



Towards High-Performance Optical Fiber Networks: A Critical Review of Design, Metrics and Innovations

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ABSTRACT

The fast-tracking demand for ultra reliable, high-capacity data transport has cemented optical fiber communication (OFC) as the backbone of modern connectivity. This paper presents a precise review that traces OFC's evolution from 19th century semaphore and telegraph systems to today's terabit scale, wavelength division multiplexed networks. It synthesizes core technical concepts: optical transmitters, transmission links, receivers, and the contrasting roles of single mode and multimode fibers and benchmarks network performance through key indicators of availability, throughput, latency, and packet loss. Surveyed simulation and field studies consistently confirm OFC's advantages of enormous bandwidth ($>10 \text{ Tb s}^{-1}$ per fiber), low attenuation ($\sim 0.16 \text{ dB km}^{-1}$ at 1550 nm), electromagnetic immunity, and sub 40 ms latencies on optimized long-haul links, while also exposing performance gaps in under tuned 100 Gb s^{-1} channels and last mile deployments. Looking forward, the review identifies three converging trends: Migration toward fully all optical processing that eliminates electronic bottlenecks; Adoption of advanced modulation, elastic grid spectra, and coherent detection to unlock petabit capacities; and Integration of AI driven monitoring and hybrid fiber/Free Space Optical or software defined architectures for dynamic impairment mitigation. Collectively, these advances position OFC to satisfy surging bandwidth, cloud, and edge intelligence workloads while extending high quality broadband to underserved regions. The paper concludes that sustained innovation in devices, networking algorithms, and techno economic policy is essential to realize OFC's full global impact.

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INTRODUCTION

The world is fast becoming a global village and the process for this development is communication, for which optical communication is a major factor. Telecommunications remain a fundamental engine for development of any economy, technological advancement and a human need for growing and sharing knowledge [4, 12]. Communication therefore, include primitive but permanent information sharing tools such as face-to-face speaking, phone calling, writing a letter, conference calls, SMS, e-mails,

MMS, video calls or using Internet in high-speed technologies. For this accessibility, people need high speed Internet connections in order to be online at any time and everywhere through safe, secure and fast connections. To this end, technology development is a huge market in terms of telecommunication equipment manufacturers and service providers [7].

Communication can be divided into two forms base on the method of transfer like "Traditional Network and Optical Network". In traditional networks, the data is converted to

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electrons that travel through copper cable, whereas in this work our emphasis is on optical networks that focus on the transmission of data by light energy and then travel through fiber cable [11].

Optical fiber communication therefore, encompasses the conversion of an electrical signal to an optical (light) signal by the optical transmitter, transmitting the signal through the cable of fiber (link), ensuring that the signal doesn't get too distorted, interfered or get attenuated during transmission process, reception of the signal (optical) and then conversion of the

optical signal back to an electrical signal [5, 6]. Fiber Optical Network is preferred over electrical network cabling when high bandwidth, long distance, or immunity to electromagnetic interference are required. This type of communication can transmit voice, video, and telemetry through local area networks, computer networks, or across long distances [12, 14]. Generally, the transmission of data in OFC involves three key components of optical transmitter, optical transmission link and optical receiver as illustrated in fig. 1 below [3].



Figure 1: Simple block diagram of Optical Communication System [3].

The signals in a fiber optic communication are transmitted from the optical transmitter. The Optical fiber cable acts as a transmission link Or medium between transmitter unit and receiver unit which passes the information to the photo detector. The receiver receives the optical information and converts it into electrical form this electrical information is then analyzed with the help of eye analyzer to check Q factor and BER of converted signal. In many parts of the world, the Fiber to the Home (FTTH) turns into fact, providing broadband capability up to the doorstep of home [12] .

Optical fiber networks are characterized by high Bandwidth, enabling high-speed data transmission, low attenuation that offers and allows long distances transmission of data and are very highly resistance/immunity to electromagnetic interference (EMI). Optical fiber systems are very small in size with low security risks and its weight are very light. Optical fiber networks are useful in many Telecommunications companies to transmit telephone signals, Internet communication, and cable television signals, Medical, Networking, broadcast, industrial / commercial, military/defense, data storage and in Government [5, 14]. Therefore, Optical fiber communication is mostly preferred to copper wire communication currently and nowadays.

Meanwhile, the present scenario shows that optical communication will become the leading network system in the future for better communication [6, 11].

