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Towards 6G: A Review of Optical Transport Challenges for Intelligent and Autonomous Communications

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Abstract

The advent of sixth-generation (6G) communications envisions a paradigm of ubiquitous intelligence and seamless physical–digital fusion, demanding unprecedented performance from the optical transport infrastructure. Achieving terabit-per-second capacities, microsecond latency, and nanosecond synchronisation precision requires a convergent, flexible, open, and AI-native x-Haul architecture that integrates communication with distributed edge computing. This study conducts a systematic literature review of recent advances, challenges, and enabling optical technologies for intelligent and autonomous 6G networks. Using the PRISMA methodology, it analyses sources from IEEE, ACM, and major international conferences, complemented by standards from ITU-T, 3GPP, and O-RAN. The review examines key optical domains including Coherent PON (CPON), Spatial Division Multiplexing (SDM), Hollow-Core Fibre (HCF), Free-Space Optics (FSO), Photonic Integrated Circuits (PICs), and reconfigurable optical switching, together with intelligent management driven by SDN, NFV, and AI/ML. The findings reveal that achieving 6G transport targets will require synergistic integration of multiple optical technologies, AI-based orchestration, and nanosecond-level synchronisation through Precision Time Protocol (PTP) over fibre. However, challenges persist regarding scalability, cost, energy efficiency, and global standardisation. Overcoming these barriers will demand strategic R&D investment, open and programmable architectures, early AI-native integration, and sustainability-oriented network design to make optical fibre a key enabler of the intelligent and autonomous 6G ecosystem.

Keywords: 6G; AI-native; artificial intelligence/machine learning (AI/ML); coherent passive optical network (CPON); spatial division multiplexing (SDM); hollow-core fibres (HCF)

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1. Introduction

The history of mobile communications is a narrative of constant evolution, marked by generational leaps that have redefined connectivity and enabled new capabilities. From the introduction of analogue mobile voice (1G) to the era of broadband mobile Internet with 4G and 5G, each generation has responded to an exponential demand for data and increasingly sophisticated services. The fifth generation (5G), whose specifications and early deployments laid the foundations for a more connected society, introduced three pillars of use cases: Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC), and Massive Machine-Type Communications (mMTC). Technologies such as millimetre waves (mmWave), Massive MIMO (mMIMO), and Network Function Virtualisation (NFV) were fundamental to achieving these objectives.

However, the vision for the sixth generation (6G), also known as IMT-2030 by the International Telecommunication Union (ITU), transcends the mere quantitative enhancement of 5G parameters. 6G aspires to catalyse a profound fusion between the physical, digital, and human worlds, creating an intelligent and ubiquitous connective fabric [1]. This vision will enable transformative applications that are only beginning to emerge today: truly immersive and multisensory extended reality (XR) experiences, holographic communications for telepresence, real-time digital twins for industry and smart cities, advanced industrial automation with remote robotic control, fully autonomous coordinated vehicles, and sophisticated telemedicine applications such as remote surgery.

To realise this ambitious vision, the underlying network infrastructure must undergo a radical evolution. In particular, the optical transport infrastructure—encompassing fronthaul, midhaul, and backhaul (collectively referred to as x-Haul)—stands as an absolutely critical pillar [2]. This optical fibre network must support unprecedented performance requirements that surpass even the most advanced 5G networks. The convergence between fixed and mobile networks, as well as the seamless integration of diverse communication technologies (terrestrial, satellite, aerial, and submarine), becomes indispensable within the 6G architecture [3].

1.1. Key 6G Requirements for Optical Transport

The transition to 6G imposes extraordinary demands on the optical transport network, establishing new benchmarks across multiple performance dimensions:

