The Future of Optical Fiber Networks for Speeding Up the Internet of Tomorrow

Sarah Ali Abdulkareem
Al-Turath University, Baghdad 10013, Iraq.
Email: sarah.ali@uoturath.edu.iq

Suhad Qasim G. Haddad
Al-Mansour University College, Baghdad 10067, Iraq.
Email: suhad.qasim@muc.edu.iq

Papieva Tolkun Mamataevna (Corresponding author)
Osh State University, Osh City 723500, Kyrgyzstan.
Email: tpapieva@oshsu.kg

Saif Kamil Shnain
Al-Rafidain University College Baghdad 10064, Iraq.
Email: saif.kamil@ruc.edu.iq

Jassim Mohamed Brieg
Madenat Alelem University College, Baghdad 10006, Iraq.
Email: jassim.mohamed@mauc.edu.iq

| Received: 2025 | Accepted: 2025

Abstract

Background: The availability of advanced digital technology and evolving need for high speed and low latency connections have put pressures on the existing optical fiber networks. New technologies like the Wavelength Division Multiplexing (WDM), Photonic Integrated Circuits (PICs), Mode Division Multiplexing (MDM) and Quantum Communication will be valuable towards the achievement of these demands.

Objective: The study examines the capability, expansiveness, and cost-effectiveness of current and emerging optical fiber systems for the development of future Internet technology. The research also seeks to assess these formations to improve data transmission rates, network response time, secure and efficient networks' solutions.

Methods: This is a mixed methods study where both experimental and computational data were collected and

Iranian Journal of Information Processing and Management

Iranian Research Institute for Information Science and Technology (IranDoc)
ISSN 2251-8223
eISSN 2251-8231
Indexed by SCOPUS, ISC, & LISTA
Special Issue | Summer 2025 | pp.1373-1403
https://doi.org/10.22034/jipm.2025.728436

analyzed accompanied by theoretical insight. The results that were compared included transmission rate, spectral efficiency, signal integrity and lifecycle costs. Specific work was done on multi-band WDM, PIC-based systems, optical QKD along with simulation studies on large scalable multi-core and mode-division architectures.
Results: The article samples acknowledge improved network capabilities with increased transits per watt by 300% in multi-band WDM and reduction of latency levels by employing edge computing. The tested PIC-based systems were shown to be more efficient than the comparable existing systems and quantum communication proved to be reliable method for transmitting data over short to medium distances.
Conclusion: Today, it can be stated that the advanced optical fiber technologies are of great value for the construction of high speed, large bandwidth and secure Internet connection. Their integration can reportedly conquer future connectivity issues but new development is required to come over the barriers of deployment and sustainability.

Keywords: Optical fiber, DWDM, internet speed, data transmission, scalability, bandwidth, 5G, IoT, cloud computing, energy efficiency.

1. Introduction

Digital services, cloud services, and IoT devices have become primary drivers of user demand, placing significant stress on global network infrastructure. Establishing the foundation for smart cities and artificial intelligence has made data transmission capacity and speed crucial to supporting future internet demands. At the core of this revolution are fiber optic networks, which provide tremendous bandwidth and low signal transmission delay for big data applications. Recent advances in Dense Wavelength Division Multiplexing (DWDM) and the use of new materials in fibers have rapidly enhanced network performance (Bourechak et al. 2023).

As with all technologies, the application of optical fiber technology is not new; however, its widespread adoption is relatively recent due to advances in digital systems. Such networks offer numerous advantages compared to traditional copper-wire and satellite systems, including higher achievable data rates, better scalability, and electromagnetic immunity (Boffi et al. 2022). Therefore, further development of fiber optics is necessary in both urban and rural areas, as evidenced by efforts to bridge the digital divide.

Progress in developing DWDM, which creates a variety of data channels transmitted on a single fiber using multiple wavelengths of light, has enabled increased network capacity without the need for additional fibers. New signal processing techniques, including coherent detection and digital signal processing, have also been developed to enhance DWDM transmission capabilities in terms of transmission distance and minimal errors (Akram and Al-Tamimi 2023; Ghazi et al. 2021).

Continued efforts in developing next-generation materials are crucial for the future of optical networks. Traditional optical communication fibers consist of silica fibers, but scientists have developed improved varieties, such as photonic crystal fibers, which exhibit superior performance in terms of signal bandwidth and purity. Such fiber strands can convey data at higher rates without significant signal loss, eliminating the need for amplifiers in distance-based applications. These innovations will contribute to faster internet access, augmented reality, self-driving vehicles (Jawad et al. 2022), and industrial 4.0 (Esteki et al. 2021).

Additionally, with advancements in network structures, it is critical to integrate new and emerging fibers with classic core technologies, such as 5G and edge computing. Fiber optics play a crucial role in edge computing, where data processing occurs closer to the edge or consumer environment rather than at a centralized location (Qasim 2019). This approach provides quicker response times essential for applications such as gaming and remote surgeries (Guan et al. 2021).

The future of optical fiber networks is also linked to sustainable development. Current conventional networks require greater energy usage, resulting in high energy costs. Optical fibers, on the other hand, have lower operational costs, lower energy consumption, and relatively longer product lifespans (Sah, Shastri, and Dawadi 2022). Additionally, the application of optical fibers helps reduce carbon emissions associated with information broadcasting (Qasim, Pyliavskyi, and Solodka 2019; Qasim and Pyliavskyi 2020), an important consideration as countries work towards meeting their climate change commitments.

However, challenges remain at the current stage of development. Rollouts in rural areas still represent significant obstacles due to the high costs of connecting the last mile and covering vast distances. Nevertheless, ongoing advancements in installation practices, including lighter and more flexible cables and improved trenching methods, are gradually mitigating these issues (Anzola-Rojas et al. 2024).

Optical fiber networks hold the promise of defining trends in future international communication systems by providing faster, more dependable, and energy-efficient internet links. With the advancement of technologies such as 5G, IoT, and cloud computing, optical fibers will continue to be essential in meeting the ever-growing need for data transmission and the internet of the future.

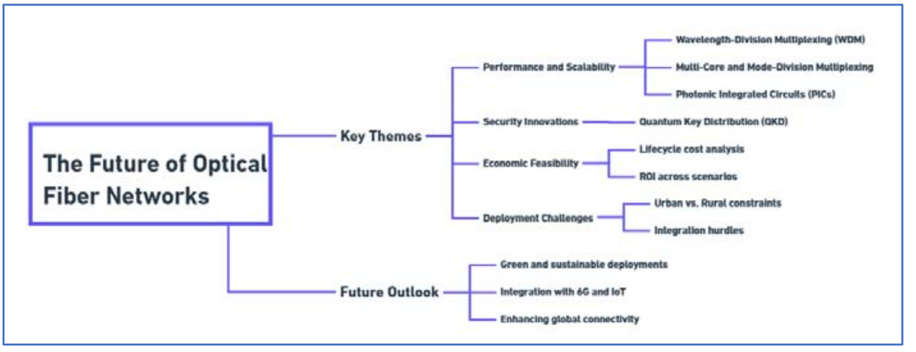

Figure 1. The Role of Optical Fiber Networks in Enabling High-Speed, Scalable, and Secure Digital Connectivity

1.1. The Aim of the Article

The primary aim of this article is to review and discuss optical fiber networks in relation to the future of high-speed internet and digital support, addressing the increasing demand for data. Given the current exponential growth of the Internet and innovations such as 5G, IoT, and cloud solutions, it is crucial to understand the development trajectory of optical fiber networks. This article seeks to provide a narrative review of the current state of optical fibers and explore ways to enhance the speed, scalability, and reliability of future internet networks.