Evolution of Optical Communication

The knowledge of signaling system impression Semaphore was first established in 1791 by Chappe from France. The Semaphore telegraphy devices in which fire, light, etc was used to transmit the message. The invention of the telegraph by Samuel F. B. Morse in 1838 changes the system of communication which led to an era of electrical communication. The use of visible frequencies to communicate between source and destination was very common for many years. Early to the nineteenth-century the data transferring rate was so low. In fact, at that time the human eye acted as a receiver the speed was limited [5, 6, 11]

The discovery of fiber optics in 1970 revolutionized the telecommunications industry by the speed of light. In 1970, a team of researchers with Corning Glass introduced fiber optic wire or "optical wave guided fibers" capable of carrying 65,000 times more information than copper wire, through which information carried by a pattern of light waves could be decoded at a destination even 1,000 miles away. In 1977, the first optical



phone communication system was installed for a distance of approximately 1.5 miles under downtown Chicago, and each optical fiber carried the equivalent of 672 voice channels (GARY AND THURMAN 2011). For some time, it was difficult to get fiber optic service without a long wait or agreeing to long-term commitments. But things turned around during the telecom bubble in 2001, when it became apparent that the fiber optic infrastructure was overbuilt. In fact, it was reported that 90% of all the fiber installed in the U.S. was still dark. Since internet and wireless demand has grown significantly since 2008, the current recession has had very little effect on the market for fiber [6].

After the invention of the optical laser, the development of optical fiber communication, it gives a very high breakthrough for transferring data. In the early century of OFC, the data transferring rate was too loose. In early 1996, the transmission capacity was reported about terabit/sec on a single fiber which launches the "tera era" perspective for OFC. All three approaches used WDM techniques. In the next five years, this capacity range was increased by 100 per decade, about 10Tb/Fiber. This was an incredible capacity and great achievement in OFC. Today, more than 80% of the world's long-distance traffic is secured over optical fiber cables [11].

Optical Fiber Communication System Description.

Fiber optic communication system is the process of sending information or data from the transmitter along the optical fiber cable which is known as transmission link to the desired destination by the optical receiver in form of light

pulse. The OFC system is a fastest and simple method of the communication as compared to any other communication system. OFC consist of three key components. These are: Optical Transmitters, Fiber- Optical Link and Optical Receivers [3, 5].

The Optical Transmitter

The optical transmitter of OFC consists of driver circuit, light source and fiber fly-lead, see fig. 2. At the transmitter, an electric signal is applied to the optical transmitter and the driver circuit energizes the light source. The light source changes an electrical signal to optical signal. Then, the Fiber fly-lead is used to connect optical signal to optical fiber [9, 26].

The Fiber- Optical Link (Transmission Line)

The transmission channel or link consists of a cable that provides mechanical and environmental protection to the optical fibers contained inside the system. Separately optical fiber acts as an individual channel. However, Optical connection is used to permanently connect two individual optical fibers and Optical connector is for brief non-fixed joints between two individual optical fibers. Optical splitter or coupler delivers signal to other devices. Meanwhile, repeater changes the optical signal into electrical signal using optical receiver and send it to electronic circuit where it is reformed and amplified as it gets attenuated and distorted with increasing distance because of scattering, dispersion and absorption in waveguides, then this signal is formerly again transformed into optical signal by the optical transmitter [9].

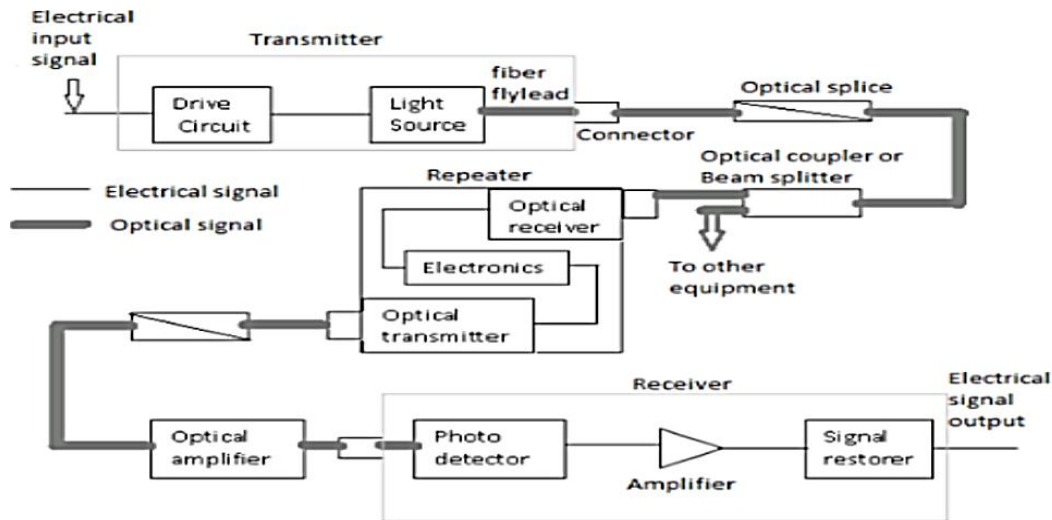


Figure 2: Block Diagram of Fiber-Optic Communication System Description [9].