- Throughput: Peak per-device data rates are expected to reach or exceed 1 terabit per second (Tbps), with user-experienced data rates sustained in the range of hundreds of gigabits per second (Gbps). This represents an increase of 50–100 times compared with peak 5G capabilities. Specific applications, such as high-fidelity holographic communications, may require even greater capacities, potentially exceeding 4 Tbps per stream [4].
- Latency: End-to-end (E2E) latency must be drastically reduced from the millisecond (ms) range typical of 5G URLLC to microsecond (μs) levels, targeting 10–100 μs [5]. This constitutes a 10- to 100-fold reduction compared with 5G [6]. Moreover, not only must average latency be low, but it must also be deterministic, with minimal variation (jitter) [7].
- Reliability: The levels of reliability required for hyper-reliable and low-latency communications (HRLLC or eRLLC in 6G terminology) reach extremely high thresholds, with transmission success rates between 99.9999% and 99.9999999%—commonly referred to as “seven to nine nines”.
- Connection Density: The 6G network must be capable of supporting a massive density of simultaneously connected devices, potentially ranging between 10^7 and 10^8 devices per square kilometre [5]. This is fundamental for the Internet of Everything (IoE).
- Synchronisation: The precise coordination of complex network operations, such as advanced beamforming, distributed computing, and cooperative radio interfaces, demands time synchronisation accuracy at the nanosecond (ns) level across the optical network [8].
- Energy Efficiency: A significant increase in energy efficiency, measured in bits transmitted per joule of consumed energy, is expected—with improvement targets of up to 100 times compared with 5G [5]. It is important to note, however, that higher efficiency per bit does not necessarily guarantee a reduction in the network’s total energy consumption, given the exponential growth expected in traffic volume [9].
- AI-Native Intelligence: A fundamental and transversal requirement is that the 6G network architecture must be inherently intelligent (AI-Native). This means that Artificial Intelligence (AI) and Machine Learning (ML) are not merely overlaid applications but are deeply integrated into the fabric of the network—from design to operation and optimisation—including the optical transport layer [10].

Table 1. Comparison of Key 5G vs. 6G KPIs for Optical Transport.

KPI (Key Performance Indicator)	Unit	Typical 5G Value	Target 6G Value	Improvement Factor (Approx.)	Sources
Peak Data Rate per Device	Gbps/Tbps	20 Gbps	>1 Tbps	>50x	[11]

User-Experienced Data Rate	Mbps/Gbps	100 Mbps	>1 Gbps	>10x	-
End-to-End (E2E) Latency (User Plane)	ms/µs	~1 ms	10 - 100 µs	10x - 100x	[11]
Reliability (URLLC/HRLLC)	%	99.999% (five nines)	99.9999%–99.9999999% (seven–nine nines)	>100× (in error rate)	-
Connection Density	devices/km^2	10^6	10^7–10^8	10x - 100x	[11]
Synchronisation Accuracy	µs/ns	~µs	~ns	1000x	[12]
Energy Efficiency (Network)	bits/Joule	~10^7	~10^9	~100×	[11]

Table 1 summarises the magnitude of the leap required in key performance indicators (KPIs) between 5G and 6G, specifically from the perspective of optical transport infrastructure. This table highlights the monumental challenge facing optical infrastructure. The objectives are not merely incremental; they demand a fundamental rethinking of transport architecture and technology to bridge the gap between current capabilities and the ambitious performance targets envisioned for 6G.

1.2. Second-Order Perspective: Beyond Connectivity

It is essential to understand that the requirements of 6G, when viewed as a whole, signal a qualitative transformation in the role of the network. It is not simply a linear extension of 5G capabilities. The synergistic combination of terabit-per-second data rates, stable latency in the microsecond range, extreme reliability, and native support for distributed artificial intelligence indicates that 6G is being designed as a platform for real-time interaction between the physical and digital worlds, enabling cyber–physical control on an unprecedented scale—far beyond the mere exchange of data [13].

While 5G introduced the ability to support high speed (eMBB), low latency (URLLC), or high density (mMTC), 6G demands the simultaneity of these attributes at extreme levels: ultra-high speed, ultra-low latency, extreme reliability, and high connection density, often required concurrently within the same service or application. This simultaneity is an indispensable prerequisite for the transformative applications defining the 6G vision, such as truly immersive extended reality (XR), precise remote robotic control, and digital twins that reflect and act upon the physical world instantaneously. These applications not only require the transmission of massive data volumes but also their processing, analysis through AI, and, crucially, real-time action on the physical environment (control) with near-instantaneous responsiveness.

This fundamentally redefines the role of the optical transport network. It can no longer be regarded as a passive “bit pipe”, but must be conceived and designed as an integrated and active platform for communication, computation, and potentially sensing—geographically distributed and synchronised with nanosecond precision. The location of computing capabilities (at the edge) and the need for ultra-precise synchronisation thus become first-order architectural considerations for 6G optical infrastructure.