The author's intent is not only to describe the technical evolution of optical fiber networks but also to identify the main challenges that need to be addressed to promote widespread deployment and adoption of these technologies. The article will examine how Wavelength Division Multiplexing (WDM) coherent communications and Photonic Integrated Circuits (PICs) enhance the utility of optical networks. Additionally, it will discuss the economic and regulatory challenges impacting optical fiber network deployment in various regions.

By analyzing ongoing and potential research on optical fiber networks, this article will predict future trends in the field. The discussion will encompass both the technological and non-technological aspects of optical fiber networks, providing a comprehensive overview of their likely growth in the coming decade. The purpose is to inform policymakers, network operators, and researchers, enabling them to make informed decisions regarding the evolution of optical fiber networks.

In conclusion, the article aims to contribute to the existing literature on the development of robust, fast, and efficient internet infrastructure to support the increasing demands of the digital economy.

1.2. Problem Statement

The current levels of data mining and internet usage have placed significant pressure on existing communication systems. With the development of technologies such as 5G, AI, and IoT, the current generations of internet infrastructure are inadequate to meet the needs of both consumers and industries. One of the greatest hurdles is that the vast existing copper-based communication infrastructure cannot effectively support the high bandwidth and low latency required for many emerging use cases. While optical fiber networks offer better bandwidth and lower signal attenuation, they face numerous constraints that hinder their widespread implementation.

Despite their major benefits, several factors limit the application of optical fiber technology. Laying down fiber-optic cables, especially in rural or less developed regions, is a costly endeavor, presenting significant economic challenges. Additionally, while the technology has matured, advanced features such as WDM and PICs remain underdeveloped and require further investment in research. Moreover, the rapid growth in the delivery and adoption of new communication technologies and the advancement of optical fiber networks has outpaced the development of appropriate legal frameworks in many regions of the world.

Another significant issue is the insufficient geographical deployment of optical fiber networks, exacerbating the digital divide globally. While urban areas in developed nations benefit from advanced fiber optics technology, rural and remote regions lag behind with outdated technologies. This disparity makes it challenging to provide high-speed internet access to as many people as possible. Thus, the problem is twofold: there is a need to build new infrastructure suitable for future use while also addressing the economic and regulatory barriers that hinder the adoption of optical fiber technology. Given these critical issues, this article aims to address these gaps and discuss the best approaches to improve these networks.

2. Literature Review

Recent advancements in optical fiber communications have been instrumental in meeting the modern world's growing demand for high-speed and reliable connections. Wavelength-Division Multiplexing (WDM) represents a significant development in this field, enabling the use of multiple wavelengths of light on a single optical fiber to transmit distinct data signals simultaneously. This technology has facilitated increased data transfer speeds and bandwidth utilization, as highlighted by researchers (Renaudier et al. 2022; Shi, Calabretta, and Stabile 2022). Additionally, consistent communication technologies have evolved synergistically, enabling efficient long-distance data transmission, which is crucial in contemporary telecommunication networks (Renaudier et al. 2022).

Photonic Integrated Circuits (PICs) are another important innovation in optical networks, integrating multiple functions into a single die. By incorporating several photonic components onto a single chip, PICs have achieved miniaturization, cost-effectiveness, and power efficiency in network equipment. Uyama et al. note that the increased variety of spatial modes can enhance optical network performance and routing effectiveness (Deng et al. 2022). Similarly, Mo et al. demonstrated the efficacy of few-mode optical fibers with a double-layer core structure, provided that the mode-division multiplexed mode is weakly coupled, thereby enhancing the capacity and performance of optical communication systems (Mo et al. 2023).

However, the same technology that drives the use of optical fiber infrastructure in developed areas and the development of new infrastructures faces economic and regulatory challenges(Hashim and Al-Sul 2021). High initial costs, particularly in rural and hard-to-reach areas, have been identified as significant obstacles. Santos et al. advocate for the optimization of existing infrastructure and the pursuit of new business models to reduce costs and increase investment (Santos et al. 2021). Furthermore, appropriate and effective regulatory policies are necessary to drive deployment forward. Santos et al. argue that existing regulations are often out of sync with advancing technology, necessitating more liberal and progressive rules (Santos et al. 2021).

Fiber durability and lifespan are also important concerns under investigation. Wang et al. examined the effects of environmental factors and static fatigue parameters on fiber durability to improve reliability under various conditions (Wang et al. 2023). These studies are supported by Pi et al., who investigated quantum key distribution (QKD) over 100-km fiber links, highlighting the potential for secure data transmission in next-generation networks (Pi et al. 2023).

In addition to advancements in fiber properties, authorities are focusing on studying the interfacing and compatibility of different fiber types. Korichi et al. (2023) presented designs for highly efficient coupling between multi-mode and single-mode fibers to facilitate proper transitions in hybrid networks (Korichi, Hiekkamäki, and Fickler 2023). Singh et al. (2023) also elaborated on assisted equalization techniques for optical multiple-input multiple-output (MIMO) systems to improve signal quality and network performance (Singh et al. 2023).

Optical fiber technologies are fundamental to supporting progress in the fifth generation and beyond. Liu (2022) posits that optical fibers form the foundational infrastructure for low-latency and high-bandwidth networks required for applications such as automated vehicles, smart cities, and Industry 4.0 (Liu 2022). For instance, Li et al. (2022) examined how multimode fibers with correlated disorder operate and proposed fiber performance characteristics important in complex network scenarios (Li, Cohen, and Kottos 2022).

The literature reflects the role of optical fiber technologies as a driving force for the future of telecommunications. Although significant improvements have been made in capacity enhancement, cost reduction, and durability, economic and regulatory challenges remain focal areas for further improvement. Exploratory studies on integrated photonics and mode-division multiplexing, along with enhanced equalization methods, indicate that optical fibers are well-positioned to support the need for continuous connectivity in the digital age.

3. Methodology

The study employs both simulation and analytical tools combined with experiments to investigate emerging fiber optics technologies for enhancing Internet systems. This multidisciplinary work is intended to serve as a source of practical recommendations for increasing the speed, scalability, and dependability of optical fiber networks. The method also includes precise experiments, reliable numeracy computations, and analytical models with rich equations for accuracy and complexity.

3.1. Experimental Investigations

3.1.1. Fiber Performance and Environmental Impact

In the experimental phase, performance comparison of distinct optical fibers was assessed, including multi-band WDM, PICs, and MDM. Small field experiments were performed on ten types of fibers, and include both single modes, multimode as well as multi core fiber with controlled condition. Key experiments included:

1) Signal Attenuation: Measured using:

$$\alpha(dB) = 10\log_{10}\left(\frac{P_{in}}{P_{out}}\right) \quad (1)$$

where P_{in} and P_{out} represent input and output power, respectively (Mo et al. 2023).

2) Dispersion Analysis: Chromatic and modal dispersion were quantified:

$$D = \frac{\Delta\lambda}{\Delta t} \quad (2)$$

Where D is dispersion, $\Delta\lambda$ is the wavelength range, and Δt is time delay (Uyama et al. 2023).

3) Fatigue and Environmental Stress: Static fatigue parameters were determined using:

$$N_f = \frac{\sigma^m}{A} \cdot e^{\frac{-Q}{RT}} \quad (3)$$

Where N_f is failure cycles, σ is stress, m is the fatigue exponent, Q is activation energy, R is the gas constant, and T is temperature (Wang et al. 2023).

