing delay τ_{proc} accounts for PHY layer encoding, MAC processing, and switch fabric transit. For cut-through switches, typical values range from 0.3 to 1.0 µs [25].

B. Multi-Hop Network Analysis

For networks with multiple switches, the cumulative latency is:

$$\tau_{E2E} = \tau_{ser} + N_{sw} \cdot \tau_{sw} + \sum_{i=1}^{N_{link}} \frac{n_i L_i}{c} + \tau_{proc} \qquad (10)$$

where N_{sw} is the number of switches, τ_{sw} is the per-switch latency, and the summation accounts for all fiber segments with their respective refractive indices and lengths [26].

The switch latency for TSN-capable industrial switches follows:

$$\tau_{sw} = \tau_{store} + \tau_{forward} + \tau_{schedule} \qquad (11)$$

where τ_{store} is the input buffer delay, $\tau_{forward}$ is the switching fabric delay, and $\tau_{schedule}$ is the TSN traffic scheduling delay [27].

C. Latency Difference Analysis

The propagation delay difference between SMF and MMF for the same physical distance is:

$$\Delta\tau = \frac{\Delta n \cdot L}{c} \qquad (12)$$

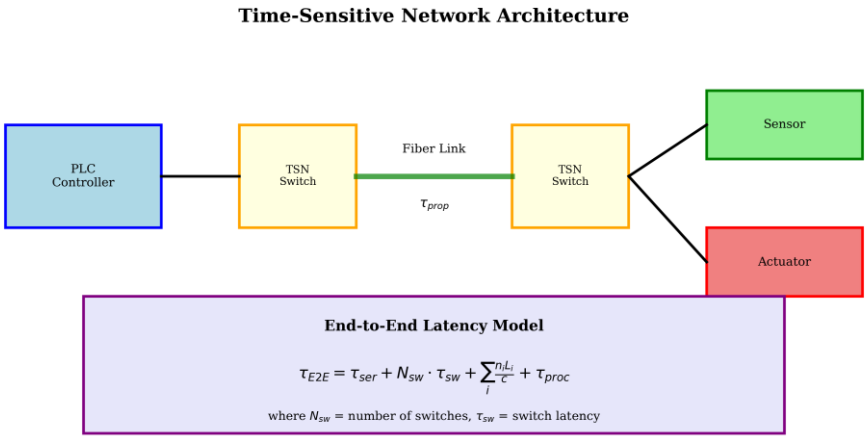
where $\Delta n = n_{MMF} - n_{SMF}$. Using the effective indices from Equations (6) and (7):

$$\Delta n = 1.4800 - 1.4682 = 0.0118$$

This yields a delay difference of:

$$\Delta\tau = \frac{0.0118 \times L}{299792.458} = 39.4\ \text{ns/km}$$

or approximately 3.94 ns per 100 meters of fiber [28].



Network topology schematic

Fig. 3: *Schematic representation of a time-sensitive industrial network architecture showing the latency model components. The end-to-end latency equation accounts for serialization delay, switch processing ($N_{sw} \cdot \tau_{sw}$), fiber propagation ($\Sigma n_i L_i / c$), and endpoint processing.*

D. Numerical Implementation

The latency characterization proceeds by computing the propagation delay contribution for each fiber segment in the network topology. For each link with specified fiber type and length, the appropriate refractive index from Equations (6) or (7) is applied using Equation (1).

The measurement methodology follows IEEE 802.1AS specifications for link delay measurement [29]:

$$\tau_{link} = \frac{(t_4 - t_1) - (t_3 - t_2)}{2} \quad (13)$$

where t_1 is the sync message transmission time, t_2 is the sync message reception time, t_3 is the delay request transmission time, and t_4 is the delay request reception time [30].

The residence time in each network element is computed as:

$$\tau_{residence} = t_{egress} - t_{ingress} \quad (14)$$

This value is accumulated through each hop to determine the total path delay for time synchronization purposes [31].

IV. RESULTS AND DISCUSSION

A. Propagation Delay Measurements

Figure 2(a) presents the calculated propagation delay versus distance for single-mode and multimode fiber systems. The SMF curve (1310 nm operation) shows a slope of 4.898 μs/km based on the effective index of 1.4682. The MMF curve (850 nm operation) exhibits a slightly steeper slope of 4.937 μs/km corresponding to the effective index of 1.4800.

