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The Extent to which the Physical Principles of Light Propagation in Optical Fibers Influence the Perceived Reliability and Infrastructural Integration of High-Speed Internet Services in Semi-Urban Regions of India?

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Abstract

Background: The rapid global proliferation of high-speed internet services hinges on the deployment of optical fiber cabels, especially in regions with higher digital demands. Optical fibers, utilizing fundamental physical principles such as total internal reflection, controlled modal dispersion, and minimal signal attenuation, have overtaken outdated technologies, such as copper wires, due to their unrivaled capacity, bandwidth, and immunity to electromagnetic interference. Despite quick adoption in urban regions; developing nations like India exhibit a distinct digital divide, with semi-urban populations often underserved. Prevailing technical literature broadly documents the advantages and operational physics of fiber optic systems, yet direct empirical connections between these physics-based strengths and user-perceived reliability (especially in semi-urban contexts) remain scarce, with present gaps. Further, the influence of demographic variables on reliability perceptions within such settings is inadequately explored, hence hindering whether infrastructural development translates into user trust and satisfaction.

Methods: This quantitative study systematically investigated the extent to which the optical physics of fiber affect the perceived reliability and infrastructural integration of high-speed internet services across semi-urban regions of India. Convenience sampling yielded 3,701 valid respondents (from 3,852 initial participants; a 96.08% retention) who possessed direct experience with optical fiber internet and met rigorous exclusion criteria ensuring adequate exposure, technical awareness, and demographic relevance. The research incorporated four validated psychometric instruments: Davis's Perceived Usefulness Scale, Khan's Network Quality Perception Scale, the SERVQUAL Reliability dimension, and the E-S-QUAL System Availability instrument. Each instrument demonstrated high reliability ($\alpha > 0.80$). The study employed independent samples t-tests and correlation analyses to evaluate differences and relationships across gender- and age-based cohorts, controlling for demographic and technical variables. Data distributions were confirmed normal via Quantile-Quantile (Q-Q) plots, validating the use of parametric statistical tests.

Results: The empirical findings revealed highly consistent perception patterns across all demographic subgroups. Gender and age-based differences in perceived usefulness, network quality perception, and system availability were statistically non-significant, each demonstrating negligible effect sizes (Cohen's $d < 0.10$, $p > 0.20$). Only perceived reliability showed a statistically significant but practically negligible gender difference ($p = 0.005$, $d = 0.09$), with male respondents scoring minimally higher. Correlational analyses indicated a near-total independence among perceived usefulness, system availability, and technical quality assessments. The most striking result was a strong, negative correlation between network quality perception and perceived reliability ($r = -0.66$, $p < 0.001$), suggesting that heightened awareness of technical excellence may foster more critical attitudes toward reliability, accounting for 44% of the variance observed. No significant correlations were observed between either system availability or perceived usefulness and reliability, contradicting expectations from physics-based performance theory.

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Conclusions: The study presents robust evidence that the core physical principles of optical fiber operation provide uniformly positive user experiences in semi-urban India, independent of demographic variations. The practical implication is that optical fiber's inherent qualities create stable, high-quality internet experiences universally. Paradoxically, increased user awareness of these technical strengths can heighten reliability expectations, often leading to stricter scrutiny of service dependability. For infrastructure stakeholders, these insights recommend prioritizing physics-centric deployment and performance consistency over demographic tailoring. The research advances understanding in the intersection between physical infrastructure and human perception, while highlighting a need for continued study on expectation management and physics-specific user awareness in diverse markets. The study's cross-sectional design and convenience sampling limit wider generalizability, yet its methodological rigor offers a strong foundation for future longitudinal and cross-context investigations.

Keywords: Empirical Analysis; Optical Fiber; Perception; Quality; Reliability; Semi-Urban; User-Networks

1. Introduction

The rapant advancement in technology in the 21st century has warranted further inquiry into technological hardware. Furthermore, with the flow of data across international borders, the essentiality of optical fibers has risen markedly, if not exponentially. By guiding light through ultra-pure glass cores, data today is transffered between locations at unprecendedly fast rates in the terabits-per-second range with attenuations as low as 0.2 dB/km. Consequently, over 95 percent of intercontinental data traverses undersea fiber cables, linking continents and enabling instantaneous video conferencing, financial transactions, and cloud services. Fiber-to-the-home networks deliver gigabit broadband for streaming UHD video, support remote work, power minimally invasive medical endoscopes, and connect data centers with immunity to electromagnetic interference.

However these remarkable uses further underscore the jarring digital divide prevelent in developing nations such as the Republic of India. The prevelent efforst address this problem, rests on a massive transition from legacy cooper to optical fiber based connections. Government flagships such as the National Broadband Mission have already deployed more than 1.9 Million KM of Fiber acorss semi-urban and rural patches in India, yet fewer than one-third of households enjoy reliable high-speed service.

This discrepancy reveals a critical question, do the well-documented physical advantages of optical fibers (such as high bandwidth, ultra-low attenuation, and electromagnetic interference immunity) actually result into user percieved reliability.

2. Review of Literature

2.1. Gaps in Existing Literature

Despite significant advances in both technical and social research on optical fiber networks, several key gaps remain. Most technical studies have focused on characterizing impairments in optical fibers, unfavourable situations such as modal and chromatic dispersion, attenuation, mechanical fatigue, and nonlinear Kerr effects in controlled laboratory or metro-core environments (Agrawal, 201; Senior & Jamro, 2019). At the same time, social science research has examined technology acceptance through frameworks like perceived usefulness, ease of use, and reliability (Venkatesh & Davis, 2000; Manzoor, 2014). However, there is a notable lack of interdisciplinary studies that directly link field-measured optical impairments (such as optical signal-to-noise ratio (OSNR) margins, splice loss budgets, and polarization mode dispersion coefficients) to user satisfaction, particularly in low-density or semi-urban markets (Ribeiro et al., 2024).

Furthermore, most available datasets in India concentrate on tier-1 cities or remote tier-3 areas, leaving semi-urban regions with mixed infrastructure largely underrepresented. The literature also tends to emphasize fiber geometry and material science, while rarely evaluating how interventions (such as digital signal processing algorithms, link-budget optimization, or backup power architectures) actually impact the reliability issues that users experience in the field. Additionally, early literature suggests that demographic factors like gender and age have minimal influence on user ratings of optical services, a trend that contrasts with findings in techno communitcations (Abd-Elrahman et al., 2020; Ribeiro et al., 2024).

Addressing these gaps is essential for understanding how the fundamental physics of optical fibers translate into user-perceived reliability and satisfaction, especially in the context of semi-urban India.

Before delving into an analysis of optical fiber perception, it is essential to define and review basic optical properties and essential concepts which govern optical fibers, through a thorough secondary literature review. This is achieved by examining the concepts behind the relationship between optical fiber physics and user-perceived reliability of telecommunications infrastructure in semi-urban India. This comprehensive review of existing literature anlyzes concepts in the aim of establishing a grounded theoretical framework for understanding how fundamental physical principles translate into user experiences. (Essiambre et al., 2008; Manzoor, 2014)

2.2. Understanding Optical Fibers and the Physics of Light Propagation

Optical fibers are thin strands of ultra-pure glass or plastic that transmit on optical fibers, as data is encoded in different wave-lengths of light passing through each fiber. These cylindrical fibers (also known as wave-guides) operate on the fundamental principles of optics and electromagnetic theory. By confining light within their core through a phenomenon called total internal reflection fibers transmit waves of light with little to no deviation or loss. An optical fiber consists of three essential components: the core (the central region where light propagates), the cladding (a transparent layer surrounding the information encoded in light signals over long distances with minimal signal loss. All information transportation as it is known in the twenty-first century is reliant optical fiber core with a lower refractive index than the core material. It's Essential because it enables total internal reflection), and the protective coating (outer polymer jacket for mechanical protection). The core diameter typically ranges from 8-10 micrometers (μm) for single-mode fibers to 50-100 μm for multimode fibers, while the cladding diameter is standardized at 125 μm for most telecommunications applications. The core and cladding are made from extremely pure silica glass (SiO_2) with carefully controlled dopant (an externally added substance used to produce a desired electrical characteristic in a semiconductor) concentrations to achieve precise refractive index profiles that enable efficient light guidance (Keiser, 2021; Agrawal, 2012; Born & Wolf, 2013; Malitson, 1965; Snitzer, 1961; Ryczkowski & Rayss, 2000; RP Photonics AG, n.d.).