A. The Optical Receiver

At the receiving end, Optical signal is applied to the optical receiver from through the optical link. It consists of photo detector, amplifier and signal restorer, see fig 2. The photo detector changes the optical signal to electrical signal. Meanwhile, Signal restorers and amplifiers are used to improve signal to noise ratio (SNR) of the signal as there are chances of noise to be introduced in the signal due to the use of photo detectors [9].

The Fiber-Optical Cable Assembly

The optical fiber cable is a very thin glass cable just similar to human hair extracted

from Silica glass. It is chemically purified and has very low absorption loss. Traditional wires are replaced with these optical fiber cables. These cables are used as the transmission medium having higher bandwidth to carry the information or data in form of light from source to the destination. Fiber optical cable is a type of cable that uses light to transmit data as light signal in OFC. Optical cables play a crucial role in modern communication infrastructure, enabling high-speed data transmission and providing a foundation for fiber various application and services [12]. Fig. 3 shows the structure of optic cable.

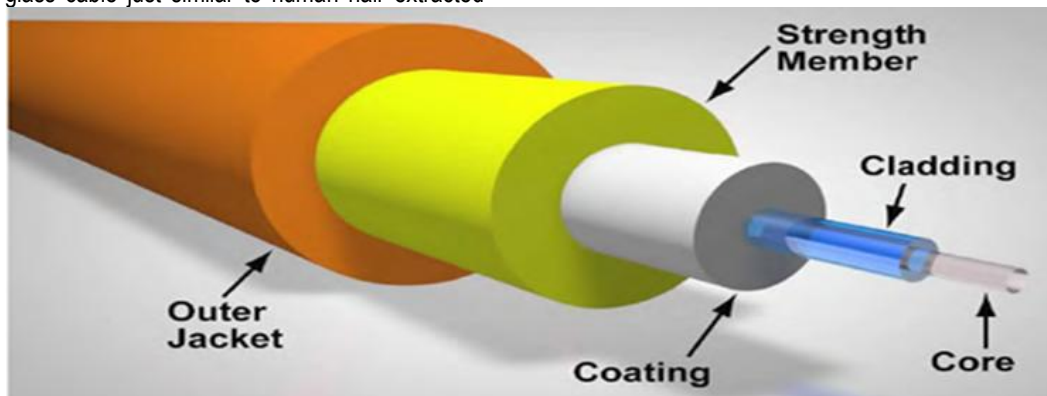


Figure 3: Fiber Optic Cable Structure [15].

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The fiber-optical Cable structure consists of a plastic of a high refractive index called the core. The core is enclosed by a cover of glass or plastic called cladding. The core has a diameter of 10 μm to 100 μm . The refractive index of the cladding is less than that of the core (which is a must condition for the working of the optical fiber). The difference between the two indices is very small of order 10-3. The core and the cladding are enclosed in an outer protective jacket made of plastic to provide strength to the optical fiber. The refractive index can change from core to cladding abruptly (as in step-index fiber) or gradually (as in graded-index fiber). An optical fiber is a thin, transparent fiber usually made of glass or plastic, for transmitting light. The construction of a single optical fiber is shown in the figure. The basic functional structure of an optical fiber consists of an outer protective cladding and an inner core through which light pulses travel [9, 16].

Types of Fiber-Optical Cable

Fiber-optical cable serves as transmission link for sending and reception of information or data in OFC. Therefore, when the necessity to transfer big data arises, fiber optic cables are an optimal solution, for its installing a small network or setting up a data center for a high-capacity/high-volume networking. Arriving and finding the right cable to be used can be very challenging due to the different fiber optic cable types available. However, understanding the purpose behind the different types of cable can be helpful in system performance in OFC. All fiber optic cable types are comprised of a core that transmits light. Generally, either glass or plastic, a cladding which reflects that light to prevent loss, and surrounded by sheathing meant to protect the core and cladding from damage. The thickness of these layers can vary, depending on where the cable will be placed and what kind of performance is needed. There are two types of optical fiber cables that are currently used for the transmission

of information or data in OFC which are given as Single mode fiber-optic cable (SMF) and Multimode fiber-optic cable (MMF) [9, 16].

The Single Mode Fiber (SMF)

The SMF supports a single path/track for light to be transmitted, it can be used for long distances having high Bandwidth. SMF, in other word is also designed to carry a single signal source with low transmission loss over great distances [16, 24]. It is frequently used for communication systems due to the clarity it provides. This type of fiber optic cable has the smallest core and the thickest sheathing. Generally, in the OFC system, single-mode fiber is preferably used as it has comparatively easy to achieve a high-speed transmission rate [9, 16, 17]. Fig. 4, shows Single mode fiber cable structure.