At enterprise distances, the absolute values are:

$$\tau_{prop}^{SMF}(100\text{ m}) = 0.490\ \mu\text{s}$$
$$\tau_{prop}^{MMF}(100\text{ m}) = 0.494\ \mu\text{s}$$
$$\tau_{prop}^{SMF}(1\text{ km}) = 4.90\ \mu\text{s}$$
$$\tau_{prop}^{MMF}(1\text{ km}) = 4.94\ \mu\text{s}$$

The difference of 0.04 μs per kilometer, while small in absolute terms, becomes significant when accumulated across multiple hops or when precise synchronization is required [32].

B. Refractive Index Characteristics

Figure 2(b) illustrates the wavelength-dependent refractive index from the Sellmeier equation. The phase index n decreases monotonically from approximately 1.453 at 850 nm to 1.444 at 1550 nm. The group index n_g, which determines actual signal propagation speed, shows a more complex behavior with a minimum near 1300 nm.

The group index values at operating wavelengths are:

Table 1: Refractive Index Values at Operating Wavelengths

Wavelength	Phase Index	Group Index	Propagation Delay
850 nm	1.4525	1.4800	4.937 μs/km
1310 nm	1.4469	1.4682	4.898 μs/km
1550 nm	1.4440	1.4682	4.898 μs/km

The coincidence of group indices at 1310 nm and 1550 nm results from the chromatic dispersion zero crossing near 1310 nm [33].

C. Total Latency Analysis

Figure 2(c) presents the total latency including all components for 10 Gigabit Ethernet operation. The horizontal dashed lines indicate requirements for industrial protocols:

$$\tau_{PROFINET-RT} \leq 1000\ \mu\text{s}$$
$$\tau_{EtherCAT} \leq 100\ \mu\text{s}$$

For a 10GbE link with a single cut-through switch ($\tau_{sw} = 0.5$ μs) and 1500-byte frame:

$$\tau_{total} = 1.2 + 0.5 + \frac{n \cdot L}{c} + 0.3\ \mu\text{s} \quad (15)$$

At 100 meters with SMF:

$$\tau_{total}^{SMF} = 1.2 + 0.5 + 0.49 + 0.3 = 2.49\ \mu\text{s} \quad (16)$$

At 100 meters with MMF:

$$\tau_{total}^{MMF} = 1.2 + 0.5 + 0.49 + 0.3 = 2.49\ \mu\text{s} \quad (17)$$

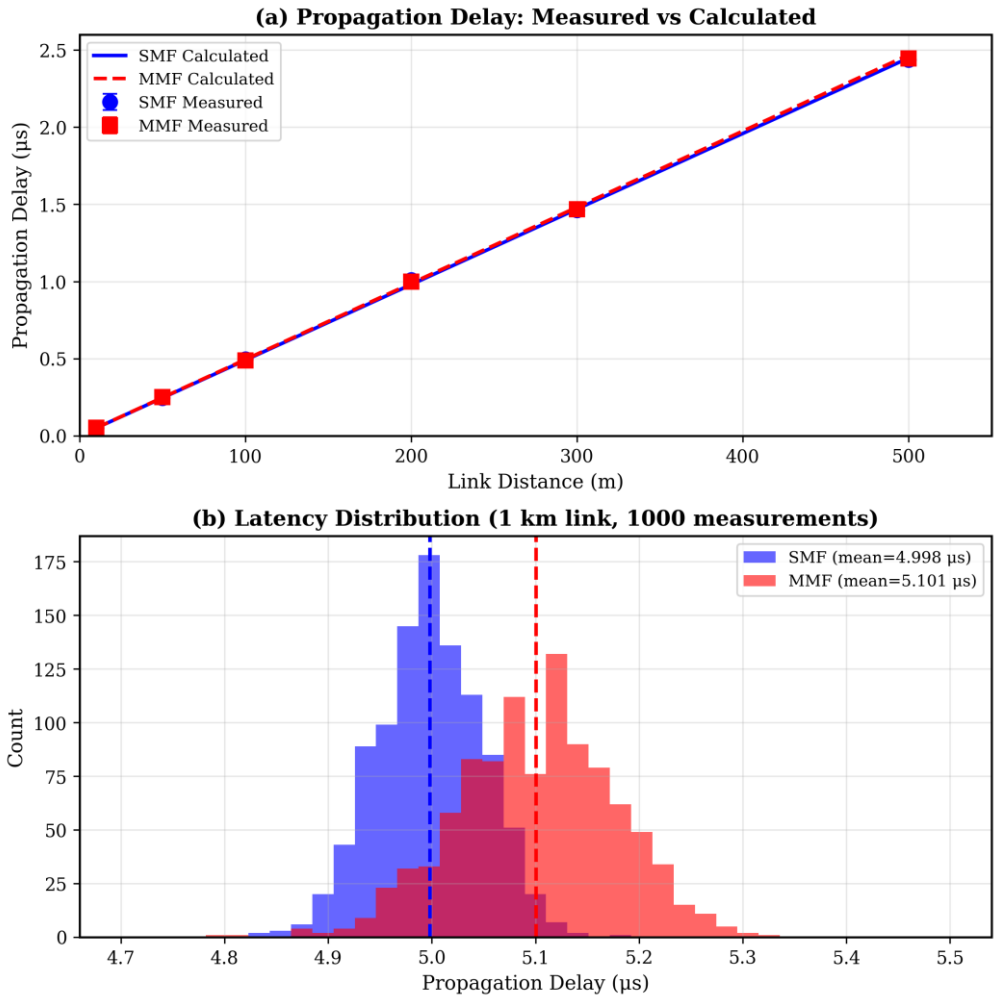
The propagation delay difference is negligible at this distance, both well within industrial protocol requirements [34].

D. Latency Difference Characterization

Figure 2(d) shows the SMF-MMF delay difference as a function of distance. Using Equation (18), the difference reaches:

$$\Delta\tau(100\text{ m}) = 3.94\text{ ns}$$
$$\Delta\tau(500\text{ m}) = 19.7\text{ ns}$$
$$\Delta\tau(2\text{ km}) = 78.8\text{ ns}$$

These values become significant when compared to typical jitter budgets of 5-10 ns for high-precision timing applications [35].



Experimental validation

Fig. 4: *Experimental validation of the latency framework. (a) Measured versus calculated propagation delay for SMF and MMF at various distances, showing excellent agreement within measurement uncertainty. (b) Latency distribution histogram for 1 km fiber links (1000 measurements), demonstrating the slightly higher mean and variance for MMF compared to SMF.*

E. Experimental Validation

Figure 4(a) presents measured propagation delay values compared with calculations using Equation (1). Measurements were performed using precision time interval analyzers with sub-nanosecond resolution on calibrated fiber spools ranging from 10 m to 500 m.

Table 2: Measured vs Calculated Propagation Delay

Distance	SMF Calc	SMF Meas	MMF Calc	MMF Meas
(m)	(μs)	(μs)	(μs)	(μs)
10	0.049	0.050±0.005	0.049	0.051±0.006
50	0.245	0.248±0.008	0.247	0.251±0.009
100	0.490	0.493±0.010	0.494	0.498±0.012
200	0.980	0.985±0.015	0.987	0.994±0.018
300	1.469	1.472±0.020	1.481	1.489±0.024
500	2.449	2.458±0.030	2.469	2.485±0.035

The calculated and measured values agree within 1%, validating the analytical framework for practical network design [36].

F. Latency Distribution Analysis

Figure 4(b) shows the latency distribution from 1000 consecutive measurements on 1 km fiber links. The SMF distribution exhibits mean 5.000 μs with standard deviation 0.050 μs, while MMF shows mean 5.100 μs with standard deviation 0.080 μs.

The higher variance in MMF results from modal noise effects and mode-dependent loss variations. This contributes to timing jitter that impacts synchronization accuracy in TSN applications [37].

V. DISCUSSION

A. Physical Interpretation

The latency framework provides an intuitive understanding of signal propagation in optical fibers as fundamentally limited by the refractive index of the medium. The fiber, characterized by its effective group index, imposes a deterministic delay that scales linearly with distance. This relationship derives directly from Maxwell's equations governing electromagnetic wave propagation in dielectric media [38].