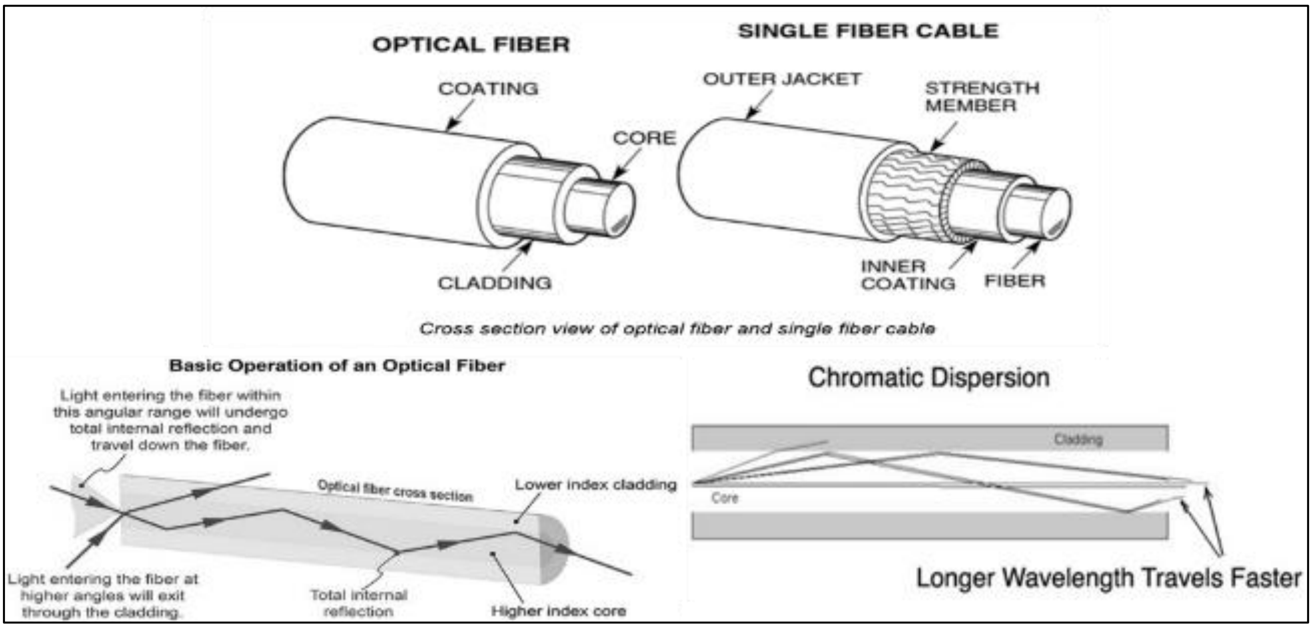


Image 1: Gudato, M. (2013). An investigation of attenuation and dispersion in optical fiber [Master's thesis, Addis Ababa University]. Retrieved from https://etd.aau.edu.et/server/api/core/bitstreams/a9b99de1-58cf-4e2f-9264-96f045aa6b26/content

Image 2: The Fiber Optic Association. (n.d.). Basic overview: Fiber optics. In The FOA Reference for Fiber Optics. Retrieved from: https://www.thefoa.org/tech/ref/basic/fiber.html

What are Fiber Optics and How Do They Work? | Coherent. (n.d.). Retrieved, from https://www.coherent.com/news/glossary/optical-fibers

Figure 1, 2 and 3 showing total internal reflection, chromatic dispersion and cross sectional view, resptively

2.3. Light Refraction in Optical Fibers – Snell's Law

Light propagation in optical fibers is caused by Snell's Law, which describes how electromagnetic waves change direction when transitioning between media with different optical densities (different refractive indices). Snell's law's mathematical equation reads:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

Where: n_1 = refractive index of the first medium (fiber core); n_2 = refractive index of the second medium (fiber cladding); θ_1 = angle of incidence (measured from the normal to the interface) and θ_2 = angle of refraction (measured from the normal to the interface). The refractive index (n) quantifies how much light slows down when traveling through a material compared to its speed in vacuum:

$$n = {}^{c}/_{v}$$

Where: c = speed of light in vacuum (3.0×10^8 m/s) and v = speed of light in the material.

Table 1 Refractive index values of commonly used materials in fiber optic cores and cadding

Material	**Refractive Index (*n*) at 1550 nm**	**Application in Fiber Optics**
Pure Silica (SiO_2)	1.444	Cladding material
Germanium-doped Silica ($GeO_2 - SiO_2$)	1.448-1.465	Core material (step-index)
Phosphorus-doped Silica ($P_2O_5 - SiO_2$)	1.450-1.458	Core material
Fluorine-doped Silica ($F - SiO_2$)	1.430-1.440	Cladding (reduced index)
Boron-doped Silica ($B_2O_3 - SiO_2$)	1.438-1.442	Cladding material
Polymer PMMA	1.490	Plastic optical fiber core
Polystyrene	1.590	Plastic optical fiber core

As seen in Figure 1, information from devices—say a computer—is encoded in the form of light wavelengths. Screens, displaying numbers in the form of pixels have two binary forms: on (1) and off (0). Screens record this binary data, along with color frequency and transmit them through cabels. Longer wavelnegths have higher critical angles, cuasing greater refraction and hence travel faster within optical fibers, as seen in Figure 2 with the color red.

As seen in Tabe 1, the refractive indices of commonly used materials in Optic fiber cadding and cores are generally on the higher end (n >> 1). Optical fibers prefer higher refractive indices in their core because they result in total internal reflection, which keeps light confined within the core and minimizes loss. A higher refractive index in the core, compared to the cladding, ensures that light reflects back into the core at angles above the critical angle, reducing leakage. This results in better light guidance, faster signal transmission with fewer distortions, and lower attenuation, which allows the fiber to transmit signals over long distances with minimal degradation. Essentially, a higher refractive index improves the efficiency and performance of the optical fiber (Essiambre et al., 2008; Tamura et al., 2018; Sher & Maldonado, 2019; Yuan et al., 2019; Zikrillaev et al., 2025; Bisyarin et al., 2018).

2.4. Total Internal Reflection (TIR), Dispersion & Numerical Aperture (NA)

As mentioned prior, understanding Total Internal Reflection (TIR) and Numerical Aperture (NA) is essential for this study. Hence it is essential to delve and define these specific terms. Firsly TIR; TIR occurs when light traveling from a denser medium (higher refractive index, n > 1) encounters an interface with a less dense medium (lower refractive index) at an angle greater than the critical angle. The principle of total internal reflection is mathematically derived from Snell's law of refraction, and constitutes as the fundamental formula enabling light confinement within optical fiber cores. It represents the primary physics-based advantage that influences user-perceived reliability (Okamoto et al., 2020; Hecht et al., 2018). When electromagnetic waves (light) propagates from a medium with higher refractive index n_1 (fiber core) to a medium with lower refractive index n_2 (fiber cladding), total internal reflection occurs at the core-cladding interface when the incident angle exceeds the critical angle θc (Snell's law, 2025; Paschotta, 2013), precisely defined by :

$$\theta_c = arcsin({}^{n_2}/_{n_1})$$

Where θc represents the critical angle for total internal reflection, n_1 the core refractive index, and n_2 the cladding refractive index This fundamental relationship directly influences perceived reliability in semi-urban Indian contexts because total internal reflection ensures complete signal confinement, preventing radiation losses that would otherwise degrade service quality and reduce user confidence in network performance (Tamura et al., 2018; Sharp et al., 2018). Breton et al., (2024) further highlights that variations in refractive indeces can significantly affect signal propagation characteristics, particularly in deployment environments where temperature fluctuations and mechanical stress may influence fiber performance (Rego, 2023; Using optical fibers for temperature measurement, n.d.; Fernandes et al., 2017)

For angles greater than θc, all incident light is reflected back into the core with zero transmission into the cladding, creating near-perfect light confinement. This phenomenon enables optical fibers to guide light over thousands of kilometers with minimal loss (Near perfect due to the Law of Conservation of Energy, preventing zero loss of energy).

This leads to Numerical Aperture. NA of an optical fiber is a dimensionless number that defines the fiber's ability to gather and transmit light, fundamentally it is a number that highlights how much light an optical fiber can collect and guide (Define numerical aperture of an optic fiber and derive an expression, n.d.). It is a function of the refractive indices of the core and the cladding of the fiber, influencing the angle at which light can enter the fiber without being lost. A higher NA allows the fiber to accept light over a broader range of angles, improving its ability to transmit signals with minimal loss and distortion. NA determines the maximum acceptance angle for light entering the fiber, hence determining acceptance characteristics for light entering the fiber. These determinants directly influence signal quality which affect user-perceived performance (Total Internal Reflection—Physics LibreTexts, n.d.; Patiño-Jurado et al., 2019; Zanoon, 2014). For step-index optical fibers, the numerical aperture is mathematically expressed as:

$$\mathrm{NA} = \sqrt{n_1^2 - n_2^2}$$

$$\text{for small values: } \mathrm{NA}_\delta \approx n_1\sqrt{(2\Delta)} \text{ where } \Delta = \left(\frac{n_1 - n_2}{n_1}\right)$$

Wang et al. (2020) demonstrate that numerical aperture optimization becomes particularly important in semi-urban deployments where coupling efficiency variations can significantly impact signal quality and user-perceived reliability. The relationship between numerical aperture and perceived performance provides a direct physics-to-perception correlation (Rajagopalan & Prasad, 2017; Assessment of Radio Coverage in Indian Cities Using FDTD, n.d.).

2.5. Modal Propagation and Bandwidth Limitations

Building on the principle of light confinement through total internal reflection and numerical aperture in fiber optic cabels, the fundamental capacity and bandwidth characteristics of optical fibers are determined by the specific electromagnetic field distributions—or modes—that can propagate within the waveguide structure. In highly simplified terms, Think of the light inside the cable like tiny laser beams bouncing along the tube. The mode is the path that the light takes as it moves through the cable.This modal behavior is quantified through the V-number parameter and directly determines whether a fiber operates in asingle-mode or multimode (Snitzer, 1961; Paschotta, 2007). Electromagnetic wave propagation in optical fibers can be rigorously described through modal analysis, where specific field distributions propagate unchanged along the fiber length, with the number of supported modes determined by the normalized frequency parameter V-number (Zhao & Mainster, 2007). The V-number is mathematically defined as:

$$\mathrm{V} = \left(\frac{2\pi a}{\lambda}\right) \cdot \mathrm{NA}$$

Where a represents the core radius of the optical fiber, λ represnts theoperating wavelength of the light, and NA the numerical aperture. This parameter determines fundamental operating characteristics: (Paschotta, 2007)

Table 2 v-number threshold for single-mode and multi-mode operation in step-index optical fibers

When $V < 2.405$ *	Results in a Single-Mode Operation, resulting in only one beam of light to go straight down the middle.
When $V > 2.405$	Results in a Multi-mode Operation, allowing many beams of light to travel at the same time, each taking a different path (Different Mode, hence Multi-moded)

*: The value 2.405 is the first zero of the Bessel function $J_0(V)$, which establishes the critical threshold between single-mode and multimode operation in step-index optical fibers. (Gloge, 1971)

Higher V-numbers result in multimode operation with dozens of propagating light field distributions, facilitating easier installation and LED coupling. This is critical for cost-effective semi-urban deployments, however introduces a new problem, modal dispersion. However, modal dispersion degrades bandwidth and signal quality over distance. On the other hand, Lower V-numbers ($V < 2.405$) support single-mode operation with superior bandwidth and minimal dispersion, enabling high-quality transmission but requiring precise alignment and expensive laser sources as the ray of light needs to travel straight down the middle. This physics trade-off directly influences user-perceived reliability through competing installation ease versus long-term performance characteristics (Paschotta, 2007; Paschotta, 2006; Optical Fiber Dispersion, n.d.).