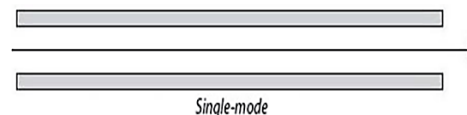


Figure 4: Single Mode Fiber Cable Structure [9].

The Multimode fiber cable (MMF)

The MMF supports hundreds of paths/tracks for light to be transmitted. This type of mode is applicable only for the small distance and is having a low Bandwidth [11, 12]. Nonetheless, MMFs maintain significant presence in enterprise networks and data centres, where transmission distances rarely exceed 550 metres. According to Patel and Thompson (2021, p. 462), "OM4 multi-mode fibres achieve cost reductions of 37-42% compared to single-mode deployments in hyperscale computing environments whilst supporting 400Gbps transmission across intra-facility links." This cost-performance trade-off continues to shape fibre deployment strategies across diverse telecommunications architectures [24]. See Figure 5 for The Multimode fiber cable structure (MMF).

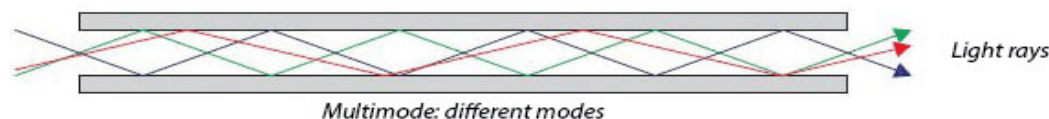


Figure 5: Multimode Fiber Cable Structure (MMF) [9].

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The Need for Fiber Optic Communication

A Rapid growth in the request and demand of high-speed data rate by customers and the growing consumer index requires large network capacity with reliability over long distances. Optical fiber system is capable of satisfying all the demands of current and future network requirements [1, 8]. Optical fibres have largely replaced copper wire communications in core networks in the developed world, due its advantages over electrical transmission [5, 6]. Generally, optical fiber system can transmit data over long distances without significant signal degradation between the optical transmitter and optical receiver along the optical cable link. Also, optical fiber systems offer high Bandwidth, enabling fast or speedy data transmission rates during the transmission process.

Categorically, optical fiber systems are highly resistant to electromagnetic interference (EMI) by ensuring that reliable and safe data is delivered to the destination from the transmission process. However, optical fiber systems are very small in size with low security risks and its weight are light (Patibandla., et al). The global internet traffic of OFC has passed one zeta-bytes (10^{21} bytes) in 2016 and still growing faster. Therefore, Optical fiber communication is mostly preferred to copper wire communication currently and nowadays [11].

Future Trends of Optical Fiber Communication

Since a very high quality and reliable data transmission is crucial in optical fiber communication for the optical signals, nearly to zero attenuation levels or distorted waveform with low signal to noise ration during processing and transmission. Regular and adequate improvement on the optical transceiver is also key to embrace new and advanced modulation techniques [5]. Therefore, optical fiber communication network will be entirely optical; the signals also will be completely optically and also totally processed without any electrical conversions at any stage during signal transmission. Currently, transmission involves signals been converted to electrical form before processing is done indicating that signals switching takes place in

both electrical and optical areas. After processing and directing, the signals are then converted to optical form for it to be transmitted over long distances. Generally, the process of converting signals from electrical form to optical form and verse visa gives rise to delays in communication which limits high data rate transmissions in optical fiber [5, 11].

Optic Fiber Benchmark Requirements

Optic fiber benchmark requirements in communication system refers to the standards and specifications that define the performance characteristics of optical fiber cables and systems. Generally, there are many benchmark requirements in order to attain good and reliable Quality of service during signal or data transmission in communication system. However, this paper only focusses on optical network performance as the benchmark requirements.

Network Performance KPIs

Key Performance Indicators (KPIs) are measuring tools that can track performance [18]. This paper considered the followings measurable key performance indicators for optical fiber network as: Availability, Throughput, Latency and Packet loss as the benchmark requirements in the optical network performance.

1. **Availability:** In optical fiber network, availability is one of very vital indicator of network performance and therefore, it measures the percentage of time the network is available and functioning properly or correctly to the users.
2. **Throughput:** This is the actual amount of data that is transmitted without errors over an optical fiber link, and it's expressed in bits per second since it is always measured per unit time. It is an average rate that is measured depending on the available bandwidth or capacity of the link and also depends on the latency or delay in that link. Throughput is affected by a diversity of factors, some are as follows: transmission media limitations, which prevent a channel or link from carrying more data than it was designed to; latency;

network congestion; packet losses and errors; and throughput of a fiber link. Theoretically, a given link's throughput is 95% of its available bandwidth. The throughput of a network must be measured or tested for that network to operate better. Optimization can be done by identifying the bottlenecks, increasing the bandwidth of the channel if possible, replacing faulty devices on the network, and also ensuring the quality of services so that the critical traffic is not affected by congestion in the network [5, 6].

