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Review Paper

5G Technology and the Evolution of Fiber-Optic Systems: Architecture, Standards and Convergence

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Abstract

This paper presents the significance of 5G technology and how optimum use of optical fiber can help in achieving digital inclusiveness. 5G technology is going to make inroads into the country very soon. Top smart phone manufacturer in India have already released phones with 5G capability. With over 117 crore telecom users and more than 82 crore internet subscribers, India is one of the fastest growing for digital consumers. Digital infrastructures, which seamlessly integrates with physical and traditional infrastructure is crucial to India's growth story and the country's thrust towards self-reliance. Internet connectivity is critical for making the digital India project inclusive and wide spread use of optical fiber in the remotest corners of the country. The commercial success of 5G hinges on an optical transport fabric capable of delivering massive bandwidth, tight synchronization, and deterministic latency from highly distributed radios to virtualized cores and edge clouds. This review surveys 5G system architecture and the parallel evolution of fiber‑optic systems, highlighting how converged xHaul (fronthaul, midhaul, and backhaul) over dense wavelength division multiplexing (DWDM), passive optical networks (PON), and packet‑optical technologies underpins enhanced mobile broadband (eMBB), ultra‑reliable low‑latency communications (URLLC), and massive machine‑type communications (mMTC). We synthesize the standards landscape across 3GPP, ITU‑T, IEEE, IETF, and the O‑RAN Alliance and discuss engineering trade‑offs, security, economics and sustainability. We conclude with open challenges and a roadmap toward 5G‑Advanced and early 6G directions where coherent optics, time‑sensitive networking, and cloud‑native automation will further tighten fixed–mobile convergence.

Keywords: 5G, Fiber optics, xHaul, DWDM, PON, O-RAN, Convergence.

Introduction

Optical Fiber is basic need for 5G networks and it acts as high-speed backbone which supports the dense networks of wireless small cells required for 5G technology. As we are working in digital era and things are ramping up quickly. GSMA intelligence tells us we are on track to heat over two billion 5G connective globally by 2025 with advance of 5G, industry leader an unanimously agree that Fiber perpetration must increase significantly to fully harness the benefit of 5G services. 5G is not just a step-up from 4G; it's a significant leap forward, opening doors to technological advancements, and application that were impossible earlier. Now with the support of an optical Fiber network 5G is all set to transform the digital landscape[1]. An optical Fiber is a thin, flexible, transparent Fiber that acts as a waveguide or "light pipe: to transmit light between the two ends of Fiber. Wired communication like twisted pair in low and high frequency and optical fiber is in very high and ultra-high domain which is based on communication technology where a large data transmission takes places[2]. Also wave guide use for high power applications and considerer as wired line[3]. Wireless communication includes transferring of information over a range from meters and thousands of kilometers[4]. Two transmit information such as image, speech or data over a range the concept of carrier wave communication is generally use[5]. An optical Fiber communication system used like wave mechanism two transfers the data over a Fiber by changing electronic signals into light[6]. So for as concerned to the optical Fiber infrastructure (Figure-1)[7] it consists a central core in which the like is guided, included in an outer cladding of a little bit of lower refractive index[8].

5G technology is going to make inroads into the country very soon. Top Smartphone manufacturers in India have already released phone with 5G capability. With over 117 crore telecom users and more than 82 core internet subscribers, India is one of the fastest-growing markets for digital consumers.

In the fast-paced world of 5G, optical Fiber network plays a pivotal role in meeting the stringent requirements and ambitious goals of this next gen technology. Developing a strong Fiber infrastructure is a fundamental part of communication. Building

4G and 5g networks requires a robust Fiber backhaul. 5G network rely on a denser network of smaller cell towers, as opposed to the larger macro cell towers of 4G necessitating, high speed backhaul connections to the core network over long distance. With small cells becoming crucial in the 45G rollout, having a fiberized backhaul becomes extremely important.