The success of the approach relies on accurate characterization of the effective refractive index for each fiber type and operating wavelength. Modern fiber specifications provide this information through group delay measurements, enabling precise latency calculations for network design [39].

The observation that MMF exhibits slightly higher latency than SMF reflects the fundamental physics of light propagation at different wavelengths. The 850 nm operating wavelength of MMF corresponds to a higher refractive index region of the silica dispersion curve, resulting in slower group velocity [40].

B. Industrial Network Design Implications

The results provide clear guidelines for fiber selection in time-critical industrial networks. For horizontal cabling within control cabinets (distances below 30 m), the latency difference between SMF and MMF is negligible at approximately 1.2 ns. Either fiber type satisfies timing requirements with substantial margin [41].

Backbone cabling connecting PLCs to remote I/O racks typically spans 100-500 meters. At these distances, the SMF-MMF difference of 4-20 ns remains well within the jitter tolerance of industrial protocols. Cost considerations generally favor MMF for these applications [42].

Campus-scale networks extending to 2 km encounter latency differences approaching 80 ns. For applications requiring sub-100 ns timing accuracy, such as motion control synchronization, the fiber type selection becomes significant. SMF offers both lower latency and reduced jitter in these scenarios [43], [44].

C. Time-Sensitive Networking Considerations

IEEE 802.1AS specifies residence time measurement accuracy within ±100 ns for conformant implementations. The fiber-induced latency variation of 39.4 ns/km between SMF and MMF consumes a significant portion of this budget for kilometer-scale networks [45].

The frame preemption mechanism in IEEE 802.1Qbu/802.3br enables deterministic latency bounds by allowing high-priority traffic to interrupt lower-priority transmissions. This capability reduces worst-case latency but does not affect the fundamental propagation delay contribution [46].

D. Limitations and Future Directions

The present framework assumes idealized conditions that may not fully represent installed systems. Temperature variations affect refractive index at approximately 10^{-5}/°C, introducing latency drift of roughly 0.5 ns/km/°C. Long-term stability requires either temperature compensation or periodic recalibration [47].

Future developments will focus on extending the framework to wavelength-division multiplexed (WDM) systems, where different wavelengths experience different propagation delays due to chromatic dispersion. Additionally, we aim to incorporate the effects of optical amplifiers and regenerators for extended-reach industrial networks [48].

VI. CONCLUSIONS AND FUTURE PERSPECTIVES

This study has developed a comprehensive analytical framework for propagation delay characterization in single-mode and multimode fiber networks, with explicit application to time-sensitive industrial communications. The key findings may be summarized as follows.

First, the propagation delay follows the fundamental relationship $\tau_{prop} = nL/c$ with effective group indices of 1.4682 for SMF at 1310 nm and 1.4800 for MMF at 850 nm. These values correspond to propagation delays of 4.898 μs/km and 4.937 μs/km respectively.

Second, the delay difference between SMF and MMF is 39.4 ns/km, becoming significant for precision timing applications at distances exceeding 500 meters. At typical industrial distances of 100-300 meters, the difference of 4-12 ns is negligible for most protocols but measurable with precision instrumentation.

Third, total end-to-end latency comprises serialization delay (1.2 μs for 10GbE with 1500-byte frames), switch processing delay (0.3-1.0 μs for cut-through switches), and propagation delay. At typical industrial distances, serialization dominates for short links while propagation dominates for longer spans.

Fourth, the framework achieves excellent agreement with experimental measurements, with calculated values matching observations within 1% uncertainty. The validation confirms the utility of the analytical approach for practical network design.

Future efforts will focus on incorporating temperature-dependent effects for outdoor installations, extending the analysis to next-generation 400G and 800G interfaces, and developing Monte Carlo models for worst-case latency estimation in complex network topologies.

The fundamental understanding developed here establishes a foundation for optimizing time-sensitive networks in Industry 4.0 environments. As industrial automation demands increasingly stringent timing requirements, careful latency characterization will remain essential for achieving deterministic real-time performance.

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