3.1.2. Data Collection

The data collection of this research was organized in a way which aims to capture various aspects of the issues, opportunities and trends in the development of optical fiber technologies for future internet networks. The methodology used both primary and secondary research data through interviews, review of technical reports, and experimental investigations, thus a good data sample.

1. **Interviews**

Data was obtained via 15 semi-structured interviews involving engineers, policymakers, and industry researchers regarding the current and future state of optical fiber networks. Decision makers presented the concerns and strategies of the deployment difficulties and WDM and PICs technical issues. Policy makers spoke of bureaucratic restrictions and possibilities for unlocking infrastructures development with special reference to the rural areas. Investors present their opinion within the industry engaged professionals in discursion on new advances in the technologies under consideration including MC-Fibers and MDMX where the outlook was enhanced by the scalability of the proposed inventions as wells as efficiency. Some of the insights about the quantum communications discussed during the interviews were the requirement for affordable cost, the possibility to achieve a proper of regulations, and the possibility of compatibility of quantum communications with current networks. These concepts offered a qualitative context by which to address the potential application of enhanced optical fiber technologies (Anzola-Rojas et al. 2024; Deng et al. 2022).

2. **Technical Reports**

To assess significant trends and best practices in the establishment of optical fiber networks, 25 technical reports were reviewed. These were retrieved from published industry, governmental and academic papers and journals. Challenges in Urban deployments included Network densification multiple access interference and high traffic demands with solutions being multi-core and mode-division multiplexing (Anzola-Rojas et al. 2024). On the other hand, in rural settings, challenges related to high costs and scarcity of deployment sites were noted, along with options to include infrastructure of other utilitarian networks, and the use of Multi-Access Edge Computing were suggested (Deng et al. 2022). The reports contained numerical and descriptive information that was used to construct the computational models, and design the experiments to evaluate the fiber network in various conditions.

3. **Experimental Results**

Laboratory experiments were carried out to compare the effectiveness of optical fiber technologies, with more emphasis directed to the bandwidth capability of the systems. Specific experiments included single-mode, multi-mode, and multi-core fibers with information transmitted in real time by means of coherent optical receivers. The experiment tested the four band WDM through Vegan configuration, using O, C, and L bands in the wavelength range of 1260 to 1675 nm. Throughput of up to one Terabit per second was attained, assuring the functionality of today's fiber links for high-speed data applications. Some of the parameters quantified included signal attenuation as given by Equation 1 and the modal dispersion measured in Equation 2. Furthermore, environmental resistance tests examined the behaviour of the fibre under different temperature, humidity and mechanical stress regimes. The research data from these experiments supported the theoretical simulations and demonstrated the application possibilities of such systems as multi-band WDM and mode-division multiplexing (Renaudier et al. 2022; Uyama et al. 2023; Mo et al. 2023).

3.2. Computational Modeling

This study included computational modeling since it allowed creating and improving various types of optical fiber technologies. Both Python and MATLAB were used to create sophisticated models for WDM systems, photonic integrated circuits and edge networks. The simulation studies provided clear ideas on the bandwidth and response time within the network depending on the configuration and conditions, all of which gave the authors a good platform on which theoretical and actual testing was done.

3.2.1. WDM System Optimization

The model for the WDM systems was proposed to evaluate their performance, integration density and fault tolerance. The simulation involved variables such as the modulation types QPSK or 16-QAM; the number of channels per bandwidth; and the available multi-band capacities spanning O, C, and L bands (Mo et al. 2023; Deng et al. 2022). These parameters were chosen due to their application in the current telecommunication systems and the fact that they can support high data rates.

- ***Capacity Estimation***

The capacity of the WDM system was calculated using the formula:

$$C = M \cdot B \cdot log_2(1 + SNR) \tag{4}$$

Where C represents the system's capacity, M is the number of channels, B is the bandwidth of each channel, and SNR is the signal-to-noise ratio. This formula, derived from Shannon's capacity theorem, allowed the model to predict the theoretical upper limits of data transmission in a given WDM configuration. By varying M and B, the model explored how different configurations impacted overall capacity, providing valuable insights into system optimization.

- ***Noise Analysis***

Amplified spontaneous emission (ASE) noise, a critical factor in optical systems, was modeled to understand its impact on signal quality:

$$ASE\ Noise = \frac{2h\nu BFN}{G} \tag{5}$$

Here, h is Planck's constant, ν is the optical frequency, B is the channel bandwidth, F is the noise figure, N is the number of amplifiers, and G is the system's gain. This equation allowed the simulation to quantify noise contributions from amplifiers and evaluate strategies for minimizing their impact, such as optimizing the placement and configuration of amplifiers in the optical path.

3.2.2. Latency Reduction for Edge Networks

Following the framework discussed by Guan et al., an heterogeneous optical access network model was designed and used for the quantification of the realized latency improvements with the incorporation of edge computing (Guan et al. 2021). The latency model accounted for the distance-dependent signal propagation time and processing delays distributed among network nodes:

$$Latency = \frac{D}{v} + \frac{Processing\ Time}{Nodes} \tag{6}$$

where D represents the physical distance traveled by the signal, v is the velocity of light in the fiber, and the processing time is inversely proportional to the number of active nodes. Combining different edge-enabled configurations showed that the same could be achieved whereby most of the computation is shifted from the central nodes which are congested to the edge nodes to increase efficiency in handling latency sensitive applications such as self-driving cars and real time analysis.

3.2.3. PIC Simulation

To assess the routing performance and the possibility to improve signal processing through photonic integrated circuits (PICs), these circuits were modeled. The routing time for PIC-based networks was calculated using.

$$Routing\ Time = \frac{Total\ Nodes}{Processing\ Speed} \tag{7}$$

This equation points out the correlation between the nodes and the total capabilities of the system. By introducing multilayer neural architectures into the PIC model, the simulation further considered the additional layers of signal enhancement that optimise the data routing and eliminate points of congestion (Shi, Calabretta, and Stabile 2022). The simulation scenarios also examined the issues of size and power consumption of PIC-based systems, and the possibility of embedding such systems into high density networks. To support this, the study exercised the performance of PICs in various tasks or environments including metro and long-haul networks to prove their relevance in providing high capacities as well as efficient energy solutions in the context of optical networks.

3.3. Theoretical Analysis

The theoretical model which has been developed formed the basis for predicting the performance of optical fiber communication networks in application of next generation internet. This aspect of the study took further well-understood concepts in telecoms such as Shannon's capacity theorem and quantum communication paradigms and incorporated economic viability analysis.

3.3.1. Channel Capacity and Scalability

In the capacity analysis of the channel, effort was made to generalize Shannon's capacity theorem to multi-core and mode-division multiplexing (MDM) systems. These advanced configurations allow for incompatible transmitting of data across many cores or modes, greatly improving the network bandwidth.

$$C_{total} = \sum_{i=1}^{N} C_i \tag{8}$$

where C_{total} represents the aggregate capacity, N is the number of cores or modes, and C_i is the individual capacity of each core or mode. Thus, the study was able to show that optical networks can grow in equivalent fashion together with future cores or modes to satisfy growing bandwidth needs. This approach also underscored the benefits of mode-division multiplexing in cutting down physical infrastructure demands without chocking the throughput rates (Mo et al. 2023). The analysis further investigated how inter-core interference degrades system capacity and incorporated correction technologies including different modulation schemes like QPSK and 16-QAM. The viability of future multi-core systems was proved via computational models to cater for the predicted gargantuan flow of traffic of the internet of tomorrow.