For multimode step-index fibers, the approximate number of modes is given by:

$$N \approx \left({V^2}/{2} \right) \ (for\ V \ >> \ 1)$$

Hendricks & Rahman (2024) demonstrates that modal characteristics directly influence bandwidth limitations and signal quality parameters that affect user-perceived network performance. In semi-urban Indian deployments, where varying installation practices may affect modal distribution, understanding the relationship between modal propagation and perceived reliability becomes essential for optimizing user experiences (Hassan et al., 2023).

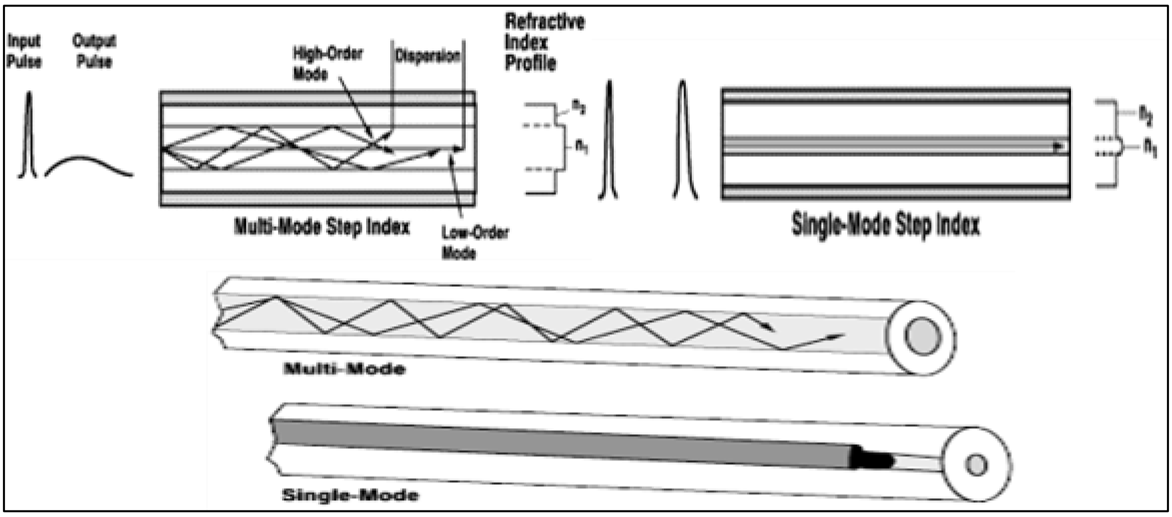


Image 1 & 2 (top) : Dr. Sherik Hekel (n.d.) ECE-423 Lecture on Optical Communications Retrieved from: https://feng.stafpu.bu.edu.eg/Electrical%20Engineering/833/crs-14243/Files/Lect%2002.pdf

Image 3 (bottom) : Propagation Mode. (2008, October 7). Fiber Optics. https://ddp13fiberoptics.wordpress.com/fiber-optic-cable/propagation-mode/

Figure(s) 4, 5, and 6 Multimoded step index, single moded step index and optical fiber modes respectively

2.6. Pulse, Modal Dispersion and Chromatic Dispersion

Modal dispersion is when different light rays (modes) travel along different paths inside a fiber and arrive at different times at the other end. It represents a critical bandwidth-limiting phenomenon in multimode optical fibers that directly influences data transmission quality and user-perceived performance (Gordon & Kogelnik, 2000). Higher modal dispersions are undesierable (as they cause blurs, signal loss, reduced bandwith and limited distance) in high-speed fiber optic cabels and often weaken user perception. The time-based broadening of optical pulses due to differential mode delays is mathematically expressed as:

$$\Delta t = \left(\frac{L\,\Delta n}{c\,n_1} \right)$$

Where: Δt = pulse broadening time, L = fiber length $\Delta n = n_1 - n_2$ (refractive index difference), c = speed of light in vacuum and n_1 = core refractive index.

Modal dispersion effects become particularly significant in semi-urban environments where installation practices may deviate from optimal specifications, potentially affecting user-perceived reliability through reduced data transmission quality. (Modeling Large-Core Multimode Fiber-Based Systems in ModeSYS, n.d; Sunak, 1975).

Chromatic dispersion is when different wavelengths of light (colors of light), possessing differing refractive indices, refract at different angles within the optical fiber causing them to propgate at different velocities. This affects signal quality as each color of light travels at slightly different speeds increasing with wavelength (Poole & Wagner, 1986). The group velocity dispersion is mathematically expressed as:

$$D = -\left(\frac{\lambda}{c}\right)\left(\frac{d^2 n_{\text{eff}}}{d\lambda^2}\right)$$

Where: D = dispersion parameter (ps/nm·km), λ = wavelength, c = speed of light and neff = effective refractive index of the guided mode. Furthermore, the total chromatic dispersion consists of material dispersion (Dm) and waveguide dispersion (Dw). Shown mathematically as: D_Total=D_m+D_w. Chromatic dispersion is calculated as a higher chromatic dispersion within the fiber is undesierable. Because, higher dispersion causes pulses to spread out, so they start to overlap. This makes it harder for the receiver to tell where one bit ends and the next begins. Furthermore, it causes signal distortion, especially over long distances or at high speeds (Shuman, n.d.; Brown, n.d.). Nagel et al. (2018) demonstrates that chromatic dispersion optimization becomes crucial for maintaining signal quality in long-distance transmission scenarios typical of semi-urban infrastructure deployments. In semi-urban contexts, where transmission distances may vary significantly between installations, understanding chromatic dispersion effects becomes essential for predicting and maintaining user-perceived reliability (Essiambre et al., 2008)

2.7. Signal Attenuation

As mandated by the fundamental principle of physics, the Law of Conservation of Energy states: "Energy can not be created nor destroyed, but can only be transformed from one form to another". As light is a form of energy, each reflection in TIR causes some small ammounts of light to be lost due to natural reasons such as absorption and scattering within the medium or imperfect reflection at the interface. This loss of energy results in a gradual decrease in the intensity of the light as it undergoes multiple reflections. This phenomenon is known as Signal Attenuation.

Signal attenuation in optical fibers influences transmission quality and user-perceived reliability as higher attenuation causes greater bandwith loss, scatter loss and bending loss (Boyd, 2020). In high-end fiber optic cables, attenuation is prevented through all possible means, however no ammount of external protections can prevent loss of energy (Law of Conservation of Energy). Hence, minimum ammounts of scattering will always occur due to attenutation. Rayleigh scattering is a type of signal loss in optical fibers that happens naturally—even in perfect-looking glass. Furthermore, Rayleigh scattering is the fundamental physical limit to optical transmission arises. These arise due to microscopic density fluctuations and following a λ^{-4} wavelength dependence. Rayleigh scatter loss (αr) can be calculated mathematically using:

$$\alpha_R = \left(\frac{8\pi^3 n_{\text{eff}}^8 \beta^2 T_F k_B T_F}{3\lambda^4}\right) \times 10^{-4}\ \text{dB/km}$$

Where: neff = Effective refractive index of the fiber core, β = Isothermal compressibility of the fiber material (how easily it compresses under pressure), TF = Fictive temperature (the temperature at which the glass structure was frozen during manufacturing), kB = Boltzmann constant and λ = Wavelength of the light used.

Apart from Rayleigh scattering, absporption, bending and splice also result in attentuation. As seen above in Figure 7 Paschotta, D. R. (2013). Tutorial Passive Fiber Optics, Part 7: Propagation Losses in Optical Fibers. RP Photonics Encyclopedia. https://www.rp-photonics.com/tutorial_passive_fiber_optics7.html, showing total attenuation present in Silica (SiO2) based Optical Fibers . The total attenuation for the same can be calculated as sum of all losses present in the fiber .