3. **Latency:** Latency refers to delay in transmission time or in the time it takes for information to transfer through a fiber cable, and it is a very vital indicator of network performance. Since the information in optical fiber is transmitted through pulses of light, the delay is seen or occurs in the time taken for the light pulses to travel through a fiber cable [5, 6, 23].

Latency can be calculated using Equation (1) [5, 6]:

$$D = T \times V \quad (1)$$

Where:

D is the distance light travels through a given fiber cable,

T is the time the light pulses take to travel a given distance D and

V is the velocity of light

Latency is not good as far as communication is concerned so it should be reduced in one way or the other to ensure a seamless optical fiber communication. Latency can be reduced through the use of high-quality fiber cable as light tends to travel through it faster compared to low-quality fiber, carefully handling fiber during constructions and also ensuring that fiber requirements conform with the standards defined by IEEE and ITU [5,6, 23].

D. Packet loss:

It measures the number of packets lost during transmission affecting data integrity. An essential characteristic of optical fiber network is its reliability, achieved by detecting and retransmitting any segments that go unacknowledged, often due to network congestion and resultant packet loss. Because each retransmission introduces extra delay and thus elevates latency, packet loss serves as a critical performance metric. One way to quantify a flow's packet loss rate is to compare the number of retransmitted segments, r , against the total segments transmitted, t , over the duration of the measured connection. Therefore, the retransmission rate (RR) can be calculated with the formula of Equation (2):

$$R = r / t \quad (2)$$

While retransmissions are a natural behavior in TCP, this value should nevertheless be kept low and sudden increases further investigated [25].

Quality of Service (QoS) in Optical Networks

Quality of Service (QoS) in optical networks refers to the capability to provide differentiated service to various types of network traffic, ensuring that critical applications receive preferential treatment [19]. Fundamentally, QoS mechanisms in optical networks can be broadly categorized based on how resources are managed. Firstly, resource reservation techniques, such as Differentiated Services (DiffServ), classify traffic into different classes and allocate bandwidth accordingly. Secondly, priority scheduling mechanisms ensure that higher priority traffic is forwarded before lower priority traffic. Thirdly, wavelength assignment strategies in WDM networks can be employed to allocate dedicated wavelengths or sub-wavelength bandwidth to specific services.

The implementation of effective QoS mechanisms is crucial for supporting diverse applications with varying requirements, such as real-time video streaming, VoIP, and data transfer. Empirical studies have indicated that implementing DiffServ in optical burst switching



networks can significantly improve the performance of delay-sensitive traffic [20]. The advent of flexible grid optical networks has enabled more granular bandwidth allocation, enhancing the ability to provide tailored QoS [21]. Recent research has explored the integration of Software-Defined Networking (SDN) with optical networks to facilitate dynamic and adaptive QoS provisioning [22]. Therefore, for Nigeria's urban-rural fibre deployment, particularly with hybrid architectures supporting diverse user needs, the incorporation of robust QoS mechanisms is essential to guarantee satisfactory user experience across different service types and geographical locations.

Review of Related Work

Agboje *et al.*, (2017) examined the current state of fibre optic networks in Nigeria. The study categorised the fibre optic network infrastructure into three levels: core, backbone/backhaul, and access/last-mile. The research analysed the spread of these networks, the application of fibre optic technologies, and the obstacles to deploying fibre optics for greater internet broadband penetration. It conducted a review of existing literature and data on fibre optic deployment in Nigeria. The study examined reports from the Nigerian Communications Commission (NCC) and other sources to assess the extent of fibre optic penetration and the challenges involved. The study also considered the various fibre optic technologies and their applications within the Nigerian context.

The review highlighted that while Nigeria has substantial core and backbone fibre optic networks, the last-mile connectivity is lacking. A significant portion (99%) of internet access in Nigeria is through mobile wireless networks. The work identified challenges in deploying last-mile fibre optic networks, including high costs. The study is a review, and therefore its findings are limited by the scope of the sources it analysed. The study acknowledged the heavy reliance on mobile wireless for internet access in Nigeria, but do not proffer any solutions. A more detailed analysis of the economic and logistical barriers to last-mile deployment, and potential

strategies to overcome them, would be a valuable extension of this work.