Fiber optic cables are renowned for their ability to transmit data a lightning speed. Unlike their copper counterparts. Fiber cables can support the significantly higher data rates required by 5G which are expected to be up to 100 times faster than 4G networks. This speed is vital for handling the enormous data demands of a 5G network, which is designed to connect countless devices and support data-intensive application.

This paper provides a detailed review of how fiber-optic systems have evolved to meet the demands of 5G, how the 5G architecture is shaped by optical transport, and how global standards converge to support interoperability and future readiness. The significant of 5G technology and how optimum use of optical Fiber of can help in achieving digital inclusiveness is also presented in this paper.

Evolution of Fiber‑Optic Systems

Advances in Fiber optic technology continues to push the envelope, with companies now exploring 4-Gbit/sec and 100-Gbit/sec speeds. Such advancements are not just theoretical but are being implemented across various regions.

The promise of 5G is not just in its speed but also in its remarkably low latency. Optical Fiber cables are crucial in achieving this, offering minimal delay in data transmission. This is particularly important for applications such as autonomous vehicles, telemedicine, and augmented reality, where even a millisecond delay can be detrimental.

Optical Fiber Characteristic: Optical Fiber possesses high bandwidth and low attenuation features which make a ideal for large transmission[9]. The Fiber optic feature can be categories as linear and nonlinear. Nonlinear characteristics are effective by parameters such as power level, channel spacing Bit rate[10]. Evaluation of Fiber optic system comprises as first generation of light wave system uses GaAs semiconductor laser and operating region was near 0.8μm. The other specification of the first generation is Bit rate 45Mb/s and repeater spacing 10 km, the second generation comprises Bit rate 100 Mb/s to 1.7Gb/s along with repeater spacing 50km and operation wavelength 1.3 μm. Second generation light wave system uses in GaAsP. The third-generation Fiber optic system have Bit rate 10Gb/s along with repeater spacing 100km and operating wave length 1.55 μm.