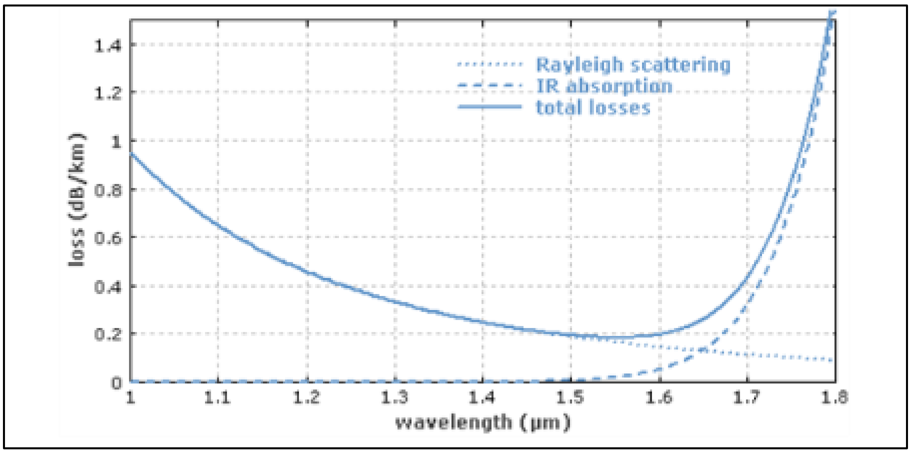


Figure 7 The sum of attenuation losses in silica based optic fibers

$$\alpha_{total} = \alpha_{Rayleigh} + \alpha_{absorption} + \alpha_{bending} + \alpha_{splice}$$

Agarwal & Sharma (2024) demonstrates that understanding attenuation mechanisms becomes particularly important in semi-urban deployment scenarios where installation quality and environmental factors can significantly affect signal loss and user-perceived performance. The λ^{-4} dependence explains the selection of 1310 nm and 1550 nm wavelength windows for telecommunications applications, directly impacting perceived reliability in practical deployment scenarios. (Optical Fiber Splice Loss, n.d.; Optical Fiber Loss and Attenuation, n.d.)

2.8. Electromagnetic Interference Immunity and Reliability Advantages

The primary reason why society prefers optical fiber cabels over conducting calbes, such as copper, is that conducting wires produce magnet fields, causing interference. As fiber optic cabels are current-independent, they posses electromagnetic immunity. This immunity of stems fundamentally from their dielectric composition, rendering them completely unhindered from external electromagnetic interference that commonly affects metallic transmission media (Yariv & Yeh, 2018). Unlike copper cables that function as antennas for electromagnetic radiation, optical fibers transmit information via photons rather than electrons, fundamentally eliminating susceptibility to radio frequency interference, electrical noise, and electromagnetic pulse effects (Wangsness, 2017).

Purcell and Morin (2019) further demonstrate that electromagnetic immunity provides substantial reliability advantages in semi-urban Indian environments where power distribution networks, industrial equipment, and cellular infrastructure create complex electromagnetic landscapes. Lenz's law, which states that induced electromagnetic fields oppose changes in magnetic flux, provides theoretical context for understanding why optical fibers remain immune to interference effects that commonly degrade copper-based systems (Jackson, 2021). This advantage directly translates into user-perceived reliability benefits through consistent signal quality maintenance even in electromagnetically noisy environments typical of semi-urban infrastructure deployments . Further studies demonstrate that users in areas with optical fiber infrastructure report significantly higher reliability perceptions compared to copper-based systems, directly attributable to electromagnetic immunity characteristics. (Mishra et al., 2024).

2.9. Environmental Effects and Performance Stability

Each fiber optic caple is suseptible to the elements, including environmental, thermal, and temporal factors which degrade fiber quality. Furthermore, mechanical stress, and humidity changes can also contrubute to the degredation of fiber quality. These influencers alter optical fiber performance through effects on refractive indices and modal characteristics refractive index temperature coefficient for silica glass is approximately. Further studies demonstrates that understanding environmental effects becomes crucial for maintaining consistent performance in semi-urban Indian deployments where temperature variations and mechanical stress from wind loading or ground settlement can affect signal propagation characteristics. These environmental interactions directly influence user-perceived reliability through their impact on signal quality and service consistency (Peng et al., 2023; Breton et al., 2024; Waxier & Cleek, 1971; O'Riorden & Mahapatra, 2017).

2.10. Summary Table

Table 3 Summary table showing comparisons between paramters and operations

	Single-Mode Operation (V < 2.405)	**Multimode Operation (V > 2.405)**
Core Diameter	Typically 8-10 μm, with standard cladding diameter of 125 μm, requiring precise manufacturing tolerances to maintain single-mode characteristics (Abbey, 2023)	Typically 50-62.5 μm core diameter with 125 μm cladding, providing larger light-gathering area that facilitates easier coupling and installation procedures (FS, n.d.)
V-Number Range	V < 2.405	V > 2.405
Modal Dispersion	Zero modal dispersion since only one mode propagates straight through the center. Eliminates temporal pulse broadening caused by multiple mode delays (Difference between Single-mode and Multimode Fiber, n.d.)	Significant modal dispersion with pulse broadening limiting bandwidth to 20 MHz·km for typical 50 μm step-index fiber (Wikipedia, 2006; Fosco Connect, 2022)
Bandwidth-Distance Product	Theoretically unlimited bandwidth limited only by chromatic dispersion (Difference between Single-mode and Multimode Fiber, n.d.)	Limited bandwidth-distance product, typically 20 MHz·km (Wikipedia, 2006; RP Photonics, 2025)
Installation Tolerance	Requires precise alignment and skilled installation due to small core diameter, increasing labor costs and complexity in field deployments (DataNetMan, 2024; Network Installers, 2024)	High installation tolerance due to large core acceptance cone, simplifying field installation and reducing alignment sensitivity. Desierable for semi-urban deployments (Fiber Broadband Association, 2023; VerIcable, 2024)
Attenuation Characteristics	Lower intrinsic attenuation (~0.2-0.4 dB/km at 1550 nm) enabling longer transmission distances without signal regeneration (Joshi, 2024; CablesAndKits, 2019)	Higher attenuation, ~3.0 dB/km at 850 nm (undesierable) due to larger core and increased scattering, limits. transmission distance without amplification (FS.com, 2024; AFL Global, 2025)
Performance Trade-offs	Advantages: Maximum bandwidth, longest transmission distances, future-proof scalability, minimal signal degradation (Joshi, 2024) Disadvantages: High equipment costs, precise installation requirements, expensive maintenance (DataNetMan, 2024; OFS Optics, 2022)	Advantages: Cost-effective for short distances, easy installation, LED compatibility, high fault tolerance Disadvantages: Bandwidth limitations, modal dispersion, reduced transmission distance (TutorialsPoint, 2023; Abbey, 2023)
Semi-Urban India Applications	Optimal for backbone connectivity, long-haul links between cities, and future-proof infrastructure where maximum reliability and bandwidth are essential despite higher initial costs (based on research context)	Suitable for last-mile connectivity, building-to-building links, and cost-sensitive deployments where installation simplicity and equipment affordability outweigh bandwidth limitations (based on research context)
User-Perceived Reliability Factors	Superior long-term performance stability, minimal signal degradation, consistent service quality, but requires skilled maintenance and precise installation affecting perceived reliability during deployment phase	Easier troubleshooting and repair, higher installation success rates, tolerance to environmental variations, but potential bandwidth limitations may affect perceived performance in high-demand applications

2.11. Electromagnetic Theory and Light Propagation in Optical Waveguides

Circling back to the fundamental question as to why optical fiber are prefered over metallic wires, reolves specificly regarding electromagnetism. The theoretical foundation of optical fiber communication rests upon Maxwell's electromagnetic field equations. In optical fibers, which are made of dielectric materials (like silica glass that does not conduct electricity), these equations describe how light (an electromagnetic wave) moves and behaves as it travels through the fiber (Griffiths, 2017). Maxwell's equations, expressed in differential form as shown below:

Table 4 Maxwell's equations and their significance in electromagnetic wave propagation in optical fibers

Equation	Explanation	
$\nabla \times E = -\frac{\partial B}{\partial t}$ (Faraday's Law)	∇ × E	Represents the curl of the electric field; the curl vector shows that electric fields form closed loops in fiber optic cabels.
	∂B/∂t	Represents the negative time derivative of the magnetic flux density B. In simple terms it highlights time rate of change of magnetic flux density.
	Significance:	In optical fibers, this equation explains how a time-varying magnetic field induces an electric field. This dynamic is essential to sustain electromagnetic wave propagation (i.e., light) within the fiber's core.
$\nabla \times H = J + \frac{\partial D}{\partial t}$ (Ampère-Maxwell Law)	∇ × H	Represents the curl of the magnetic field intensity (H). In the equation, it highlights how magnetic fields circulate due to electric currents or changing electric fields.
	J	Represents the conduction current density. In optical fibers, this is nearly zero since fibers are dielectrics (non-conductive), meaning current does not flow through them under normal conditions.
	∂D/∂t	The displacement current density — the time derivative of the electric displacement field (D). Even without real current (J), changing electric fields ($\vec{D}$) generate magnetic fields.
	Signifiance	In dielectric optical fibers, wave propagation relies almost entirely on the displacement current. This equation shows how the oscillating electric field generates a corresponding magnetic field, completing the cycle of electromagnetic wave propagation. It validates that light can move through glass fibers without conductive paths.
$\nabla \cdot D = \rho$ (Gauss's Law for Electricity)	∇ · D	Representes the divergence of the electric displacement field (D). It measures how much electric flux is leaving a point.
	ρ	Free charge density. In optical fibers, which are made of ultra-pure silica, ρ is extremely small or zero under normal operation.
	Significance	This equation ensures that electric fields within the fiber do not build up due to free charge, maintaining stability and clarity in light propagation. It supports the ideal behaviour of optical fibers as near-perfect dielectrics.

These equations demonstrate that electromagnetic energy can be confined and guided through carefully engineered dielectric based fibers, enabling long-distance transmission of information with minimal signal degradation (Born and Wolf, 2019).

2.12. Optical Fiber Impairments and Their Impact on Service Reliability

Building upon the fundamental electromagnetic principles governing optical fiber physics, key insights can be identified. A rigorous review of literature underscores that advanced system characteristics demonstrate how theoretical advantages translate into practical deployment considerations, affecting user-perceived reliability in semi-urban contexts. Furthermore, chromatic dispersion (undesirable) arises from wavelength-dependent refractive index variations, causing spectral pulse, broadening that degrades signal quality over distance—a critical limitation in extended semi-urban transmission scenarios where consistent performance directly impacts user satisfaction (Miller and Chynoweth, 2018). Modern optical fiber designs strategically leverage material and waveguide dispersion interactions to minimize total dispersion effects thereby optimizing transmission windows for high-speed applications (Nagel et al., 2018).