Akintola & Eleazar (2019) examined Design and Performance Analysis of Fiber Optic Network System Using FUTA as Case Study. The paper presented a simulation-based study of a passive optical network (PON) deployed on the Federal University of Technology, Akure (FUTA) campus. It evaluated key performance metrics such as: optical power loss, bit error rate (BER), and Q-factor, for a typical fiber-optic link comprising an Optical Line Terminal (OLT), an Optical Distribution Network (ODN), and an Optical Network Unit (ONU). Specifically, the research modeled a simple point-to-multipoint PON in Opti-System v15.2. It varied input optical power and fiber link length to observe their effects on BER and Q-factor. It also generated eye diagrams and BER analyzer plots to visually assess signal integrity. The study was conducted using Simulation of Environment which Employed Opti-System for end-to-end modeling of the PON. It also used Parameter Sweep to Input Power Variation that Tested launch powers at 5 dBm, 10 dBm, 15 dBm, 20 dBm, and 25 dBm.

Fiber Length Variation was Simulated using spans of 2 km, 4 km, 6 km, 10 km, and 12 km. Q-factor was Computed via the ratio of the difference between logic-1 and logic-0 mean currents to the sum of their standard deviations. BER was derived from the Q-factor and directly measured by the BER analyzer block. The results from the study clearly shows that Overall, the network achieved "satisfactory" performance across the tested parameter ranges, with clear trade-offs between launch power, link length, and signal quality. However, its simplified assumptions, limited parameter space, and lack of experimental validation constrain its impact on real-world network planning. Future work should deepen the model's realism and broaden its scope to enhance both academic rigor and practical relevance.

Swarnjeet & Malik (2021) presented review of optical fiber communication system - introduction and applications. The study outlined a comprehensive survey of single-mode optical fiber communication (OFC) systems. Its coverts fiber

design and manufacturing, fundamental propagation theory, modulation formats, system performance metrics (BER, Q-factor), and real-world applications. The study was conducted using Literature synthesis of fiber fabrication, System block–diagram analysis and Tabular and graphical comparisons of popular digital modulation formats. The results from the research shows that Modulation efficiency CSRZ yielded the lowest BER among NRZ/RZ formats, with RZ & CSRZ both outperforming NRZ in nonlinear-limited regimes. Lack of new experimental data, Survey scope Focused primarily on SMF + DCF links and simulation summaries are the major challenges of the study.

Asaba et al., (2023) investigated Performance Analysis of An Optical Fiber Communication Network. The study was carried out field-trial performance evaluation of a four-fiber-pair submarine OFC link, focusing on throughput and latency metrics at 10 Gb/s and 100 Gb/s line rates, benchmarked against IEEE/ITU standards. The study was conducted using a Viavi T-BERT/MTS 5800 test kit to inject test traffic and measure round-trip times and data-rate attainment. It also deployed in situ on a submarine link via internal/external ODF panels and conducted tests at multiple intervals to capture temporal variation.

Throughput was logged in Mbps over fixed intervals (e.g., 5 000 s spans), and latency captured in μ s. The results of the study shows that 10 Gb/s link achieved 100 % of committed bandwidth (>95 % target), with stable latencies of ~37 ms and ~20 ms in two separate tests—well within <30 ms spec. However, 100 Gb/s link underachieved at ~90 Gb/s (90 % of bandwidth) and exhibited high, constant latency of ~92 ms—exceeding recommended caps. Metric scope showed only throughput and latency were measured. Meanwhile, packet jitter, frame loss and QoE indices and other metrics were omitted.

Asaba et al., (2025) carried out field measurements of throughput and latency on both 10 G and 100 G single-mode undersea fiber links owned by a Ugandan telecom operator, using a VIAVI T-BERT/MTS-5800 test set. Four separate tests were performed at different times of day to

capture diurnal variations. The study was conducted using Test setup an undersea four fiber pair link, terminated at submarine landing stations and routed through internal/external ODFs, was instrumented at both client and line interfaces. Also, measurement process was conducted and each test ran for 5 000 s, during which approximately 13 data points were exchanged. Throughput (Mbps) was computed by dividing the number of bits transferred by the elapsed time. However, latency (ms) was measured and read directly from the VIAVI kit. Results were benchmarked against ITU/IEEE standards (≥ 95 % of available bandwidth for throughput, and < 30 ms for latency). Data obtained was analyzed Test results were tabulated (Table II) and compared to ITU benchmarks, and root causes of non-conformance were investigated.

It shows that tests 1, 2, and 4 achieved 100 %, 100 %, and 95 % for 10 G link of available bandwidth respectively (meeting the ≥ 95 % criterion), with latencies of 37 ms, 20 ms and 92 ms (only Test 2 met the < 30 ms requirement). Test 3, conducted during peak hours, yielded 0 Mbps and 0 ms (no traffic). Also, for 100 G link, only test 2 (100 % throughput, 0 ms latency) met both criteria. Tests 1 and 4 fell slightly below throughput requirements (89 % and 90 %) and exceeded latency limits (76 ms and 92 ms), while Test 3 again saw 0 Mbps due to congestion. Many or other metrics are omitted, although packet jitter and frame-loss rates are mentioned as KPIs, but detailed results for these are not reported. However, mitigation guidance was only conceptual. Meanwhile, recommendations (e.g., bandwidth upgrades, repeaters, maintenance) are provided, but their practical efficacy was not experimentally validated.