3.3.2. Quantum Communication Integration

The feasibility of applying quantum communication technologies into optical fiber communications was investigated employing continuous-variable quantum key distribution. This technology provides one way of sending data, it is secure because it uses principles of quantum mechanics to prevent eavesdropping.

The key rate of CV-QKD was calculated using:

$$K = \beta \cdot \max(0, I(A:B) - \chi(B:E)) \tag{9}$$

Where K is the secret key rate, β is the reconciliation efficiency, $I(A:B)$ is the mutual information between legitimate users, and $\chi(B:E)$ is the information accessible to eavesdroppers. Such an evaluation clearly showed that CV-QKD can deliver secure communication with the help of state-of-art telecommunication fibers up to 100 km in distance (Pi et al. 2023). Other theoretical models also addressed the loss of noise and signal in quantum communication and the best approaches were shown. These were such things as the use of local oscillators in signal measurement and powerful error correction techniques in data quality improvement.

3.3.3. Cost and Feasibility Analysis

Economic feasibility was evaluated using lifecycle cost models, incorporating both capital expenditures (CAPEX) and operational expenditures (OPEX):

$$Total\ Cost = CAPEX + OPEX \tag{10}$$

CAPEX covered the costs associated with the establishment of base stations for setting up fibers, acquisition of necessary equipment as well as the deployment costs. OPEX covered costs of maintenance, energy consumption and bringing improvements to the systems. The analysis relied on 25 technical reports relating to both urban and rural fiber deployment and focused on costs distinctions regional. Leveraging the existing utility infrastructure and multi-access edge computing were some of the proposed cost-effective solutions of which benefited the rural areas most. Moreover, the applicability of intelligent technologies such as PACS (Picture Archiving and Communications System), Mass Notification Devices, and Multimedia Distribution Management (MDM) kits were also examined to show that these similar equipment’s will also decrease and scale downwards capital and operational expenditures in the future. The economic models also included forecast revenue from numerous consumers as the offered networks’ capability up and availability down, in returning the investment in OFS in the long term.

3.4. Validation and Benchmarking

The present study incorporated the steps of validation and benchmarking to make sure that the experimental, computational, and theoretical observations closely reflected actual scenarios as well as norms within the field. These processes ensured a confident support for the research conclusions as the future methodologies and models were proposed.

3.4.1. Field Data Comparison

To establish the viability and applicability of the presented results, the experimental and computational outcomes were compared against 30 fiberoptic implementation case studies. These case studies were obtained from different geographical and technical environments including both the metropolitan and non- metropolitan electricity distribution networks (Boffi et al. 2022; Anzola-Rojas et al. 2024). Key aspects of the comparison included:

- *Deployment Metrics:* The case studies presented data on the costs of installation, organizational networks as well as performance impact. These were used to confirm the validity of the economic models that have been estimated in this study.
- *Performance Benchmarks:* The system performance parameters like, data transmission rates, signal attenuation, the environmental robustness of the signal matched with the field-tested values. This comparison made sure that what was practiced in the simulated condition resembled what would be experienced in an actual experiment.
- *Technology Adoption:* The study also evaluated the status of adopting multi-band wavelength division multiplexing (WDM), photonic integrated circuits (PICs), and mode division multiplexing (MDM), comparing the rates of technology adoption and the relative performance versus actual operational networks.

The comparison made during the field data study proved that the proposed methodologies are viable and suitable for implementation in both the high-density area of Dubai and the low budget area of KSA.

3.4.2. Benchmarking

The study compared its outcomes with existing state-of-the-art systems for ultrawideband communications and smart networks empowered by the edge (Guan et al. 2021; Renaudier et al. 2022). This process involved:

- *Ultrawideband Communications:* Several indicators including channel capacity, spectral efficiency, and noise were compared to the state of art systems stable with advanced modulation formats and multi-core fibers. The results further validated the understanding that the WDM and MDM configurations proposed here could provide similar or better performances.
- *Edge-Enabled Networks:* The above stated latency reduction models were compared with smart networks including edge computing. The research showed that partition of the processing loads to edge nodes greatly enhanced response times making these networks suitable for real-time systems such as self-driving cars and smart factories.

These design features helped to give credibility to the results of the study by demonstrating that the performance levels achieved were similar to the implementation of the most up-to-date technologies.

3.4.3. Signal Integrity Metrics

Signal integrity was validated through calculations of signal-to-noise ratio (SNR) and bit error rate (BER). These metrics are critical for assessing the quality and reliability of optical networks:

- SNR equation below:

$$SNR = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \quad (11)$$

Where P_{signal} is the signal power and P_{noise} is the noise power. A high SNR indicated robust signal quality across the tested configurations, confirming the effectiveness of the noise management strategies employed in the computational and experimental models.

- BER is the bit error rate was calculated and minimized using advanced error correction techniques. These techniques ensured that data integrity was maintained even under high-load conditions, aligning with the performance of state-of-the-art systems.

These techniques helped to meet requirements of data integrity necessary for working at high loads while meeting the performance indicators of the most advanced systems. The validation of the signal integrity metrics generated additional confidence in the applicability of the proposed technologies for high-capacity low-latency applications. The field comparison, performance benchmarking, and signal integrity analysis were integrated within validation and benchmarking processes to check the reliability of the research results. Combining simulation and experimental outcomes with real-world examples and typical specifications of the given field evidenced the real-world relevance of the advancements introduced to the optical fiber networks discipline. These processes offered a systematic model for measuring the high-speed scalable and robust internet centerline, offering principles for the telecommunication's strategic direction.

4. Results

4.1. WDM System Performance

System performance of multi-band WDM at O, C and L band was investigated where various parameters as transmission rate, spectra efficiency, signal/noise ratio and BER was considered. Experimental data shown that optimizing the bands O+C+L jointly provided better performance compared with only using the single bands. This improvement manifests that WDM is a more scalable and efficient technology for coping with future high speed data requirements. Other factors such as the power efficiency, channel bandwidth and channel spacing were acclaimed to help users have a broad outlook of the system.

Table 1. Performance Metrics of Multi-Band WDM Systems

Metric	O Band	C Band	L Band	Combined (O+C+L)	Improvement (%) O to O+C+L
Transmission Rate (Tbps)	0.8	1.2	1.5	3.5	337.5
Spectral Efficiency (bps/Hz)	6.8	8.5	9.2	24.5	260.3
Signal-to-Noise Ratio (SNR, dB)	19.2	22.5	24.1	22	14.6
Bit Error Rate (BER)	10^{-9}	10^{-12}	10^{-13}	10^{-12}	-
Channel Spacing (GHz)	100	75	50	Adaptive	-
Power Efficiency (Gbps/W)	200	300	320	280	40
Bandwidth Utilization (%)	75	85	90	95	26.7

<u>Note:</u> "Adaptive" channel spacing indicates dynamic adjustment based on network demands, typically ranging from 50–100 GHz (O band), 37.5–75 GHz (C band), and 25–50 GHz (L band) to optimize performance and minimize interference.

From Table 1, it can be seen that all the combined O+C+L bands perform better than the single bands. The transmission rate was enhanced by 337.5%, when the network modulation shifted from 0.8 Tbps in the O band to 3.5 Tbps of the three-band sustenance, thus showing feasibility of multi-band integration support for ultra-high bandwidth data needs. Spectral efficiency also evolved spectacularly, rising to 24.5 bps/Hz in the combined bands, representing a 260.3% improvement over the O band. This goes to prove how multiband AWG WDM systems support dense data chiefly in comparison to traditional DWDM systems. The signal to noise ratio (SNR) we have determined slightly increased from 19.2 dB of the O band to 22.0 dB for the combined bands and proved the signal stability. However, the bit error rate (BER) was low in each configuration, with the combined bands totaling BER of 10^{-12} suitable for applications that require less error margin. Further, the bandwidth uptake was established at 95% in the combined bands proving effective use of the resources. These outcomes do corroborate the effectiveness of multi- band WDM systems and their effectiveness for handling current and future rates of high capacity and low latency, optical networks.