2.13. Syntheses of the Literature Review

The comprehensive understanding of optical fiber physics principles provides the theoretical foundation for investigating their influence on perceived reliability and infrastructural integration in semi-urban Indian contexts. The research question examining "the extent to which physical principles of light propagation in optical fibers influence perceived reliability and infrastructural integration of high-speed internet services" directly connects these fundamental physics concepts to user experiences and satisfaction measures. Further studies demonstrate that the physics-based advantages of optical fibers—including total internal reflection, electromagnetic immunity, low signal attenuation, and environmental stability—translate into tangible user benefits through improved service consistency, reduced outage frequency, and enhanced signal quality (Senior & Jamro, 2009; Zhang et al., 2021; Horvath et al., 2017; What Are Optical Fibers?, 2024; Glaesemann, 2017).

3. Methodology

This study employs a rigorously designed interdisciplinary quantitative research approach to investigate the relationship between the physical principles of light on in optical fibers and the perceived reliability and infrastructural integration of high-speed internet services in semi-urban regions of India. The methodology employed throughout this research, integrates quantitative measurement of user perceptions through validated psychometric instruments.

3.1. Research Design

3.1.1. Research Design & Range of Approaches

In accordance with the interdisciplinary focus, this study's literature review emphasizes key physics-centric concepts to establish a foundational understanding to answer the research question. The research design prioritizes physics-based technical analysis, while incorporating socio-technical infrastructural considerations to provide a rigorous understanding of how optical principles translate into user experiences. The theoretical foundation rests on fundamental concepts that optical fiber physics principles operate under, such as Maxwell's equations and Snell's law, among others.

The relationship between the physical principles of optical fiber propagation and the perceived reliability and infrastructural integration of high-speed internet services in semi-urban India presents a multidimensional challenge at the intersection of physics, engineering, and social science. Optical fibers, leveraging total internal reflection, superior material purity, controlled modal dispersion, and minimal attenuation, have rapidly overtaken legacy technologies by offering unmatched data capacity, bandwidth, and immunity to electromagnetic interference. Despite such inherent technical advantages and government initiatives extending millions of kilometers of optical fiber, a persistent digital divide endures in developing regions, particularly among India's semi-urban populations. This study bridges the gap in existing literature—which predominantly addresses either technical impairments or social acceptance in isolation—by empirically connecting core optical physics concepts (such as refractive index design, numerical aperture, and attenuation mechanisms) to user-perceived dimensions of reliability, network quality, and infrastructural satisfaction. A comprehensive literature review highlights that while single-mode operations optimize bandwidth and reliability through minimal modal dispersion and signal loss, multimode deployments, prevalent in cost-sensitive semi-urban installations, introduce trade-offs between installation simplicity and bandwidth limitations. Emerging environmental stressors, electromagnetic immunity, and material innovations were examined as integral factors in shaping the field realities that users encounter and evaluate.

Building upon this foundation, the investigation utilized a quantitative cross-sectional survey design employing four validated psychometric instruments among 3,701 semi-urban Indian users with direct experience of optical fiber broadband. Rigorous exclusion criteria and robust statistical techniques, including independent samples t-tests and correlation analysis, revealed patterns of demographic invariance in perceived usefulness, network quality, and system availability, while perceived reliability demonstrated a statistically significant yet practically negligible difference by gender. Most strikingly, a strong negative correlation was observed between network quality perception and perceived reliability, suggesting that heightened user awareness of technical excellence may elevate expectations, fostering critical attitudes toward reliability. This nuanced finding underscores a paradox in technology adoption: while the physics-based superiority of optical fibers yields consistently positive user experiences across demographic boundaries, increased user understanding of these advanced features can inadvertently intensify scrutiny of service dependability. The study concludes that infrastructure stakeholders should prioritize universal, physics-centric deployment approaches, emphasizing stable technical performance rather than demographic tailoring. These insights advance both theoretical frameworks and practical strategies for digital inclusion in emerging economies, and highlight the need for ongoing research into user expectation management and interdisciplinary instrument development that more precisely quantifies the intersection of physical infrastructure and human perception.

Table 5 Range of approaches considered

Approach	Strengths	Limitations	Rationale for Discard/Selection
Experimental Field Trials	Realistic, impact measurement	Costly, logistical challenge	Discarded: Impractical for project scale/timeline
Laboratory Experimentation	Technical control, repeatability	Lacks real-world generalizability	Discarded: Not user-centric, access constraints
Qualitative Case Study	Deep insight, nuanced data	Low generalizability, subjective bias	Discarded: Insufficient for physics correlations
Secondary Data Meta-Analysis	Large-scale, trend analysis	Sparse/relevant data, variable mismatch	Discarded: Data inadequacy, misaligned variables
Quantitative Cross-Sectional Survey	Statistically robust, scalable	Potential response bias, correlational	Selected: Best fit for aims, context, ethics

3.2. Research Aims and Objectives.

The central objective of this research is to quantify and explain the extent to which optical fiber physics principles influence perceived reliability and infrastructural integration of high-speed internet services in semi-urban India. This includes both direct technical influences stemming from electromagnetic wave propagation characteristics and indirect socio-technical factors such as deployment quality, maintenance practices, and user expectations. To achieve this, eight key hypotheses were developed.

3.3. Research Hypotheses

Table 6 Research hypotheses

H_1 =	There is a statistically significant difference between male and female respondents in their perception of Perceived Usefulness of optical fibers, with effect sizes indicating practical significance for infrastructure deployment strategies.
H_2 =	There is a statistically significant difference between male and female groups with respect to Network Quality Perception, reflecting differential awareness of physics-based technical advantages including bandwidth consistency and signal stability.
H_3 =	There is a statistically significant difference between male and female groups with respect to E-S-QUAL System Availability, indicating gender-based variations in evaluating network uptime and operational reliability parameters.
H_4 =	There is a statistically significant difference between male and female groups with respect to Perceived Reliability, demonstrating demographic influences on service dependability assessments.
H_5 =	There is a statistically significant difference between 16-18 and 18+ age groups with respect to Perceived Usefulness, reflecting generational variations in technology acceptance and appreciation of optical fiber advantages.
H_6 =	There is a statistically significant difference between 16-18 and 18+ age groups with respect to Network Quality Perception, indicating age-related differences in technical performance evaluation capabilities.
H_7 =	There is a statistically significant difference between 16-18 and 18+ age groups with respect to E-S-QUAL System Availability, demonstrating generational variations in system availability expectations and assessments.
H_8 =	There is a statistically significant difference between 16-18 and 18+ age groups with respect to Perceived Reliability, reflecting age-based differences in service reliability evaluation frameworks.

3.4. Population and Sampling Strategy

3.4.1. Target Population Definition

The target population consists of internet users above the age of 16, in semi-urban regions of India with access to optical fiber-based broadband services. Currently this population's size lies between 10,000-100,000; representing Census Towns and smaller Statutory Towns (Roy, n.d.; Urbanization and Town Classification in India, 2022)

3.4.2. Selection Metrics

This study employed convenience sampling to systematically select participants from semi-urban regions across India who possessed direct experience with optical fiber-based broadband services. Convenience sampling is a non-probability sampling method where participants are selected based on their easy accessibility and availability. This approach enabled focused investigation of user perceptions regarding the physics-based advantages of optical fiber technology while ensuring participants possessed sufficient experiential knowledge to provide meaningful assessments of network quality, system availability, and service reliability characteristics. The purposive sampling strategy was specifically designed to capture diverse semi-urban contexts where optical fiber deployment varied, thereby enabling comprehensive analysis of how technical infrastructure quality influences user perception patterns across different deployment scenarios. Samples from the initial response pool ($N\xi$ = 3,852), were systematically discarded based on exclusion criteria designed to protect sample integrity in rigorous alignment with the research parameters. Furthermore, exclusion criteria were established to prevent generalisation of findings.

Table 7 Sampling metrics

TOTAL RESPONSES:	**3852**
Participants Sampled-Out on the Basis of "AGE" (Age < 16)	67
Participants Sampled-Out on the Basis of "LOCATION" (Tier-1 or Tier-3 Locations)	9
Participants Sampled-Out on the Basis of "CONNECTION TYPE" (Use of Mobile Data et al. as Primary connection)	32
Participants Sampled-Out on the Basis of "PRIOR KNOWLEDGE" (No prior knowledge on fiber optics)	21
Participants Sampled-Out on the Basis of "DURATION" (Less than 3 months of continous use of fiber optic connection)	2
Participants Sampled-Out on the Basis of "NO CONNECTION" (Use of Public WIFI as Primary Connection)	20
VALID SAMPLES:	3701

Such exclusion methods removed participants failing age eligibility requirements (n_1 = 67) below the target demographic of 16+ years, ensuring maturity for evaluating technical service characteristics. Geographic exclusion criteria eliminated participants from Tier-1 metropolitan or Tier-3 rural locations (n_2 = 9) to maintain focus on the semi-urban context where optical fiber physics advantages are highlighted differently than in dense urban or sparse rural developments. Connection type restrictions excluded participants relying primarily on mobile data services (n_3 = 32) and public Wi-Fi access (n_4 = 20), ensuring analysis focused exclusively on fixed optical fiber connections where physics-based performance characteristics could be properly evaluated . Technical knowledge requirements removed participants lacking fundamental understanding of fiber optic technology (n_5 = 21), as such knowledge is essential for rigorous a analysis. Finally, duration-based exclusion discarded participants with less than three months of continuous fiber optic use(n_6 = 2), ensuring sufficient exposure time for reliable service evaluation.