Esmail (2023) examined the critical challenge of performance monitoring in hybrid optical communication systems that combined fibre-optic and Free Space Optical (FSO) technologies. The research proposes a machine learning-based approach for real-time impairment prediction in such systems, focusing on three key parameters: optical signal-to-noise ratio (OSNR), chromatic dispersion (CD), and atmospheric turbulence (quantified via the refractive index

structure parameter). The study employed Gaussian Process Regression (GPR), a non-parametric ML technique known for its robustness in small datasets and non-linear modelling. The simulation model is developed using the Transmission Maker 11.1 platform, which enables synthetic data generation under varying impairments for system training and evaluation. Data were acquired asynchronously and processed via amplitude histograms to form training features.

The study shows that the GPR model achieved high predictive accuracy, with R^2 values up to 1.00 for OSNR and CD predictions in isolated conditions. However, performance degraded slightly under joint impairments especially in strong Amplified Spontaneous Emission (ASE) noise scenarios, where the model struggled to accurately predict low turbulence levels. The GPR model outperformed Support Vector Machines (SVM) and Random Forests (RF), particularly in scenarios with limited or noisy data. The study limitations include the model's sensitivity to high ASE noise and its computational complexity in larger datasets. Future work may explore advanced architectures like quantum neural networks or graph-based models for enhanced scalability and real-time deployment.

Gajjar & Mishra (2025) did Evaluation and Significance of Optical Fiber Communication: A Concise Review. The study carried out succinct overview tracing OFC from early signaling (semaphore, telegraph) through laser invention to modern fiber systems, explaining core principles, fiber types, system architectures, key enabling technologies (WDM/DWDM, solitons), and diverse applications (telecom, military, sensors, computing). The research was conducted using Historical mapping of milestones, technical exposition of fiber construction (core/cladding materials and refractive-index profiles) and review of multiplexing (WDM, DWDM), dispersion compensation, and advanced modulation (solitons achieving 80 Gb/s over 10 000 km). The results from the work shows that Band-width leaps with fiber attenuation reduced to ~0.16 dB/km at 1 550 nm. The research depends purely on a

narrative review without simulation or field-test data.

Comparative Summary of Reviewed Optical Fiber Communication Studies

A. Common Themes

- i. **Deployment Trends:** Several studies contrast backbone connectivity with access networks. For instance, Agboje *et al.* (2017) note Nigeria's extensive submarine- and terrestrial-fiber backbones as solutions to capacity limits, whereas campus/PON scenarios are considered in others (e.g. Akintola & Eleazar 2019 simulate a FUTA campus PON. However, Swarnjeet & Malik (2021) emphasize high-bandwidth SMF links (FTTx) and modulation choices in end-user access, and Gajjar & Mishra (2025) address ring-type WDM metro networks. Overall, the literature spans core/backhaul (long-haul) deployment and last-mile/FTTx challenges.
- ii. **Performance Metrics:** Across the works, standard optical metrics repeat. BER and Q-factor are common (e.g. Akintola & Eleazar use BER, Q-factor and power loss. Swarnjeet & Malik listed BER in keywords. Throughput and latency measurements feature in Asaba *et al.* (2023, 2025). However, recent studies incorporate additional KPIs: Esmail (2023) predicts OSNR and dispersion degradation, and Gajjar & Mishra (2025) optimize energy efficiency, packet delivery ratio and congestion in WDM links. These works also cite ITU/IEEE benchmarks (e.g. Asaba *et al.*, comparing measured latency/throughput against standards).
- iii. **Simulation vs Field Methods:** There is a mix of simulation-based analysis and empirical testing. Simulation platforms are widely used: Opti-System-based PON models (Akintola & Eleazar 2019), MATLAB/algorithmic models for routing (Gajjar & Mishra 2025), and ML training (Esmail 2023). In contrast, Asaba *et al.*

(2023, 2025) conduct field experiments on real fiber links using VIAVI T-BERD/MTS test kits. Swarnjeet & Malik (2021) is largely a literature survey. Thus, many results are obtained via simulation or modeling, with only a few studies (Asaba *et al.*) providing in-situ fiber measurements.

- iv. **Advanced Techniques:** Many studies apply modern methods. Modulation format comparisons are detailed in Swarnjeet & Malik (2021). Machine learning appears in some recent works: Esmail (2023) uses Gaussian process regression to self-monitor a hybrid fiber/FSO channel, and Gajjar & Mishra (2025) incorporate an MLP predictor into a dynamic WDM routing algorithm. These apply AI tools for impairment prediction and traffic optimization. Other advances include novel topologies and algorithms (e.g. heuristic adaptation for ring networks). In summary, beyond conventional analysis, newer studies leverage ML and heuristic methods to address fiber link challenges.