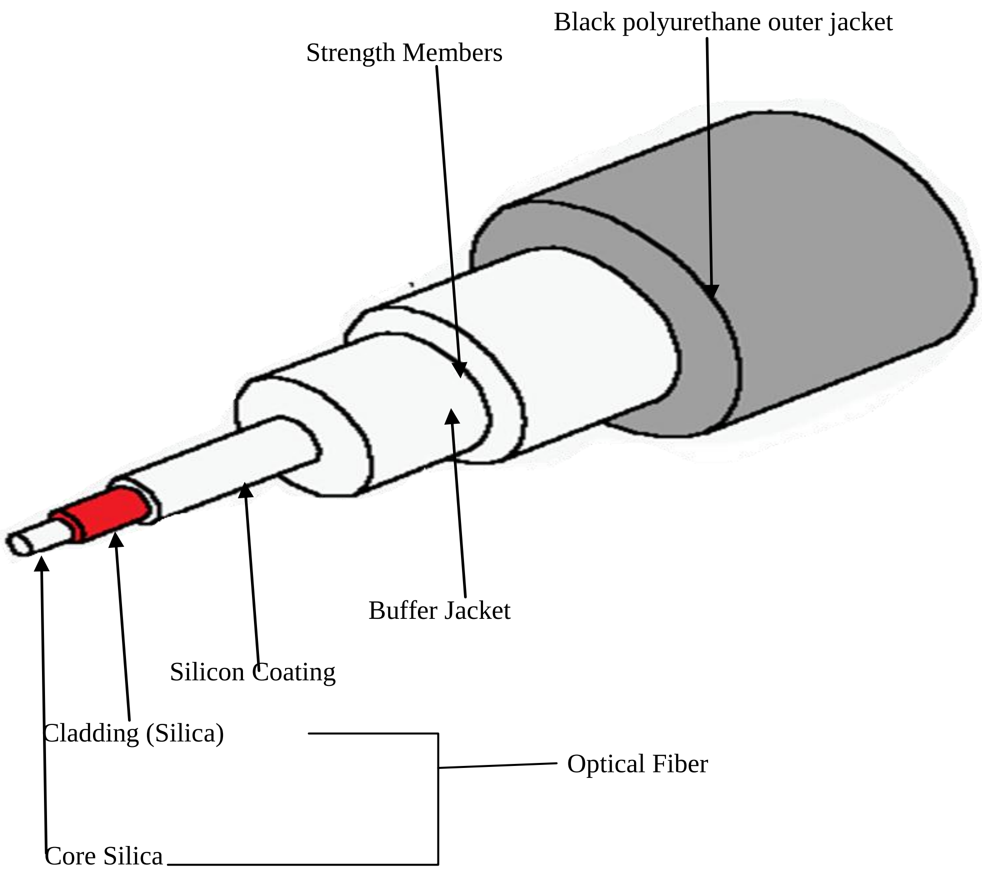

Figure-1: Optical fiber infrastructure.

The fourth generation of light wave system uses WDM technique along with Bit rate 10Tb/s, repeater spacing >10000km along with operating wave length 1.45 to 1.62 µm. Finally, the fifth-generation light wave system uses Raman amplification technique and optical solitons consist of Bit rate 40-160Gb/s, repeater spacing 24000km to 35000km along with operating wave length 1.53 to 1.57µm. With modern development, communication have become an important part of human life and cannot the dispensed with, the communication, process involves, information operation, transmission, reception and interpretation. Wide, bandwidth for signal transmission with low delay is a key requirement in present day application. Fiber optic is now the transmission medium of data for long distance and it has high data rate transmission for Telecommunication networks. Earlier authors[11] presented detailed look and the communication concept of wire, in particular the characteristic and application of Fiber optic along with architecture and optical Fiber system. Earlier studies also suggested that a huge amount of development can be made by making more research and work on optical Fiber[12].

Evaluation of coherent/WDM per wavelength rate are shown in Figure-2.

5G System Architecture: 5G is the 5th generation mobile network. It is a new global wireless standard after 1G, 2G, 3G and 4G networks. 5G works in 3 bands (Low, Mid and High Frequency spectrum) – all of which have their own uses as well as limitations. It enables a new kind of network that is designed to connect virtually everyone and everything together including machines, objects, and devices. In India, Satcom Industry Association-India (SIA) has voiced concerns over the Government plan to include the Millimeter Wave (mm Wave) bands in the 5G spectrum auction.

Radio Access Network (RAN): The 5G gNB decomposes into distributed and centralized functions to balance latency and pooling gains. A common split places higher‑PHY/packet scheduling in the Distributed Unit (DU) near the cell site and lower‑PHY and RF in the Radio Unit (RU), with the Central Unit (CU) hosting PDCP/RRC and higher‑layer protocols. Functional split options (e.g., 7‑2x) carried over eCPRI govern fronthaul bandwidth and delay budgets. Open RAN disaggregates vendor domains and introduces open fronthaul, near‑real‑time RAN intelligent control, and service management/orchestration interfaces.

5G Core and Edge: The 5G Core adopts a service-based architecture with control and user plane separation. User Plane Functions (UPFs) can be placed deep in the network or at the edge to localize traffic, enabling multi-access edge computing (MEC). Network slicing partitions resources end‑to‑end across RAN, transport, and core to meet diverse SLAs for eMBB, URLLC, and mMTC workloads.

Timing and Synchronization: Tight frequency, phase, and time alignment are mandatory for advanced features such as TDD, coordinated multi‑point, and massive MIMO. Practically, operators combine Synchronous Ethernet for frequency and IEEE 1588v2 Precision Time Protocol for time/phase distribution, with boundary and transparent clocks used to bound packet delay variation across Ethernet segments.

Fiber Transport for 5G xHaul: Fiber transport for 5G xHaul consisting rediounit, distributed unit, central unit and core is soon in Figure-3.