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2. Evolution of Optical Network Architecture for 6G (x-Haul)

2.1. Limitations of the Current 5G Optical Infrastructure

The optical transport infrastructure deployed for 5G, although representing a significant advancement over 4G, presents intrinsic limitations that prevent it from directly meeting the demanding requirements of 6G. These limitations are mainly evident in the fronthaul segment, which is the most latency-sensitive and capacity-intensive part of the network.

2.1.1. 5G Fronthaul (CPRI/eCPRI over Ethernet/PON)

- Capacity: The Common Public Radio Interface (CPRI) protocol, widely used in 4G and early 5G deployments, has a practical bandwidth limit of approximately 24 Gbps per link and does not scale efficiently to support massive MIMO configurations and the much wider channel bandwidths anticipated for 6G [14]. The enhanced CPRI (eCPRI) protocol, designed to be more bandwidth-efficient by transporting data in the frequency domain or through higher functional splits, reduces the load but may still prove insufficient for the projected demands of hundreds of Gbps or even Tbps per cell site in 6G [15]. It is estimated that 6G fronthaul could require more than 500 Gbps per individual cell, aggregating traffic that exceeds 1 Tbps or even 10 Tbps in sites hosting multiple radio units (RUs) [16].
- Latency and Jitter: Standard Ethernet, while flexible and cost-effective, lacks inherent mechanisms to guarantee deterministic latency. The variability in packet delay (Packet Delay Variation – PDV), or jitter, introduced by conventional Ethernet switching, is incompatible with the microsecond-level latency requirements and temporal stability necessary for 6G fronthaul [14]. Passive Optical Network (PON) solutions based on time-division multiplexing (TDM-PON), such as GPON or XGS-PON, although efficient for backhaul or FTTH applications, introduce significant latency (>100 μs) due to their dynamic bandwidth allocation (DBA) mechanisms, making them unsuitable for the most stringent 6G fronthaul segments [16].
- Synchronisation: The inherent delay variation in conventional packet-based Ethernet networks poses a major challenge for accurate timing transfer, which is essential to achieve the nanosecond-level synchronisation required by 6G [14]. Although protocols such as Precision Time Protocol (PTP) over Ethernet can improve accuracy, achieving the nanometric stability and precision required across multiple packetised network hops remains difficult [14]. A maximum time error of approximately 3 μs is required in O-RAN interfaces, and potentially much lower for advanced 6G functions [8].
- 5G PON: Current generations of PON (GPON, XGS-PON, and even the emerging 25G-PON) were not designed to deliver the terabit capacities or microsecond latencies expected to be necessary for aggregated 6G x-Haul transport [11]. Although 25G-PON represents a significant advancement and may be applicable in certain 5G/5.5G scenarios, a much deeper technological evolution will be required for 6G transport [16].

The following table summarises these specific limitations of 5G optical transport in contrast to the projected requirements for 6G x-Haul.

Table 2. Limitations of 5G Optical Transport versus 6G x-Haul Requirements.

Parameter	Typical 5G Technology	Typical 5G Limitation	Target 6G Requirement	Sources
Fronthaul Capacity (per cell)	eCPRI over Ethernet/PON	Tens of Gbps	>500 Gbps	[14]

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Aggregated Capacity (per site)	Aggregated Ethernet/PON	Hundreds of Gbps	>1-10 Tbps	[16]
Fronthaul Latency (E2E)	Standard Ethernet / TDM-PON	>100 µs (variable)	<100 µs (deterministic)	[14]
Fronthaul Jitter (PDV)	Standard Ethernet	Variable / High	Very Low / Controlled	[14]
Synchronisation Accuracy (Fronthaul)	PTP over Ethernet/PON	~µs (variable)	~ns (stable)	[14]

This table demonstrates that the optical technologies and architectures of 5G, although adequate for their generation, represent a significant bottleneck for 6G. Overcoming these limitations requires not merely incremental improvements but a redefinition of the overall architecture and the adoption of fundamentally new optical technologies.

2.1.2. Arquitectura x-Haul Convergente y Flexible Para 6G

To address the challenges and enable the 6G vision, the optical transport architecture must evolve towards a convergent, flexible, open, and intrinsically intelligent model.