B. Strengths

- i. **Innovative Methodologies:** many works introduce noteworthy tools. Asaba *et al.* (2025) deploy a VIAVI T-BERD/MTS 5800 field test kit to gather real 10G/100G throughput and latency data, providing a concrete test platform for performance evaluation. Gajjar & Mishra (2025) combine a Heuristic Adaptation Algorithm (HAA) with a neural-network (MLP) model, achieving extremely high predictive accuracy (correlation ≈ 0.997) for network metrics. Esmail (2023) applies Gaussian Process Regression to predict channel impairments in a hybrid fiber/FSO link with high fidelity. These methodological innovations (advanced test setups and ML-based models) enhance analysis beyond simpler simulation.
- ii. **Comprehensive Coverage:** Some papers offer broad perspectives.

Swarnjeet & Malik (2021) review fundamental fiber concepts from physics to system design, and present a comparative table of modulation formats and their eye-diagram performance. Agboje *et al.* (2017) survey Nigeria's entire fiber infrastructure and categorize network layers. Such works provide context and technical background, covering both historical trends (e.g. submarine cable milestones) and wide-ranging applications (telecom, broadcast, etc. as noted by Swarnjeet & Malik).

- iii. **Novel Performance Evaluations:** Some studies adopt rigorous evaluation approaches. Asaba *et al.* (2023) explicitly compare measured link latency and throughput to IEEE/ITU benchmarks, identifying and quantifying non-conforming cases. Akintola & Eleazar (2019) use Opti-System simulation to quantify how input power and fiber length affect BER and Q-factor, thus systematically analyzing performance tradeoffs. Gajjar & Mishra (2025) examine trade-offs (e.g. clockwise vs. counterclockwise routing in rings) and report high lightpath utilization ($\approx 92.5\%$) under varying traffic. Overall, the studies employ detailed result analysis (graphs, eye-diagrams, statistical metrics) that enriches evaluation beyond qualitative statements.

C. Weaknesses

- i. **Reliance on Simulation/Narrative:** A number of studies are purely theoretical or review-based with limited empirical validation. For instance, Akintola & Eleazar (2019) base their conclusions solely on an OptiSystem model, and Swarnjeet & Malik (2021) provide a narrative review with performance tables, but no new measurements. Likewise, Agboje *et al.* (2017) is a qualitative broadband deployment

- review. Such works lack field data to corroborate their findings.
- ii. **Limited Experimental Scope:** Even some studies that do measure links have narrow scenarios. Asaba *et al.* (2025) focuses on one submarine cable case using specific 10G/100G links. Gajjar & Mishra (2025) simulate a ring topology with fixed assumptions. Esmail (2023) models a hybrid fiber/FSO link under certain noise conditions. In each case, parameter variation is limited (e.g. only specific fiber lengths or modulation rates), so results may not generalize across all networks.
 - iii. **Omitted Metrics and Granularity:** Some KPI gaps are evident. For example, Asaba *et al.* focus on throughput and latency but do not report BER or Q-factor, whereas other studies often emphasize BER as primary. Conversely, Akintola & Eleazar report BER/Q with no latency discussion. Jitter, spectral efficiency, or reliability measures are rarely addressed. This piecemeal metric selection means no single study covers the full performance spectrum.

CONCLUSION

This review has shown that optical fiber communication (OFC) has undergone tremendous evolution, from early fiber-optic developments in the 1970s to today's ultra-high-capacity networks. OFC offers vast bandwidth and very low attenuation, enabling ultra-fast long-distance links with minimal signal degradation and immunity to electromagnetic interference. Related studies illustrate these points: simulations of campus passive optical networks have evaluated BER and Q-factor under varying launch powers and distances, literature surveys analyze single-mode system design and modulation-format tradeoffs, and field measurements on submarine links confirm that 10 Gbps channels can achieve ~100% of their bandwidth with latencies ~20–40 ms while 100 Gbps links often underachieve (~90% bandwidth, ~90 ms latency) without

optimization. Machine-learning approaches have been proposed to predict performance impairments in hybrid fiber/free-space systems. Looking ahead, all-optical processing (eliminating electronic conversion) and advanced modulation techniques (e.g., DWDM and higher-order formats) are expected to further boost capacity, while AI/ML tools and elastic-grid optical architectures will enable dynamic performance management. These developments have broad implications: OFC's tremendous capacity and low latency are essential for meeting surging global bandwidth demand and underpinning modern Internet and smart-service infrastructure. In both dense urban networks and remote rural deployments, fiber-optic systems form the backbone of connectivity; even as challenges like rural last-mile connectivity persist, ongoing advances promise to extend fiber's reach and performance worldwide.

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