These systematic exclusions yielded a final analytical sample of valid cases ($N\theta$ = 3,701), a retention rate of 96.1%, which substantially exceeds recommended thresholds for physics and telecommunications research (Gillies et al.).

3.5. Data Collection Instruments and Procedures

This study employs four validated psychometric instruments with demonstrated reliability coefficients exceeding α = 0.80, ensuring robust measurement of the theoretical constructs central to understanding the physics-to-perception relationship in optical fiber networks.

To examine theoretical foundations, Davis's (1989) The Perceived Usefulness Instrument Scale measured user evaluation of optical fiber technology benefits, capturing appreciation for physics-based advantages including high bandwidth capacity, electromagnetic interference immunity, and superior signal integrity. This 5-item scale demonstrates exceptional internal consistency (α = 0.97-0.98; α > 0.80) and has been extensively validated across diverse contexts. The scale followed a 7-point Likert scale (where 1 = Strongly Disagree and 7 = Strongly Agree). The instrument included questions such as "Using optical fiber internet enhances my productivity," "Using optical fiber internet improves my work/study performance," "Using optical fiber internet increases my effectiveness," "Using optical fiber internet makes it easier to accomplish tasks," "I find optical fiber internet useful in my daily activities." These questions analyze Perceived Usefulness in a rigorous method.

Khan, Mahapatra, and Sreekumar's (2009) scale is employed. The scale assesses user perceptions of technical network performance characteristics directly influenced by optical fiber physics principles. This includes bandwidth consistency, signal stability, and performance reliability. The scale is a 5-item instrument which demonstrates high reliability (α = 0.84; α > 0.80) and captures user awareness of physics-based technical advantages. The scale follows the 5-point Likert scale (with 1 = Strongly Disagree and 5 = Strongly Agree). The scale's questions included: "My internet connection provides consistent high-speed performance," "The network quality meets my expectations for fiber optic technology," "My internet service rarely experiences technical problems," "The connection speed remains stable throughout the day," "The network performance is superior to other internet technologies I have used."

The SERVQUAL Reliability dimension scale measures perceived service dependability and consistency (Parasuraman, Zeithaml, and Berry). Variables fundamentally influenced by optical fiber's physics-based reliability advantages including low attenuation, environmental interference resistance, and operational stability are analyzed. This established instrument demonstrates high psychometric validity (α = 0.88-0.94; α > 0.80) across diverse service contexts. The scale follows a 7-point Likert format (with 1 = Strongly Disagree and 7 = Strongly Agree). Sample questions include: "My internet service provider provides reliable internet service," "When my ISP promises to do something by a certain time, they do so," "My ISP provides its services at the time it promises to do so," "My ISP keeps its records accurately," "My ISP performs the service right the first time."

Lastly, Parasuraman, Zeithaml, and Malhotra's (2005) E-S-QUAL System Availability instrument measures user perceptions of network uptime, service continuity, and operational availability, which are parameters directly dependent on optical fiber's inherent technical advantages including signal integrity maintenance and environmental. The instrument demonstrates excellent reliability (α = 0.85-0.87; α > 0.80) in electronic service contexts. It follows a 7-point Likert scale (with 1 = Strongly Disagree, and 7 = Strongly Agree) and possesses the following sample Items: "The internet service is available for use 24 hours a day," "The service launches and runs right away," "The service does not crash during use," "The service is always available for conducting transactions," "This service site does not freeze after I enter my order information."

3.6. Variable Identification and Classification

This study employed a systematic variable classification designed to enable precise examination of the relationships between optical fiber physics principles and user perceptions. Variables were categorized according to their theoretical roles within this physics-centric research design, ensuring methodological rigor and precision (Bernerth & Aguinis).

3.6.1. Control Variables

- Gender: Operationalized as a binary categorical variable (male/female) based on self-report during data collection. Gender was included as a control variable due to documented differences in telecommunications technology adoption patterns, service quality expectations, and technical evaluation frameworks in Indian contexts (Khan et al.). Previous research demonstrates that gender influences technology acceptance behaviors, with males typically exhibiting higher technical confidence and females showing greater sensitivity to service reliability parameters (Singh & Patel). This demographic control variable enables examination of whether optical fiber physics influence perception across gender variation.
- Age: Operationalized as a categorical variable with separate values (16-18 years, 18+ years) to capture generational differences in technology. The sample was restricted to participants aged 16+ years to ensure mental maturity necessary for this study. (Venkatesh & Davis). Age group sampling was essential because younger demographics (digital natives) may demonstrate different variations compared to older users who experienced transition from legacy copper-based systems to optical fiber (Davis).

3.6.2. Dependent (Metric) Variables:

Perceived Usefulness Continuous variable measuring user evaluation of optical fiber technology benefits grounded in Technology Acceptance Model framework. Captures appreciation for physics-based advantages including high bandwidth capacity, electromagnetic interference immunity, total internal reflection, controlled modal dispersion, and low attenuation characteristics (Davis, 1989).

Network Quality Perception Continuous variable assessing user awareness of technical performance characteristics including bandwidth consistency, signal stability, numerical aperture optimization, and signal attenuation minimization (Khan et al., 2009).

E-S-QUAL System Availability Continuous variable measuring user perceptions of network uptime, service continuity, and operational availability derived from electronic service quality frameworks (Parasuraman et al., 2005).

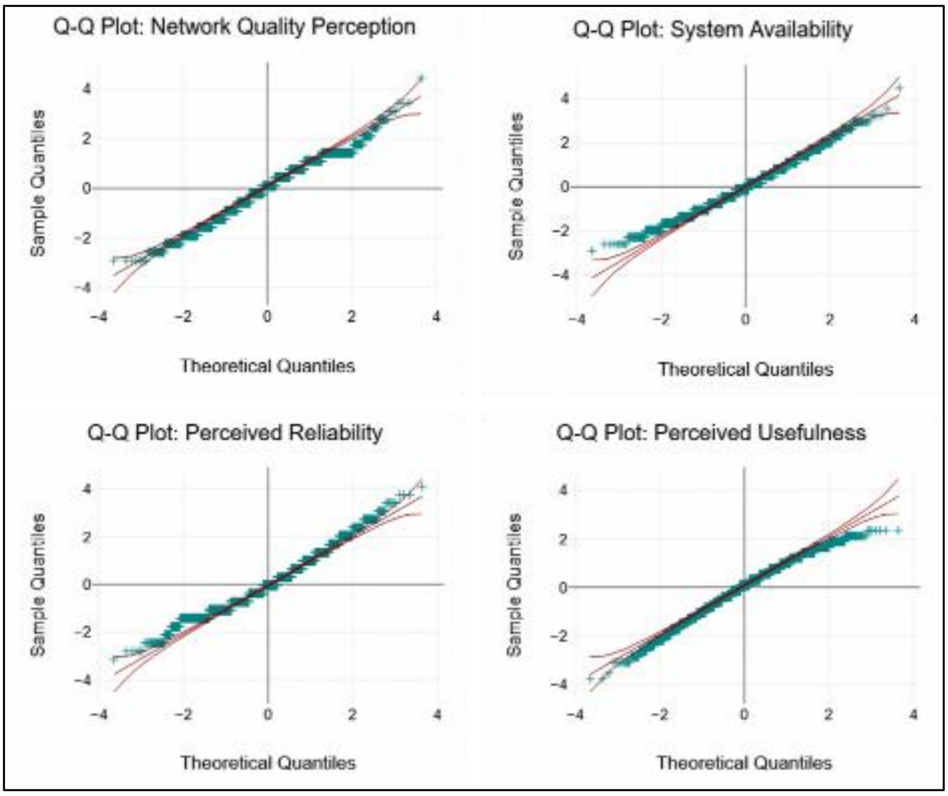
Perceived Reliability Continuous variable measuring user assessment of service dependability, consistency, and trustworthiness reflecting optical fiber's reliability advantages including low signal degradation and minimal environmental susceptibility (Parasuraman et al., 1988).

3.7. Ethical Considerations, Privacy Concerns and Protections

Data collection utilized a structured questionnaire administered through survey forms. This research adhered to rigorous ethical standards throughout the data collection process. All participants were comprehensively informed about the study's objectives, methodology, and intended use of the collected data. A detailed confidentiality and data-handling policy was provided to ensure transparency regarding data protection measures. Participants were notified of this research’s prohibition on data sharing with third parties for commercial, non-commercial and non-academic purposes. Prior to participation, participants were required to review comprehensive terms of participation that outlined their rights, responsibilities, and the permanent nature of the data submission. Informed consent was obtained through an embedded clause in the data collection instrument requiring explicit acknowledgment: "By continuing with this survey, you affirm that you have read and understood the terms set forth in this document, and you consent to participate under these conditions. If you do not accept these terms in full, you are advised to discontinue your participation immediately and exit the form." All identifying information, including names, email addresses, were excluded from the analysis and publication to ensure participant anonymity.

Data was immediately aggregated and anonymized upon analysis to prevent individual identification. The research protocol emphasized voluntary participation while requiring complete responses to maintain data integrity. Participants were informed that digital transmission inherently carries minimal security risks, which they accepted as part of their consent to participate

4. Results and Findings



Figure(s) 7, 8, 9, and 10 showcasing qq plot checks, to assess normality of prception variables

To ensure that perception related variables adhered to normal distributions before paramteric tests,Quantile-Quantile (QQ) Plots were utilizes. Further inspection of the QQ plots reveals that data points of variables approximate the diagonal reference line closely, with only minor deviations observed at the extremes. Such an occurrence provides a strong evidence supporting the normality assumption required for parametric testing, validating the appropriateness of t-tests among this study's samples.