Transport solutions span dedicated dark fiber, CWDM/DWDM over shared fiber, and PON‑ based xHaul. Fronthaul demands the most stringent latency and jitter, often favoring short‑ reach fiber pairs or low‑ latency WDM. Midhaul and backhaul can leverage statistical multiplexing with Ethernet/IP/MPLS or segment routing, grooming flows into OTN or high‑ rate Ethernet. In access, XGS‑ PON and higher speed PON can serve small cell sites alongside residential subscribers, provided DBA and QoS profiles enforce deterministic behavior for mobile traffic. 5G xHual latency budget is shown in Figure-4.

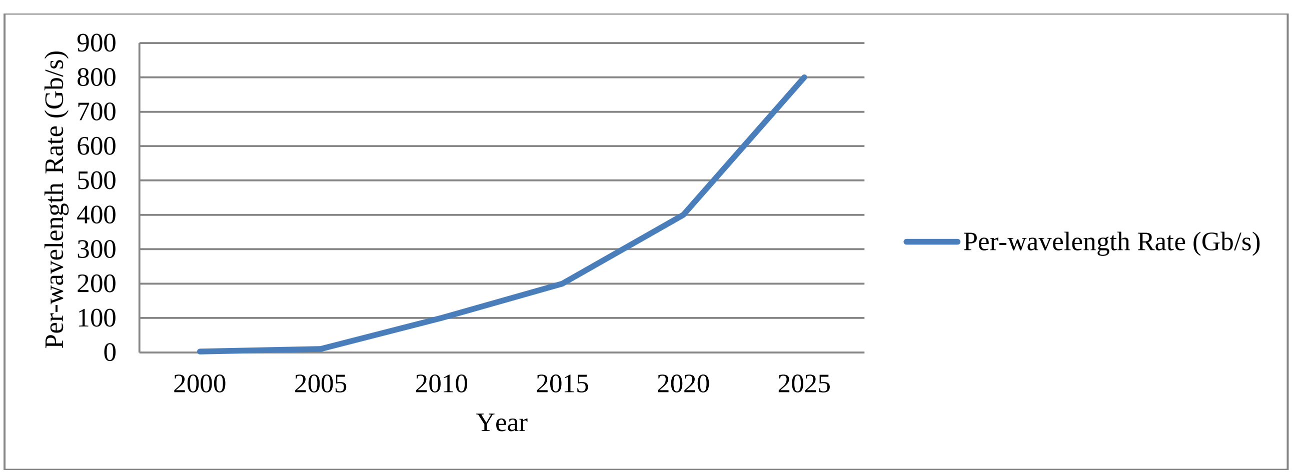

Figure-2: Illustrative per wavelength capacity milestones in optical transport.

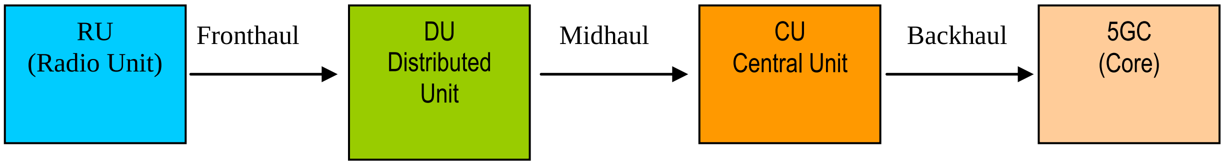

Figure-3: 5G xHaul reference architecture showing fronthaul (RU–DU), midhaul (DU–CU), and backhaul (CU–5GC) over fiber.