- x-Haul Convergence: A unified transport architecture is essential to transparently and efficiently integrate the fronthaul (RU–DU), midhaul (DU–CU), and backhaul (CU–Core/Cloud) segments [1]. This convergence should support the transport of diverse traffic types (user data, control, synchronisation, management, and AI-related data) with different QoS requirements over a shared physical infrastructure, thereby optimising resource utilisation. The architecture must be adaptable to multiple deployment scenarios, including Distributed Radio Access Networks (DRAN), Centralised (CRAN), and Virtualised (VRAN) topologies [17].
- Functional Flexibility (Splits): The disaggregation of base station functions (Baseband Unit – BBU) into Distributed Units (DU) and Centralised Units (CU), promoted by initiatives such as O-RAN, enables flexible division of radio protocol functions (functional splits) [1]. The 6G optical transport network must dynamically support multiple split options (FFS – Flexible Functional Splits) [10]. This allows optimisation of the trade-off between required fronthaul bandwidth, end-to-end latency, and the degree of baseband centralisation, adapting to the specific needs of each service and deployment scenario.
- AI-Native Integration: Unlike 5G, where AI is often introduced as an overlay layer, the 6G architecture must be conceived from the ground up to integrate AI natively (AI-Native) [10]. This means that data collection, AI processing, and ML model execution capabilities must be embedded within optical network elements and management systems, enabling intelligent optimisation, advanced automation, and the creation of AI-driven services.
- Openness and Interoperability: The adoption of open interfaces, such as those specified by the O-RAN Alliance, and the promotion of open-source approaches are crucial to eliminating vendor lock-in, fostering innovation, reducing costs, and ensuring interoperability within a multi-vendor ecosystem [3]. Global and coordinated standardisation across different organisations (ITU, IEEE, 3GPP, ETSI, O-RAN) is indispensable for the successful deployment of 6G [17].
- Proposed Optical Architecture: The emerging architectural vision for 6G x-Haul is based on highly flexible and reconfigurable Wavelength Division Multiplexing (WDM) optical networks. Elements such as Reconfigurable Optical Add-Drop Multiplexers (ROADMs) are extended beyond the core and metro layers to reach the network edge, enabling dynamic wavelength switching [18]. These reconfigurable WDM networks could be combined with advanced PON

technologies (such as Coherent PON) for access and initial aggregation, and potentially integrate other technologies such as Free-Space Optics (FSO) for specific scenarios. Mesh and flattened architectures are favoured to increase resilience and provide multiple routing paths, as opposed to more rigid ring topologies [19].

2.1.3. Integration with Edge Computing and Distributed Architectures

The 6G optical architecture cannot be designed in isolation; it must be deeply integrated with distributed computing architectures that are fundamental to enabling many 6G services.

- Cloud–Edge–Device Continuum: 6G materialises the concept of a computational continuum that extends from centralised data centres (Cloud), through multiple tiers of computing nodes at the network edge (Edge Computing, Fog Computing), to processing capabilities embedded in end-user devices themselves [19]. The optical network acts as the connective fabric that unites this continuum.
- MEC (Multi-Access Edge Computing) and Edge AI: Edge computing (MEC) is crucial for processing data and executing latency-sensitive applications—such as industrial control, AR/VR, and autonomous driving—as well as for enabling AI functions (Edge AI) close to the end user [19] . The optical transport network must provide ultra-low-latency, high-bandwidth connectivity to these MEC nodes, whose locations may range from cell sites to regional central offices [11]. The evolution of ETSI MEC is aimed at supporting 6G requirements [20].
- Distributed Computing Paradigms: Beyond MEC, the 6G architecture must support paradigms such as Fog Computing, which introduces an intermediate computing layer between the edge and the cloud, as well as other distributed approaches that optimise processing placement according to application requirements [18].
- Joint Communication–Computation Optimisation (JCC): The efficiency of distributed applications in 6G will depend on the network's ability to jointly manage and optimise communication resources (optical bandwidth, latency) and computing resources (CPU, GPU, memory, storage) across the Cloud–Edge continuum [13]. The optical network must enable this joint management by providing not only connectivity but also link-state awareness and rapid reconfiguration capabilities to support the optimal placement of computational tasks.