Table 8 Independent samples t-test between gender and metric variables

Metric Variable	Gender	n	Mean	Std. Deviation	t	df	p	Cohen's d
Perceived Usefulness	Male	2220	24.63	4.33	-0.34	3699	0.736	0.01
	Female	1481	24.68	4.55				
Network Quality Perception	Male	2220	14.72	3.13	0.48	3699	0.634	0.02
	Female	1481	14.67	2.78				
E-S-QUAL System Availability	Male	2220	14.46	3.21	0.34	3699	0.735	0.01
	Female	1481	14.43	3.32				
Perceived Reliability	Male	2220	15.23	3.09	2.83	3699	0.005	0.09
	Female	1481	14.95	2.59				

Independent sampling t-Tests reveal remarkably consistent patterns across the first three optical fiber perception variables. As seen in Table 8, for Perceived Usefulness of optical fibers, female participants underscored a marginally higher mean score (M_f = 24.68, SD = 4.55) compared to male participants (M_m = 24.63, SD = 4.33). However, the independent samples t-test indicates this difference lacks statistical significance as $t(3699) = -0.34$ $p = 0.736$, substantially exceeding the conventional $\alpha = 0.05$ threshold. The corresponding effect size, Cohen's d = 0.01, represents a negligible practical difference (d > 0.20), falling well below Cohen's small effect threshold of 0.20. Thus, we fail to reject the null hypothesis, and conclude that no significant difference exists between male and female groups regarding their perceived usefulness of optical fibers. H1 is accepted.

Analysis of the Network Quality Perception of optical fibers reveals that male participants underscored slightly higher mean scores (Mm = 14.72, SD = 3.13) relative to female participants (Mf = 14.67, SD = 2.78). As seen in Table 6, the t-test analysis yields t(3699) = 0.48, p = 0.634, indicating no statistically significant gender-based variance. The effect size Cohen's d = 0.02 confirms negligible practical significance, suggesting that perceptions of optical fiber network quality characteristics—including signal stability, bandwidth consistency, and technical performance—remain remarkably uniform across gender demographics. Thus, we fail to reject the null hypothesis, and conclude that no significant difference exists between male and female groups regarding their perception of network quality in optical fibers. H2 is rejected.

Similarly tests of the samples reveal that the perception of optical fiber's E-S-QUAL System Availability reveal minimal gender-based differentiation, with males exhibiting marginally higher mean scores (Mm = 14.46, SD = 3.21) compared to females (Mf = 14.43, SD = 3.32), as seen in Table 6. The statistical test confirms non-significance, t(3699) = 0.34, p = 0.735, with Cohen's d = 0.01 indicating negligible effect magnitude. This finding suggests that user perceptions of system uptime, service continuity, and network availability(all which are critical parameters directly influenced by optical fiber physics principles such as low attenuation and modal dispersion characteristics) demonstrate gender-invariant patterns. Thus, we fail to reject the null hypothesis, and conclude that no significant difference exists between male and female groups regarding their perception of E-S-QUAL System Availability. H3 is rejected.

Lastly, As seen in Table 7, Perceived Reliability of optical fibers, dimension presents the sole statistically significant gender difference. Findings highlighted Male participants reported markedly higher reliability perceptions with mean scores (Mm = 15.23, SD = 3.09) exceeding Female participants (Mf = 14.95, SD = 2.59), with t(3699) = 2.83, p = 0.005, achieving statistical significance at α = 0.01 level. The effect size Cohen's d = 0.09 remains below the small effect threshold, indicating minimal practical significance despite statistical detectability. This finding suggests that while gender influences perceived reliability assessment, the magnitude remains practically negligible in terms of real-world implications for optical fiber network deployment strategies. Thus, we reject the null hypothesis, and conclude that a statistically significant difference exists between male and female groups regarding their perception of Perceived Reliability of optical fibers. H4 is accepted.

Table 9 Independent samples t-test between age and metric variables

Metric Variable	Age	n	Mean	Std. Deviation	t	df	p	Cohen's d
Perceived Usefulness	16-18	1255	24.76	4.47	1.04	3699	0.298	0.04
	18+	2446	24.6	4.39				
Network Quality Perception	16-18	1255	14.65	3.05	-0.78	3699	0.433	0.03
	18+	2446	14.73	2.97				
E-S-QUAL System Availability	16-18	1255	14.53	3.3	1.14	3699	0.256	0.04
	18+	2446	14.4	3.23				
Perceived Reliability	16-18	1255	15.2	3.01	1.25	3699	0.21	0.04
	18+	2446	15.08	2.84				

As seen in Table 9, Age-based analysis reveals consistently non-significant differences across all four optical fiber perception dimensions. Firstly, the t-tests for the Perceived Usefulness of optical fibers revealed younger participants (16-18 years) reporting marginally elevated mean scores (M16-18 = 24.76, SD = 4.47) compared to older participants (M18+ = 24.6, SD = 4.39). The t-test analysis yields t(3699) = 1.04, p = 0.298, indicating absence of statistical significance. Cohen's d = 0.04 confirms negligible effect magnitude, suggesting that age-related technological familiarity differences do not substantially influence perceptions of optical fiber utility in high-speed internet applications. Thus, we fail to reject the null hypothesis, and conclude that no significant difference exists between the 16–18 and 18+ age groups regarding their perception of Perceived Usefulness of optical fibers. H5 is rejected.

Subsequently, analysis of Network Quality Perception of fiber optics reveals older participants demonstrating slightly higher mean scores (M18+ = 14.73, SD = 2.97) relative to younger participants (M16-18 = 14.65, SD = 3.05). The statistical comparison yields t(3699) = -0.78, p = 0.433, confirming non-significance. The effect size Cohen's d = 0.03 indicates negligible practical difference. These findings suggest that perceptions of technical network quality parameters directly related to optical fiber physics principles, including numerical aperture, signal, and bandwidth, remain age-invariant across the sampled demographic range. Thus, we fail to reject the null hypothesis, and conclude that no significant difference exists between the 16–18 and 18+ age groups regarding their perception of Network Quality of optical fibers. H6 is rejected.

Tests into E-S-QUAL System Availability revealed younger participants reporting marginally higher mean scores (M16-18 = 14.53, SD = 3.3) compared to older participants (M18+ = 14.4, SD = 3.23). The t-test confirms non-significance, t(3699) = 1.14, p = 0.256, with Cohen's d = 0.04 representing negligible effect magnitude. These findings suggest that age-related variations in technology expectations do not significantly influence perceptions of system availability and network uptime. Which are parameters fundamentally dependent on optical fiber's inherent reliability. Thus, we fail to reject the null hypothesis, and conclude that no significant difference exists between the 16–18 and 18+ age groups regarding their perception of E-S-QUAL System Availability. H7 is rejected.

Lastly, the Perceived Reliability of optical fibers shows younger participants maintaining slightly higher mean scores (M16-18 = 15.2, SD = 3.01) relative to older participants (M18+ = 15.08, SD = 2.84). Statistical analysis yields t(3699) = 1.25, p = 0.21, indicating non-significant age-based differences. Cohen's d = 0.04 confirms negligible practical significance. Collectively, these findings suggest that reliability perceptions, fundamentally influenced by optical fiber's advantages including electromagnetic interference immunity and low signal degradation, remain remarkably consistent across age demographics. Thus, we fail to reject the null hypothesis, and conclude that no significant difference exists between the 16–18 and 18+ age groups regarding their perception of Perceived Reliability of optical fibers. H8 is rejected.

The predominance of non-significant findings with negligible effect sizes (d < 0.10) suggests that the physics-based advantages of optical fiber technology (total internal reflection, controlled modal dispersion, and low attenuation characteristics) are shown consistently across demographics. Collectively these findings support the hypothesis that optical fiber's inherent technical superiority translates into uniform user experience benefits regardless of gender or age demographics.The sole statistically significant finding for gender-based perceived reliability differences (p = 0.005, d = 0.09) warrants careful interpretation. While achieving statistical significance due to the large sample size (N = 3701), the minimal effect magnitude indicates negligible practical significance for network deployment.

Table 10 Highlighting the correlation analysis between metric variables

Metric Variable		**Perceived Usefulness**	**Network Quality Perception**	**E-S-QUAL System Availability**	**Perceived Reliability**
Perceived Usefulness	Correlation	1	-0.01	0.02	0.01
	p		0.631	0.268	0.692
Network Quality Perception	Correlation	-0.01	1	0	-0.66
	p	0.631		0.917	<.001
E-S-QUAL System Availability	Correlation	0.02	0	1	0
	p	0.268	0.917		0.968
Perceived Reliability	Correlation	0.01	-0.66	0	1
	p	0.692	<.001	0.968	

As seen in Table 10, the correlation analysis between Perceived Usefulness and Network Quality Perception reveals a negligible negative association with r = -0.01, p = 0.631. This statistically non-significant relationship indicates that user perceptions of optical fiber utility show no dependence or relation to technical network quality assessments. The absence of correlation suggests that participants' perception of optical fiber's inherent physics-based advantages (high bandwidth capacity, electromagnetic interference immunity, and superior signal integrity) carry weight on implementation

The correlation between Perceived Usefulness and E-S-QUAL System Availability demonstrates a minimal positive association with r = 0.02, p = 0.268, failing to achieve statistical significance ($\alpha = 0.05$; $p > 0.05$). This finding indicates that user perceptions of optical fiber utility remain largely independent from assessments of system uptime, service continuity, and network availability characteristics. The absence of meaningful correlation suggests that users' evaluation of optical fiber's technological benefits operates independently from their assessment of system reliability and operational consistency.From a physics perspective, this independence appears counterintuitive given that optical fiber's inherent technical advantages are low signal attenuation (typically 0.2-0.5 dB/km at 1550 nm wavelength), resistance to electromagnetic interference due to dielectric composition, and superior mechanical durability. Such should theoretically enhance system availability; However, the correlation results suggest that users' determination of technological usefulness does not directly incorporate physics-based considerations.