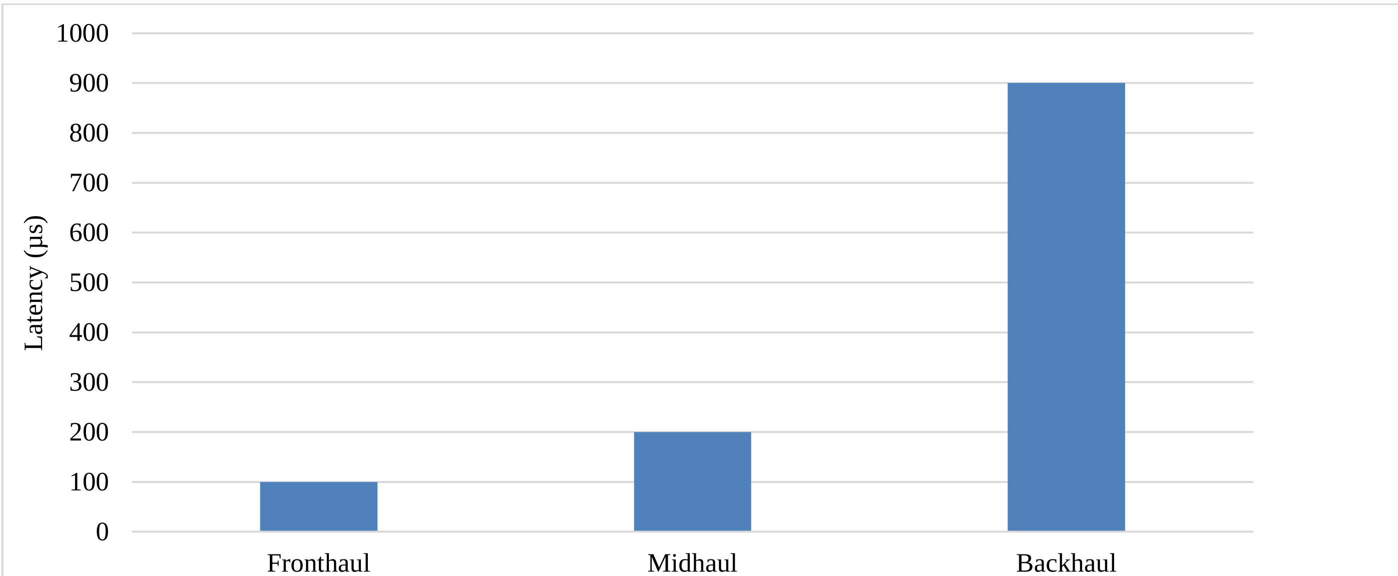

Figure-4: Illustrative latency budget decomposition across xHaul segments.

Standards Landscape and Interoperability

5G's maturity depends on stable, interoperable standards across radio, packet, and optical domains. 3GPP defines the 5G radio and core specifications across successive Releases. The O‑RAN Alliance specifies disaggregated RAN interfaces (e.g., open fronthaul) and RIC frameworks. ITU‑T standardizes fiber and PON families (e.g., XGS‑PON and higher speed PON), optical fiber characteristics for long‑haul and access, and synchronization over packet networks. IEEE 802.3 governs Ethernet PHY rates used throughout transport, while IEEE 802.1 defines time‑sensitive networking profiles applicable to fronthaul. IETF contributes segment routing, EVPN, timing security, and transport encapsulations that integrate with SDN‑based orchestration. Interoperability profiles from industry consortia and open test events further reduce integration risk.

Architectural innovation is further defined by the O-RAN Alliance[13], which specifies open interfaces across the radio access network. Functional splits such as 7.2x require stringent latency, often below 250 µs, which only fiber can guarantee. IEEE's Time-Sensitive Networking (TSN) standards enhance Ethernet to support fronthaul with bounded latency, while ITU-T continues to evolve PON standards for converged access. FSAN's[14] roadmap towards 50G-PON also illustrates the long-term synergy between optical access and mobile transport. Moreover, segment routing[15] and transport slicing in the IETF provide standardized mechanisms to map 5G slice intents into optical and packet behaviors.

On the standards front, several bodies converge on next-generation transport solutions. IEEE 1914.x defines packet-based fronthaul supporting Common Public Radio Interface (CPRI) over Ethernet, while ITU-T G.hn and G.9807 focus on high-capacity PON variants. Transport slicing[16], a critical component in IETF drafts, enables logical partitioning of optical links to map service-level agreements (SLAs) for enhanced mobile broadband, ultra-reliable low-latency communications, and massive IoT. Regional deployments further illustrate architectural choices: Japan has advanced 25G-PON[17] fronthaul trials; Korea Telecom[18] has demonstrated dynamic optical switching for RAN disaggregation; and major US operators [19] leverage segment routing to integrate IP and optical cores seamlessly.