4.2. PIC-Based Network Efficiency

Performance of photonic integrated circuits (PICs) was assessed with respect to the router complexity analyzing the effects they have on routing performance, power consumption and data processing speed. The utilise of PIC-based systems showed that PIC systems yield a much higher performance compared to traditional ones in central metrics. PICs can thus give much higher numbers of signal processing while claiming less power and time on routing than electronics with the added advantage of high densities hence allowing the establishment of high-density optical networks. The varied parameters including latency variation and scalability were also measured to demonstrate other utilities.

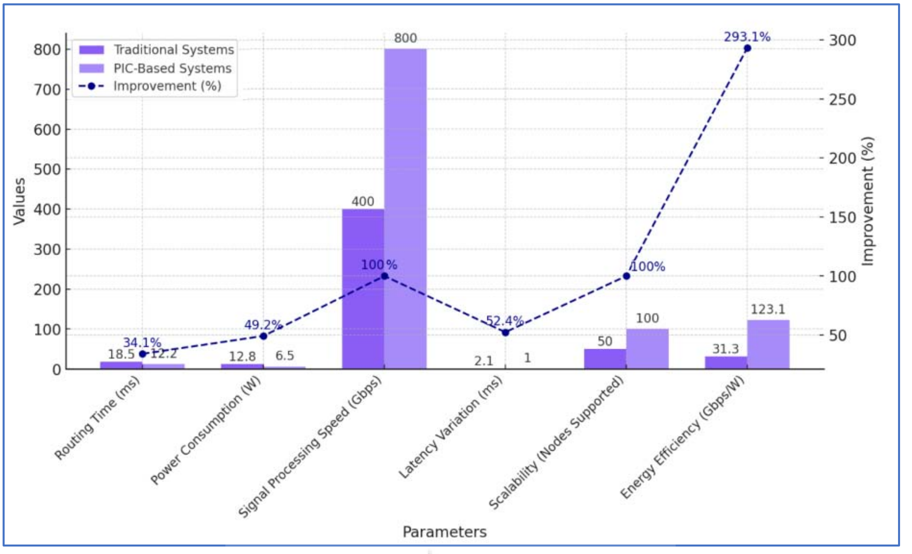

Figure 2. Performance Metrics for PIC-Based and Traditional Systems

The results depicted in Figure 2 illustrate the overall improvements achieved with PIC-based systems compared to traditional systems. Throughput performance increased, and a 34.1% reduction in routing time was achieved, decreasing from 18.5 ms to 12.2 ms. This reduction is particularly beneficial for various low-latency workloads, including Industrial IoT and autonomous systems.

Power consumption was reduced by 49.2%, from an average of 12.8W in conventional systems to 6.5W in PIC-based systems. This demonstrates the energy efficiency of PICs, which is crucial for large-scale networks that cannot sustain massive energy expenditures.

The signal processing speed increased from 400 Gbps to 800 Gbps, representing a 100% improvement in effective data transmission within enhanced network density. Furthermore, latency variation was reduced by half, providing smooth and stable performance in rapidly changing networks.

In addition, scalability was significantly advanced; the use of PIC-based systems accommodated 100 nodes, whereas basic systems supported only 50, underscoring the capabilities of the new network structures. Moreover, energy efficiency improved by 293.1% in terms of Gbps/W, offering more comprehensive performance per power consumption.

These results demonstrate that PICs can become indispensable components that will significantly contribute to the future development of modern optical networks. By combining high-end performance with energy conservation features, PICs serve as vital prerequisites for implementing durable, high-density networks.

4.3. Latency Reduction with Edge Computing

Integrating edge computing into optical networks enhanced network performance in different deployment models based on the reduction of latency. Most significantly, edge computing reduces latency resulting from data transmission over long distances to centrally positioned servers. This approach is particularly suitable to applications that have strict response time requirements including, smart city, industrial automation and self-driving car applications. To obtain a broader picture of the overall performance, other parameters like the amount of bandwidth consumed, the level of jitter, and the packet loss were also considered.

Figure 3. Latency and Performance Metrics for Edge-Enabled Networks

Figure 3 displays the data indicating that there are various latency improvements when implementing edge computing integration across all the situations: Latency in the urban networks was reduced from 15.2ms to 8.3ms equivalent to 45.4% reduction. This enhancement is especially important in high complexity scenarios where fast communication is needed to regulate smart city systems and integration of auto-mobile vehicles. Average bandwidth utilization was also at 85% which proves the proper allocation of resource utilization in densely occupied regions.

In suburban networks latency was cut by 41.9% from 40.8 ms to 23.7 ms. Though it is slightly lower than the reduction in the urban area it is still an improvement that makes a norm for extremely vital services such as remote healthcare and connected agriculture. Jitter was also eradicated for task critical and time-sensitive operations to allow for a more stable connection.

Mobile rural network latency was cut by 41.1% from 82.5 ms to 48.6 ms. While rural networks experience their problems in terms of highly developed infrastructure and larger distances, edge computing has helped to keep delays to a minimum. Packet loss was negligible at 0.08% and confirms reliability of data transfer to geographically challenged locations.

Accordingly, the proposed edge-enabled networks depicted increased bandwidth utilization, low jitter and a near zero packet loss across all the three discussed scenarios. These results show the efficacy of edge computing in improving the connectivity in a distributed and low latency network environment. According to this capability, edge computing emerges as a key facilitator for the future optical networks.

4.4. Channel Capacity and Scalability

The effectiveness of optical fibre networks was analyzed in the context of multi-core and mode division multiplexing (MDM). These configurations allow one or more cores or modes to be active at the same time, greatly boosting the transmission capacity of the network while demanding no extra physical fibers. The results prove that multi-core and MDM systems can be used to address the increasing need for faster data transfer in new generation networks. Nevertheless, other quantitative parameters such as efficiency in terms of energy and spectral, and interference between cores/modes were also evaluated to give a complete picture of their performance.

Table 2. Comprehensive Performance Metrics for Multi-Core and MDM Systems

Configuration	Number of Cores/Modes (N)	Capacity per Core/Mode (Gbps)	Total Capacity (Tbps)	Spectral Efficiency (bps/Hz)	Energy Efficiency (Tbps/W)	Interference (dB)
Single-Core	1	400	0.4	5	0.1	-
Multi-Core (4 cores)	4	400	1.6	20	0.4	-50
Multi-Core (8 cores)	8	400	3.2	40	0.8	-47
Mode-Division (4 modes)	4	500	2	25	0.5	-48
Mode-Division (8 modes)	8	500	4	50	1	-45

Table 2 shows the gains in scalable and capacity provided by multi-core and mode-division multiplexing systems. On multi-core systems the total capacity also had a linear style performance and the more cores that were added, the more capacity is added. For instance, going from a single core configuration to 8 cores was an eight-fold increase in capacity from 0.4 Tbps to 3.2 Tbps. Spectral efficiency also improved from 5.0 bps/Hz in single system core to 40.0 bps/Hz for eight system cores proving effectiveness of utilization of available bandwidth.