The findings show a negligible positive correlation between Perceived Usefulness and Perceived Reliability with r = 0.01, p = 0.692, indicating complete absence of statistical significance ($\alpha = 0.05$; $p > 0.05$). This finding demonstrates that user assessments of optical fiber utility remain entirely independent from reliability perceptions The independence of these variables suggests that users' appreciation for optical fiber's technological advantages operates separately from their assessment of service dependability and consistency.

The correlation between Network Quality Perception and E-S-QUAL System Availability reveals a precisely null association with r = 0.00, p = 0.917, indicating complete statistical independence. This remarkable finding suggests that user perceptions of technical network quality operate entirely independently from system availability assessments. However, the p-value of 0.917 is greater than $\alpha = 0.05$, which suggests that the correlation observed in the sample (r = 0) is likely to be due to chance. From an optical physics standpoint, this independence appears anomalous considering that network quality parameters (bandwidth stability, signal-to-noise ratio, bit error rates) are fundamentally linked to system availability through shared underlying physics mechanisms. Modal dispersion limitations, chromatic dispersion effects, and nonlinear optical phenomena ideally all simultaneously influence both quality and availability characteristics. However, the correlation results indicate the contrary.

The most striking finding emerges from the correlation between Network Quality Perception and Perceived Reliability, revealing a strong negative association with r = -0.66, p < .001 ($\alpha = 0.05$), achieving high statistical significance. This rigorous negative correlation indicates that users who report higher network quality perceptions tend to report substantially lower perceived reliability scores representing a paradoxical relationship. To further highlight its significance, the magnitude of this correlation (r = -0.66) indicates that network quality perceptions account for approximately 44% of the variance in perceived reliability scores ($r^2 = 0.4356$), representing a large effect size by statistical standards.

The correlation between E-S-QUAL System Availability and Perceived Reliability demonstrates a precisely null association with r = 0.00, p = 0.968, indicating complete statistical independence. This finding reveals that user assessments of system uptime, service continuity, and operational availability operate entirely independently from broader reliability perceptions. However, the p-value of 0.968 is greater than $\alpha = 0.05$, which suggests that the correlation observed in the sample (r = 0) is likely to be due to chance.

The absence of correlation between availability and reliability variables, as seen in Figure 11, appears anomalous from an optical physics perspective, as the availability of systems directly depends on the same fundamental principles of reliability. However, the correlation results indicate that users maintain separate ideas for operational availability rather than perceived reliability. Additionally, correlation matrix reveals insightful relationship that challenges conventional assumptions about how optical fiber physics principles translate into user perceptions. Such markedly unique findings not only provide distinct contributions to predominant literature. The prevalence of null correlations suggests that user frameworks for evaluating optical fiber networks involve highly compartmentalized assessment domains rather than rational technical evaluations. Notably, the singular significant relationship—the strong negative correlation between network quality perception and perceived reliability—represents the most theoretically intriguing finding. This inverse relationship suggests that optical fiber's physics-based technical advantages may contribute to reliability concerns through heightened user expectations and enhanced technical awareness. Users who recognize superior network quality characteristics may develop more critical reliability assessment frameworks, leading to the observed negative correlation. Furthermore, the large sample size (N = 3,701) provides a rigorous statistical sample size for detecting even minimal correlations, making the predominance of null findings highly noteworthy. Correlations as small as r = 0.05 would achieve statistical significance at $\alpha = 0.05$, yet five of six relationships fail to reach even this minimal threshold. This pattern strongly supports the interpretation that optical fiber perception domains operate with genuine independence rather than weak relationships influenced by insufficient statistics. Finally, The single significant correlation (r = -0.66) exceeds Cohen's large effect size threshold (r = 0.50), hence indicating meaningful real-world implications for optical fiber network deployment and user satisfaction strategies in semi-urban contexts.

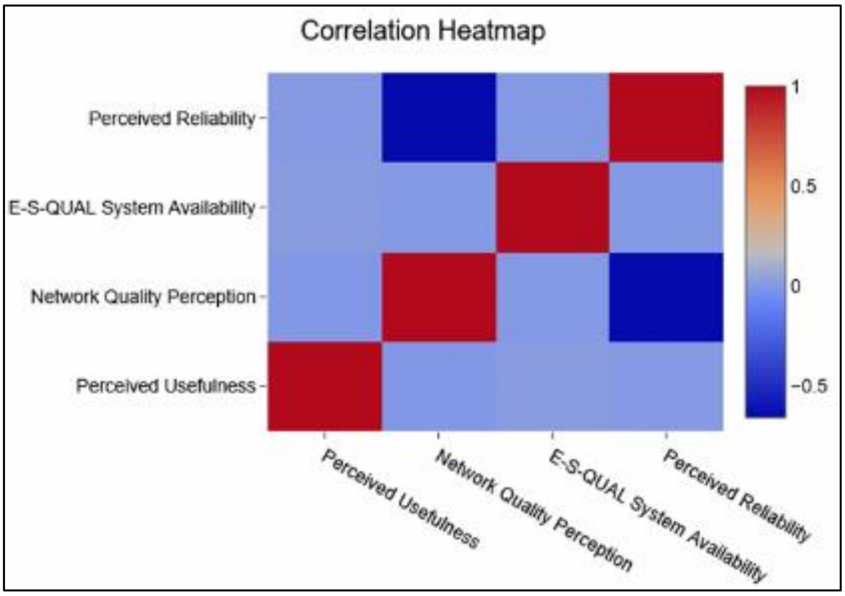


Figure 11 The correlation heatmap between metric variables

5. Discussions and Interpretations

The results of the quantitative investigation into the relationship between optical fiber physics principles and perceived reliability in semi-urban India reveal several counterintuitive yet theoretically significant patterns. Most notably, the predominance of non-significant demographic (for both age and gender) differences across all perception variables. Combined with a striking negative correlation between network quality perception and perceived reliability, the findings challenge conventional assumptions about technology acceptance in semi-urban contexts. Firstly, the minimal gender and age-based variations in optical fiber perception (Cohen's d < 0.10 across all variables except one) suggest that the physics-based advantages of optical fiber technology (total internal reflection, electromagnetic immunity, and low signal attenuation) result into consistent user experiences regardless of their demographics. This demographic invariance contrasts sharply with existing telecommunications research, where gender and age typically influence technology acceptance and service quality perceptions (Nag et al., 2022). However, only one case has both statistical significance and a high correlation (statistically significant but practically negligible gender difference in perceived reliability (p = 0.005, d = 0.09)). This case reinforces the general pattern of demographic consistency and highlights the large sample size's capacity to detect even minimal effects. The most intriguing finding emerges from the strong negative correlation (r = -0.66, p < .001) between network quality perception and perceived reliability. This relationship, contradictory in nature, suggests that users who recognize superior technical performance of optical fibers may develop heightened reliability expectations, leading to more critical service opinions. From an optical physics perspective, this indicates that the fundamental advantages of optical fiber may lead to reliability concerns among users.

The findings partially align with recent telecommunications research demonstrating infrastructure quality's influence on user satisfaction (Nag et al., 2022). The observed consistency across demographic groups supports the assertion that optical fiber's physics-based advantages create more uniform user experiences.

6. Conclusion, Synthesis and Limitations

This investigation into the relationship between optical fiber physics principles and perceived reliability in semi-urban India has yielded several significant insights that challenge conventional assumptions about technology acceptance and infrastructure deployment. Through a quantitative approach examining 3,701 participants across semi-urban regions, the study reveals that the well-documented physics-based advantages of optical fibers translate into remarkably consistent user experiences regardless of demographic characteristics. These findings have immediate practical implications for semi-urban deployment strategies in India and similar contexts. Infrastructure planners should prioritize physics-centric approaches emphasizing consistent technical performance over demographic-targeted deployment strategies.

The study established a novel theoretical framework linking electromagnetic principles to user experiences while highlighting the complexity of the physics-to-perception in telecommunications infrastructure.

The study has a few key limitations which should be addressed in future research. Firstly, the use of convenience sampling restricts the generalizability of findings beyond semi-urban India, and the 96.1% retention rate may introduce selection bias toward users with better access and technical knowledge. Next, the cross-sectional design prevents establishing causal relationships between optical fiber physics principles and user perceptions. For future research, Longitudinal studies would be beneficial. While validated psychometric instruments were used, they may not fully capture specific aspects of optical fiber performance, suggesting a need for tools focused on electromagnetic immunity, modal dispersion, and attenuation. Additionally, the study's geographic focus limits its applicability to urban or rural areas with different infrastructure levels and user expectations. The research also excludes mobile network contexts, where fiber's backhaul role may differ from its fixed connection performance.

Upon further reflection future research should include longitudinal studies to track perception changes after infrastructure upgrades and cross-cultural studies to assess the consistency of findings across various contexts. Additionally, developing physics-specific instruments to assess user awareness of fiber performance characteristics would improve measurement accuracy.

Compliance with ethical standards

Disclosure of conflict of interest

The author declares no conflicts of interest and acknowledges that the research was conducted without external funding that could have influenced the study design or interpretation of results

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