Fixed–Mobile Convergence (FMC)

FMC unifies optical access and mobile transport to maximize fiber reuse. A shared optical distribution network allows the same OLT to serve homes, enterprises, and small cells. Critical enablers include hierarchical QoS, slice aware traffic engineering, and telemetry driven automation. Where fronthaul latency is tight, operators may dedicate wavelengths or use WDM‑PON; for backhaul, stat‑mux over PON with strictQoS can suffice. Converged operations reduce truck rolls, power footprint, and space at aggregation sites. Shared passive optical network topology serving FTTH and 5G small cell.

The Impact of 5G Technology on Engineering

The main engineering considerations in the design of modern optical and 5G transport networks include several critical aspects such as capacity planning, latency, synchronization, optics selection, resilience, operations, and coexistence. Capacity planning involves determining the appropriate mix of 10/25/50/100 GbE interfaces, defining wavelength plans, and estimating the optical reach for each segment to ensure scalability and efficiency. Latency and jitter considerations focus on the placement of Distributed Units (DU) and Centralized Units (CU), the selection of functional splits, and the optimization of queuing mechanisms across network switches and routers to maintain low delay and consistent performance. Synchronization requires careful design of the Precision Time Protocol (PTP) topology, including grandmaster, boundary, and transparent clocks, as well as an effective holdover strategy to maintain timing accuracy. Optics selection is guided by the choice between NRZ and PAM4 modulation formats, gray or colored optics, and technologies such as 400ZR/ZR+ for metro Data Center Interconnect (DCI) and pluggable coherent modules in routers. Resilience emphasizes fiber path diversity, fast reroute capabilities, hitless Optical Transport Network (OTN) restoration, and coordination of failure recovery between Radio Access Network (RAN) and transport layers. Operations are enhanced through model-driven automation using NETCONF/YANG protocols, real-time streaming telemetry, and intent-based network controllers. Finally, coexistence strategies ensure that mobile network wavelengths can operate alongside legacy enterprise and residential services without interference, thereby enabling seamless and efficient multi-service network environments.

Security and Reliability

In the modern 5G transport networks have become paramount due to the transition from monolithic to highly disaggregated, software-centric architectures. This shift significantly expands the attack surface, introducing multiple entry points for potential threats. Standalone 5G deployments further broaden security dimensions, necessitating the implementation of zero-trust networking principles across all layers of the transport network. In this framework, every device and interface must be authenticated to prevent unauthorized access. The rise of quantum computing poses new challenges to traditional encryption methods, prompting the development and standardization of post-quantum cryptography (PQC) to safeguard critical infrastructure. Additionally, optical fiber itself plays a crucial role in network security, as advanced intrusion detection systems can identify minute variations in backscatter or light intensity to detect tapping attempts[20].

To enhance protection, AI-driven security frameworks are increasingly integrated into operational transport systems. These frameworks employ deep learning for real-time anomaly detection, identifying deviations in traffic patterns that may signify distributed denial-of-service (DDoS) attacks or physical fiber intrusions. Zero-trust orchestration ensures encryption, authentication, and policy enforcement across control, management, and data planes, moving away from traditional perimeter-based defences and aligning with the dynamic, software-defined nature of next-generation networks[21].

Robust encryption mechanisms such as MACsec and IPsec are deployed to secure Ethernet and IP segments, while OTN-layer encryption ensures compliance with enterprise and regulatory standards for high-value data. Timing and synchronization security is also reinforced through enhanced Precision Time Protocol (PTP) profiles that include source authentication to prevent spoofing or tampering. On the physical side, fiber plant security involves continuous monitoring to detect tapping, bending, or degradation in optical cables, thereby maintaining physical-layer integrity. Finally, reliability strategies such as redundant fiber paths, diverse routing, and proactive fiber health analytics are employed to minimize single points of failure and predict potential issues before outages occur, ensuring uninterrupted and secure network operations.