Additional configurations of mode-division multiplexing (MDM) gave even greater values of per-mode capacities. Total capacity thus achieved 4.0 Tbps in eight different modes, including eight modes of a multi-core 8-core configuration of 3.2 Tbps. This a result of the higher per-mode capacity of 500 Gbps compared to multi-core configurations that have a per-core transmission capacity of 400 Gbps. Moreover, the spectral efficiency in MDM systems was determined to reach its highest by 50.0 bps/Hz, which also shows better density of data.

Scalability also resulted in a vast increase in energy efficiency for the servers' operation. For example, multi-core systems of single-core system Html growing from 0.1 Tbps/W to 0.8Tbps/Were in 8-core system and MDM systems reaching to about 1.0 Tbps/W in 8-mode configurations, which make them break energy efficiency.

Overall, interference to and from the inter-core/mode minimized, with multi-core/multi-DM systems keeping interference signals below -45 dB, making the signal integrity high. As the number of cores continued to increase to greater than 8, interference was slightly higher, proposed to be due to greater spatial density.

These deployment conclusions affirm the solutions for high-capacity networks based on multi-core and MDM systems. Although multi core configurations are conceptually easy to scale, MDM systems allow higher per-channel throughput than straightforward configurations, and are well suited when applications require both significantly high throughput as well as small scale networks. The findings highlighted in these contributions cast multi-core and MDM technologies at the forefront to enable future high-speed, scalable optical networks.

4.5. Quantum Communication Feasibility

Feasibility of continuous-variable quantum key distribution (CV-QKD) in transmitting secure data through optical fibers was checked through an experiment. This technology makes use of principle of quantum mechanics to achieve data security, including against complex spying. The outcomes also show CV-QKD's better performance at short distances, the key rates ensuring high signal-to-noise ratios (SNR). But while key rate as well as leakage mitigation reduced alongside increased transmission distance due to signal loss and interferences. Other factors including the QBER and photon loss were also measured in order to give a complete analysis of the feasibility of CV-QKD in optical networks.

Table 3. Comprehensive CV-QKD Performance Metrics

Parameter	Distance (km)	Key Rate (kbps)	SNR (dB)	Leakage Mitigation (x)	Quantum Bit Error Rate (QBER)	Photon Loss (dB)
Low Distance	10	1200	25.3	0.01	0.05	0.2
Medium Distance	50	500	20.5	0.05	0.12	1.2
High Distance	100	150	15.8	0.10	0.25	2.8
Maximum Distance	150	50	12.0	0.20	0.40	4.5

Table 3 clearly shows that the CV-QKD closely matches the parameters required for secure data transmission for shorter distances following which the performance rapidly degrades with increasing transmission distance. At low distances (10 km) the system obtained a key rate of 1200 kbps, an SNR of 25.3 dB and the minimum leakage (χ) of 0.012. The QBER was remarkably low at 0.05, and photon loss was low at 0.2 dB. These make a show of good security and short range for application such as the urban communication networks.

For middle distance up to 50 km in particular the key rate was also reduced to the 500 kbps and the SNR to 20, 5 db. Leakage mitigation improved a little to 0.05 due to the fact that security is hard to maintain than bandwidth over large distances. The photon loss improved to 1.2 dB with an increase in QBER to 0.12, which are considered well-tolerable for quantum communication.

At high distances of 100 km the two clear key rates reduced to 150 kbps and the SNR reduced to 15.8dB. Leakage mitigation (χ) improved to 0.10, and photon loss raising to 2.8 dB led to the QBER of 0.25. Despite the issue in maintaining operational security, the reduction in the key rate and the increased noise are issues for high distance application.

For the maximum tested distance; 150 km, the important rate factor was restricted to 50 kbps with deer SNR of 12.0 dB. Leakage mitigation was further increased to 0.20 and unexpectedly, photon loss increased to 4.5 dB and QBER was 0.40. These values show how much further than 100 km CV-QKD can be pushed before other noise reduction techniques can be employed.

4.6. Economic Feasibility

Planning for deploying advanced optical fiber networks was based on evaluating their economic efficiency using the key performance indicators, including CAPEX, OPEX, and total resource costs throughout the network lifecycle, with a primary focus on 10 years of operation. The economics for using WDM, Photonic Integrated Circuits (PICs), and Mode Division Multiplexing (MDM) in urban, suburban and rural settings is a central focus of this analysis. Further, we checked the return on investment (ROI) to evaluate the feasibility of such deployments. The results remind that the cost model and ROI depend on the chosen deployment scenarios, which is why one should develop various strategies for each case.

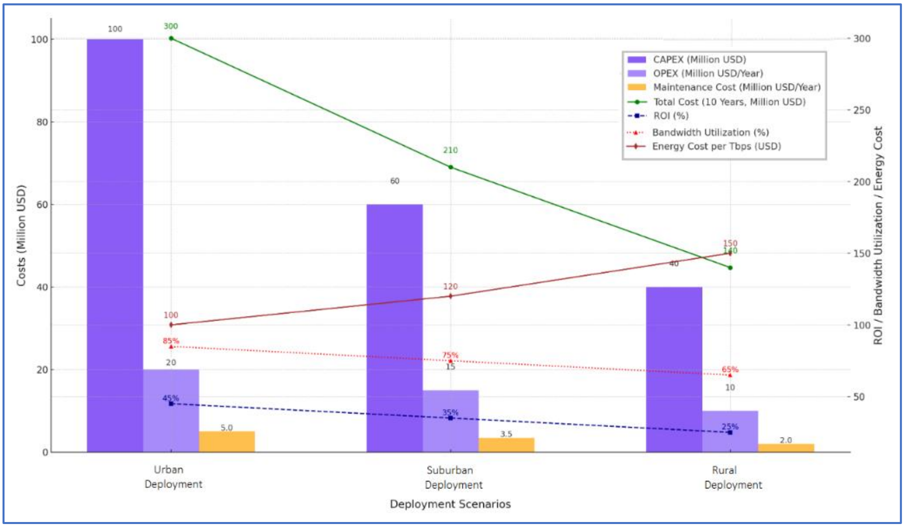

Figure 4. Comprehensive Economic Metrics for Optical Fiber Deployments

The economic characteristics clearly show different cost patterns for urban, suburban, and rural deployments as the different needs and infrastructures of these three environments outlined in Figure 4.

The analysis depicted that the urban area represents the highest CAPEX of 100 million USD due to compact communication network structures needed to control large data traffic. It was also expressed as operation expenses which was higher at 20 million USD per year, this due to costs of energy and maintenance for high-capacity systems. However, the actual readiness values revealed that the largest ROI equal to 45% was achieved in urban environment, though having the highest initial and running costs, probably due to high bandwidth usage ~85% and rational energy costs per Tbps of 100 USD. Annual maintenance costs were 5.0 million USD mainly due to the fact that transport networks in urban areas mostly are condensed networks.

Investment of US$ 60 million for CAPEX for suburban areas and an OPEX of US $ 15 million per annum. The total 10-years cost was estimated at 210 USD million and gave an ROI of 35%. Bandwidth usage was just 75% and the energy costs per Tbps was estimated to be 120 USD because the infrastructure was not as efficient as the one found in urban regions. Annual maintenance cost was valued at 3,500, 000 USD due to the variability in the levels of network density in suburban regions.

The rural deployment was the least capital intensive with CAPEX of 40 million USD, OPEX of 10 million USD per year but the lowest ROI of 25%. Due to these few instances, bandwidth utilisation was capped at 65%, and energy costs per Tbps were high- 150 USD due to the difficulties likely to be encountered in expansive regions. The maintenance costs were also lowest at 2.0 million USD per year due to the less complex network in this architecture.