Economics and Sustainability

The deployment Economics in modern 5G and fiber transport networks are influenced by several critical factors, including site density, fiber availability, spectrum strategy, and the degree of network disaggregation. From an economic perspective, fiber deployment represents the single largest capital expenditure in 5G rollouts, with civil works—such as trenching and ducting—accounting for nearly 70% of total deployment costs in Greenfield projects. To optimize investments, operators increasingly pursue fixed–mobile convergence (FMC) strategies, enabling shared fiber infrastructure to serve both fixed broadband and mobile services, thereby reducing total capital and operational expenditures[7]. Additionally, energy consumption has emerged as a key performance indicator (KPI), with studies indicating that coherent pluggable optics can lower per-bit energy usage by up to 40% compared to legacy transponders. Artificial intelligence (AI)-assisted traffic engineering further enhances efficiency by reducing idle capacity and maximizing utilization of deployed fiber assets.

Comprehensive cost modelling in network planning now includes a wide range of factors, such as civil works (trenching, permits, and ducts), the mix and cost of optical components (grey optics, coherent pluggable, and passive optical networks), as well as expenses related to licensing, software, automation platforms, power, cooling, and space in central offices and data centres. Operational tooling and workforce training are also key elements in total cost calculations. In certain regions, techno-economic analyses reveal that fiber trenching alone can contribute to nearly 80% of overall network costs, making infrastructure sharing and neutral-host models increasingly attractive options for operators.

To complement fiber connectivity, wireless backhaul solutions such as microwave or satellite links are sometimes deployed to extend coverage; however, these alternatives generally lack the scalability and low-latency performance that fiber provides. Energy efficiency measures are gaining importance, including the use of coherent pluggable optics to reduce power per bit, sleep modes in access networks to conserve energy during off-peak hours, and AI-based traffic shaping to minimize energy waste. Beyond capital and operational expenditures, modern lifecycle assessments also incorporate carbon footprint and environmental sustainability metrics. Recent studies have introduced standardized energy-per-bit indicators and sustainability scorecards for optical networks, guiding operators toward greener investments through the integration of renewable energy sources, efficient cooling systems, and long-term ecological practices that ensure both economic and environmental viability.

Deployment Patterns (Illustrative)

Network deployment strategies vary significantly across dense urban, suburban, and rural environments, each requiring tailored optical and architectural approaches to balance performance, cost, and scalability. In dense urban areas, short fronthaul connections are typically implemented using gray optics or Coarse Wavelength Division Multiplexing (CWDM), while midhaul and backhaul traffic is aggregated into high-capacity 100 GbE or 400 GbE links. These are often interconnected through 400ZR Data Center Interconnects (DCI) between edge and core networks to support the massive bandwidth demands and low-latency requirements of urban 5G infrastructure. In suburban fixed–mobile convergence (FMC) deployments, XGS-PON technology is commonly used, with specific wavelengths or traffic classes reserved for small-cell communication. Quality of Service (QoS) parameters and Dynamic Bandwidth Allocation (DBA) are finely tuned to ensure deterministic latency and consistent performance across both residential broadband and mobile backhaul services.

In rural regions, longer backhaul spans are necessary and are typically supported using Dense Wavelength Division Multiplexing (DWDM) systems with strategically placed optical amplifier sites to maintain signal strength over extended distances. To simplify the network architecture and reduce latency, Distributed Units (DUs) may be co-located with Radio Units (RUs), thereby easing fronthaul constraints and optimizing performance in less densely populated areas.

Open Challenges and Future Directions

In fiber-based transport networks are closely tied to the evolving demands of 5G-Advanced and the emerging vision of 6G. As networks progress toward 6G, fiber transport will serve as the foundation for supporting advanced technologies such as terahertz radio links, holographic MIMO arrays, and integrated sensing–communication systems. Future networks will feature intent-based orchestration, where service requirements, such as network slicing, are automatically translated into both optical and packet configurations, enabling fully autonomous and adaptive operations. Fiber transmission capabilities are expected to expand into the S-band, effectively tripling usable capacity. Additionally, green networking will become a core mandate, requiring operators to report carbon intensity metrics alongside throughput and latency performance. A major research focus also lies in the integration of quantum key distribution (QKD) with classical data channels, allowing encrypted quantum keys and user traffic to coexist securely within the same fiber infrastructure — paving the way for a sustainable and quantum-secure 6G ecosystem[20].