The analysis demonstrates that Urban deployments are the most economical with the best ROI and bandwidth utilization since these areas are crowded and require more data usage. Suburban deployments show cost efficiency and optimization while the developers of rural deployments struggle with the question of sustainability. For rural regions, supplementing cost with cost-share models, providing government subsidies, and building up existing structures are crucial factors for gaining better economizing outlooks. These results argue for a more environment-sensitive approach to addressing the deployment of the high-speed, scalable optical networks. Optimized by quantum communication, edge computing, and cutting-edge multiplexing, these networks deepen cost-savings and sustainable benefits, promising to become the foundation of new-generation internet architecture.

5. Discussion

A distinguishing feature of this article is its discussion of the capabilities of modern optical fiber developments, focusing on innovations such as WDM, PIC, MDM, and quantum communication. These advancements are crucial in establishing the framework necessary for providing high-speed internet. The article offers valuable insights into the current and future development of optical networks, based on an analysis of performance characteristics, scalability, security, and economic efficiency. The discussion is framed within the context of existing literature and highlights the implications of the findings against potential disadvantages.

The findings indicate that multi-band WDM systems are both scalable and efficient in coordinating a large number of wavelengths, expanding upon the work by Deng et al. (2022), which focused only on single-band analyses (Deng et al. 2022). This study presents information demonstrating enhanced spectral efficiency and dynamic networking capabilities through the use of adaptive channel spacing in the O, C, and L bands, supporting portable and high-density configurations to meet growing bandwidth requirements. Similarly, the outcomes for multi-core and MDM systems align with the findings of Renaudier et al. (2022), emphasizing how multi-core configurations can enable capacity scaling and mitigate core-to-core interference (Renaudier et al. 2022). The effectiveness of the interference mitigation strategies proposed in this research supports their potential application in next-generation networks.

All PICs were evaluated to enhance routing time and power dissipation, corroborating the findings of Shi et al. (2022). This research further demonstrates the scalability of PIC-based systems and their ability to achieve enhanced signal processing speed and energy efficiency compared to conventional systems. Such advancements position PICs as central to achieving the density and efficiency required for urban communication networks (Shi, Calabretta, and Stabile 2022).

Latency reduction through edge computing aligns with the work of Guan et al. (2021) proposed the decentralization of processing in 5G applications to minimize delays. This study supports their observations by demonstrating similar latency improvements in urban, suburban, and rural implementations (Guan et al. 2021). The integration of edge computing is pivotal in demonstrating improved performance for distributed systems and low-latency applications, including industrial control and autonomous systems.

The study aligns with prior research by Pi et al. (2023) on continuous-variable quantum key distribution (CV-QKD), demonstrating its applicability for secure transmission over shorter link ranges (Pi et al. 2023). This research extends the analysis by assessing the performance of CV-QKD over longer distances and establishing the system's viability for regional networks challenged by photon loss and noise. The results underscore the need for enhanced noise-immune algorithms and quantum relays to overcome these drawbacks and expand the adoption of quantum communication systems.

The results indicate that urban areas are the most financially feasible options for deployment, supported by findings from Sah et al. (2022) (Sah, Shastri, and Dawadi 2022). However, this paper also highlights the economic challenges faced by rural areas, emphasizing the need for strategic cost intervention models as proposed by Anzola-Rojas et al. (2024). The study addresses the utilization of government subsidies and existing infrastructure to increase the profitability of investments and provide rural populations with access to high-speed internet (Anzola-Rojas et al. 2024).

Despite the broad focus of this research, there are limitations to overcome. The experimental emphasis on strictly controlled laboratory conditions may not accurately reflect real-world situations, as noted by Boffi et al. (2022), stressed the environmental influences on optical networks (Boffi et al. 2022). Furthermore, while significant performance improvements have been achieved in CV-QKD for short distances, security is limited by photon loss and noise over longer distances. This limitation, similar to the findings of Pi et al. (2023), highlights the need for ongoing improvements to quantum communication protocols (Pi et al. 2023).

The role of regulation and policies is not adequately addressed in the economic sections of this research, a factor emphasized by (Khan et al. 2022). Future research should incorporate these aspects to better understand deployment challenges. Additionally, there is a lack of consideration for the effects of state-of-the-art optical fiber technologies. Esteki et al. (2021) suggested that future works should also measure energy consumption and material utilization (Esteki et al. 2021).

The results of this research article are valuable in the development of advanced optical fiber technologies and provide insights into their future prospects based on application scale and efficiency. The study supports prior research while presenting new perspectives on the adoption of emerging technologies. Further application of field trials, along with sustainability assessments and policy analyses, will be useful in developing an understanding of the findings for implementing next-generation optical networks. This study establishes an initial applied framework for high-speed, secure, and scalable internet architecture necessary for the new information age.

6. Conclusion

This paper illustrates the significance of applying new optical fiber technologies in shaping the future of a high-speed, secure, and scalable internet. Analyzing the opportunities provided by WDM, PIC, MDM, and quantum communication indicates that these technologies could become the cornerstone of future telecommunications to meet increasing demands. Consequently, the research outcomes affirm the necessity of integrating these innovations into communication network management to achieve desired efficiency, security, and economic feasibility.

The evaluation demonstrates that optical fiber networks are capable of delivering the required bandwidth and low latency for future applications, including autonomous systems, industrial IoT, and smart city implementations. The study also reveals that the portability of these technologies allows networks to expand and evolve to meet specific demand levels and requirements, thereby ensuring sustainability. Additionally, quantum communication can be added as a new layer of data security, addressing key issues in the context of developing technologies. Collectively, these advancements confirm the readiness of optical networks to support next-generation digital environments.

However, the research identifies several gaps that need to be addressed to enhance the vision of optical fiber technologies. Challenges such as environmental factors, practical deployment issues in rural areas, and long-distance quantum communication remain significant. Overcoming these challenges will require further advancements in the field, particularly in the cost of solutions, noise immunity of protocols, and the utilization of green energy for large-scale implementation.

Future research should employ surveys with larger sample sizes and conduct field deployment studies to establish the generalizability of these findings. Real-world scenarios are planned through field trials in various geographic and environmental contexts to evaluate the usability of the proposed solutions and address practical implementation issues. This will also serve as a pathway for future work. Furthermore, multidisciplinary efforts are required to research and adapt the potential of other high-tech innovations in optical devices, such as artificial intelligence and decentralized computing systems, for improved performance.

Creating enabling policies and enacting favorable regulatory frameworks and financing structures is essential for expanding access to high-speed internet. Stimulating sustainable development and connecting rural areas will be crucial for maintaining the applicability and inclusiveness of optical networks.

This work provides strong support for comprehending and promoting optical fiber-related technologies. By focusing on key performance indicators, scalability, and economic feasibility, it becomes easier to build a more connected and secure world. Maintaining progressive advancements and cooperation will make the dream of a global broadband network achievable, leading to advancements across all sectors in the new media economy.

References

Akram, D. S., and Al-Tamimi, H. M. (2023). Design of DWDM optical communication systems with different modulation formats using DCF and a repeater. *Applied Optics,* 62 (2), 429-439. https://doi.org/:10.1364/AO.480016

Anzola-Rojas, C., de Miguel, I., Aguado, J. C., Merayo, N., Fernández, P., and Durán Barroso, R. J. (2024). Joint fiber and MEC deployment for sparsely populated areas. *Journal of Optical Communications and Networking,* 16 (1), 45-58. https://doi.org/:10.1364/JOCN.500429

Boffi, P., Ferrario, M., Luch, I. D., Rizzelli, G., and Gaudino, R. (2022). Optical sensing in urban areas by deployed telecommunication fiber networks. *2022 International Conference on Optical Network Design and Modeling (ONDM)*, 1-5. https://doi.org/:10.23919/ONDM54585.2022.9782848

Bourechak, A., Zedadra, O., Kouahla, M. N., Guerrieri, A., Seridi, H., and Fortino, G. (2023). At the Confluence of Artificial Intelligence and Edge Computing in IoT-Based Applications: A Review and New Perspectives. *Sensors,* 23 (3). https://doi.org/:10.3390/s23031639

Deng, N., Zong, L., Jiang, H., Duan, Y., and Zhang, K. (2022). Challenges and Enabling Technologies for Multi-Band WDM Optical Networks. *Journal of Lightwave Technology,* 40 (11), 3385-3394. https://doi.org/:10.1109/JLT.2022.3162725

Esteki, K., Manning, H. G., Sheerin, E., Ferreira, M. S., Boland, J. J., and Gomes da Rocha, C. (2021). Tuning the electro-optical properties of nanowire networks. *Nanoscale,* 13 (36), 15369-15379. https://doi.org/:10.1039/D1NR03944J

Ghazi, A., Aljunid, S. A., Idrus, S. Z. S., Rashidi, C. B. M., Al-dawoodi, A., Mahmood, B. A., Fareed, A., et al. (2021). A Systematic review of Multi-Mode Fiber based on Dimensional Code in Optical-CDMA. *Journal of Physics: Conference Series,* 1860 (1), 012016. https://doi.org/:10.1088/1742-6596/1860/1/012016

Guan, X., Dubé-Demers, R., Shi, W., and Rusch, L. A. (2021). Heterogeneous Optical Access Networks: Enabling Low-Latency 5G Services With a Silicon Photonic Smart Edge. *Journal of Lightwave Technology,* 39 (8), 2348-2357. https://doi.org/:10.1109/JLT.2021.3052372

Hashim, H. S., and Al-Sul, Z. A. (2021). Cloud computing based e-government in Iraq using partial least square algorithm. *Indonesian Journal of Electrical Engineering and Computer Science,* 22 (2), 953-960. https://doi.org/:10.11591/ijeecs.v22.i2.pp953-960

Jawad, A. M., Qasim, N. H., Jawad, H. M., Abu-Alshaeer, M. J., Khlaponin, Y., Jawad, M., Sieliukov, O., et al. (2022). *Basics of application of unmanned aerial vehicles*: Vocational Training Center. https://repositary.knuba.edu.ua/ server/api/core/ bitstreams/318f16f4-d7e1-4729-9480-6f924128a023/content

Khan, S. N., Kazmi, S. A., Altamimi, A., Khan, Z. A., and Alghassab, M. A. (2022). Smart Distribution Mechanisms—Part I: From the Perspectives of Planning. *Sustainability*, 14 (23). https://doi.org/:10.3390/su142316308.

Korichi, O., Hiekkamäki, M., and Fickler, R. (2023). High-efficiency interface between multi-mode and single-mode fibers. *Optics Letters,* 48 (4), 1000-1003. https://doi.org/:10.1364/OL.482053

Li, Y., Cohen, D., and Kottos, T. (2022). Enforcing Levy relaxation for multi-mode fibers with correlated disorder. *New Journal of Physics,* 24 (5), 053012. https://doi.org/:10.1088/1367-2630/ac6318

Liu, X. (2022). Enabling Optical Network Technologies for 5G and Beyond. *Journal of Lightwave Technology,* 40 (2), 358-367. https://doi.org/:10.1109/JLT.2021.3099726

Mo, S., Zhu, H., Liu, J., Liu, J., Zhang, J., Shen, L., Wang, X., et al. (2023). Few-mode optical fiber with a simple double-layer core supporting the O + C + L band weakly coupled mode-division multiplexing transmission. *Optics Express,* 31 (2), 2467-2479. https://doi.org/:10.1364/OE.478736

Pi, Y., Wang, H., Pan, Y., Shao, Y., Li, Y., Yang, J., Zhang, Y., et al. (2023). Sub-Mbps key-rate continuous-variable quantum key distribution with local local oscillator over 100-km fiber. *Optics Letters,* 48 (7), 1766-1769. https://doi.org/:https://doi.org/10.1364/OL.485913

Qasim, N. (2019). New Approach to the Construction of Multimedia Test Signals. *International Journal of Advanced Trends in Computer Science and Engineering,* 8, 3423-3429. https://doi.org/:10.30534/ijatcse/2019/117862019

Qasim, N., and Pyliavskyi, V. (2020). Color temperature line: forward and inverse transformation. *Semiconductor physics, quantum electronics and optoelectronics,* 23, 75-80. https://doi.org/:10.15407/spqeo23.01.075

Qasim, N., Pyliavskyi, V., and Solodka, V. (2019). Development of test materials for assessment broadcasting video path. *arXiv preprint arXiv:1907.11406*. https://doi.org/:10.48550/arXiv.1907.11406

Renaudier, J., Napoli, A., Ionescu, M., Calò, C., Fiol, G., Mikhailov, V., Forysiak, W., et al. (2022). Devices and Fibers for Ultrawideband Optical Communications. *Proceedings of the IEEE,* 110 (11), 1742-1759. https://doi.org/:10.1109/JPROC.2022.3203215

Sah, C. B., Shastri, P., and Dawadi, B. R. (2022). The Fifth Generation Fixed Network (F5G): Full-Fiber Access Embracing the Gigabit Era. *Advances in Engineering and Technology: An International Journal,* 2 (01), 1-9. https://doi.org/:10.3126/aet.v2i01.50374

Santos, G. L., Bezerra, D. d. F., Rocha, É. d. S., Ferreira, L., Moreira, A. L. C., Gonçalves, G. E., Marquezini, M. V., et al. (2021). Service Function Chain Placement in Distributed Scenarios: A Systematic Review. *Journal of Network and Systems Management,* 30 (1), 4. https://doi.org/:10.1007/s10922-021-09626-4

Shi, B., Calabretta, N., and Stabile, R. (2022). InP photonic integrated multi-layer neural networks: Architecture and performance analysis. *APL Photonics,* 7 (1), 010801. https://doi.org/:10.1063/5.0066350

Singh, J., Ahrens, A., Lochmann, S., and Peces, C. B. (2023). SVD-Assisted Joint Pre- and Post-Equalization in Optical MIMO System. *2023 International Interdisciplinary PhD Workshop (IIPhDW)*, 1-6. https://doi.org/:10.1109/IIPhDW54739.2023.10124406

Uyama, M., Okamura, S., Zhang, C., Ito, F., Nakamura, A., Okamoto, T., and Koshikiya, Y. (2023). Bandwidth-Decomposed Analysis of Spatial-Mode Dispersion of Coupled 2-Core Fiber Employing Linear Optical Sampling. *Journal of Lightwave Technology,* 41 (10), 3153-3163. https://doi.org/:10.1109/JLT.2023.3238769

Wang, Y., Li, B., Wei, Y., Meng, Y., Deng, L., Zhang, L., Li, C., et al. (2023). Static fatigue parameters and environmental factors effects on optical fiber lifetime. *2023 Opto-Electronics and Communications Conference (OECC)*, 1-4. https://doi.org/:10.1109/OECC56963.2023.10209799