The long-term 6G vision extends beyond terrestrial connectivity, embracing the integration of non-terrestrial networks (NTNs) such as low-earth-orbit (LEO) satellites, high-altitude platforms, and unmanned aerial vehicles, all interconnected through fiber-based ground stations. This “network of networks” approach ensures global coverage, enhanced resilience, and seamless interconnectivity. Fiber will continue to serve as the backbone for aggregation, synchronization, and quantum-secure key exchange, while sustainability strategies advance to include renewable-powered edge data centres, silicon photonic transceivers with ultra-low power consumption, and circular-economy practices for optical hardware reuse and recycling.

Emerging innovations are also reshaping communication models. Side link enhancements will enable direct device-to-device communication, while high-precision positioning and integrated sensing services will become intrinsic to 6G’s functionality. AI-native control systems will drive autonomous optimization of network resources, ensuring intelligent, self-adjusting performance management. These capabilities will require sub-microsecond synchronization and near real-time telemetry to maintain ultra-reliable and low-latency operations[21].

On the optical innovation front, the introduction of 800 Gb/s coherent pluggable will significantly enhance metro and access transport capacity, while expanding the usable fiber spectrum into the C+L bands will further increase bandwidth potential. The exploration of coherent Passive Optical Network (PON) technologies promises to unify access and mobile backhaul into a single converged platform. Programmable transport architectures are expected to dominate, shifting toward intent-based models where operators define service-level targets for latency, jitter, and reliability. These systems, supported by machine learning-driven closed-loop controllers and streaming

telemetry, will enable proactive, predictive network management rather than reactive troubleshooting.
From a security perspective, the advent of quantum computing poses a major challenge, rendering current encryption methods vulnerable. To counter this, the deployment of quantum-safe cryptography and the implementation of QKD over fiber will become essential. Enhancements to Precision Time Protocol (PTP) with authentication mechanisms will also help prevent timing-based cyber attacks.

Finally, the 6G vision emphasizes the convergence of communication, sensing, and computing, with heavy reliance on fiber backbones for global connectivity, synchronization, and data aggregation. Technologies such as terahertz spectrum, holographic MIMO, and reconfigurable intelligent surfaces (RIS) will drive new possibilities in wireless communication. In parallel, sustainability imperatives will push for energy-efficient optics, renewable-powered infrastructure, and green networking practices to balance performance growth with environmental responsibility. Overall, fiber transport must evolve in terms of capacity, programmability, security, and sustainability to fully support the ambitions of 5G-Advanced and establish the groundwork for the 6G era[21].

Conclusion

The evolution of 5G demonstrates that radio innovation alone is insufficient without an equally advanced transport foundation. Fiber-optic systems—through coherent optics, dense wavelength-division multiplexing, and next-generation PON—have become inseparable from the success of 5G. By enabling deterministic latency, precise synchronization, and scalable capacity, fiber ensures that enhanced mobile broadband, ultra-reliable low-latency communication and massive machine-type communication can be delivered at scale. At the same time, open standards from 3GPP, ITU, IEEE, IETF, and the O-RAN Alliance are fostering interoperability and reducing vendor lock-in, allowing more agile and cost-efficient deployments. Convergence of fixed and mobile access is further optimizing infrastructure investment and creating a pathway toward seamless digital inclusion. As the industry progresses into 5G-Advanced and prepares for 6G, the integration of cloud-native automation, AI-driven orchestration, and sustainable fiber technologies will be essential. The long-term success of next-generation networks will hinge on balancing performance, economics, and sustainability in a globally unified transport framework.

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