2.1.4. Second- and Third-Order Perspectives: Architectural Implications

The architectural evolution described above has profound implications that extend far beyond mere technological upgrades.

First, x-Haul convergence and functional split flexibility (FFS) should not be regarded solely as technical optimisations but as critical enablers for resource efficiency and the dynamic adaptability of 6G services. This flexibility allows the network to dynamically locate both network processing functions (from RAN and Core) and application functions (such as AI models or MEC services) at the optimal point within the Cloud–Edge–Device continuum. The placement is determined in real time, based on the specific latency, bandwidth, processing capacity, and energy efficiency requirements of each service or application [1]. For example, a URLLC service may require a lower split (processing closer to the RU) to minimise latency, at the expense of increased optical fronthaul bandwidth demand, whereas an eMBB service may benefit from a higher split (more centralised processing) to conserve optical bandwidth [1]. The ability of the optical network to dynamically support and reconfigure these splits [19] is therefore fundamental to optimising global resource utilisation (fibre, spectrum, computing, and energy) and ensuring Quality of Service (QoS) for a heterogeneous mix of 6G applications. This, in turn, requires a highly programmable optical network with intelligent and automated orchestration capable of making such complex decisions in real time [21].

Second, the deep integration with Edge Computing and the imperative need to support distributed AI including paradigms such as Federated Learning (FL) [22] drive a significant decentralization of intelligence and control across the network. While this provides clear benefits in terms of latency and privacy [23], it also exponentially increases the complexity of optical network management and orchestration. The network is no longer limited to connecting points A and B; it must now intelligently and dynamically interconnect a multitude of distributed computing nodes at the edge [11]. Orchestration must now jointly consider and manage heterogeneous resources: optical capacity (wavelengths, bandwidth), optical latency, edge computing resources (CPU, GPU, NPU), distributed storage, and the AI models themselves [13]. This multidimensional and distributed management is orders of magnitude more complex than traditional connectivity management, making AI itself an indispensable tool to handle the inherent complexity of the 6G architecture [24].

3. Enabling Optical Technologies for 6G

To materialise the convergent and flexible x-Haul architecture and meet the stringent 6G KPIs, an arsenal of advanced optical technologies—some evolutionary and others disruptive—is required.

3.1. Evolution of PON: Beyond 50G

Passive Optical Networks (PON) are fundamental in current access networks due to their cost efficiency and point-to-multipoint topology. However, for 6G, they must evolve significantly in both capacity and performance.

3.1.1. 50G-PON

Standardized by the ITU-T under the G.9804.x series, 50G-PON represents the next evolutionary step, offering symmetric 50 Gbps or asymmetric configurations (50 Gbps downstream / 12.5 or 25 Gbps upstream) [25]. A key innovation is the mandatory introduction of Digital Signal Processing (DSP) to compensate for bandwidth limitations and chromatic dispersion at these data rates [26]. It allows coexistence with previous generations (GPON, XGS-PON) over the same fibre infrastructure [25]. Although it constitutes an important advance, it is regarded primarily as an intermediate step—potentially suitable for backhaul or midhaul in early 5.5G/6G scenarios, but insufficient for the most demanding 6G fronthaul requirements [16].

3.1.2. 100G/200G-PON and Beyond:

To achieve the hundreds of Gbps or even Tbps capacities required for aggregated 6G x-Haul transport, subsequent generations of PON are being actively investigated, targeting data rates of 100 Gbps, 200 Gbps per wavelength, and even higher [26]. At such rates, conventional Intensity Modulation / Direct Detection (IM/DD) technology faces severe challenges related to optical power budget limitations and chromatic dispersion penalties, particularly in the C- and L-bands [26].

3.1.3. Coherent Optical Access (CPON – Coherent PON)

Coherent PON (CPON) is emerging as a key enabling technology to overcome the limitations of IM/DD and achieve >100 Gbps speeds in PON networks [26]. Coherent detection offers several significant advantages:

- Higher Receiver Sensitivity: Enables greater optical path losses, translating into longer reach or a higher number of users per OLT port (split ratio).
- Advanced Modulation Formats: Allows the use of spectrally efficient modulation schemes (e.g., QAM), increasing the capacity per wavelength.
- DSP-Based Dispersion Compensation: The DSP inherent to coherent detection can linearly compensate for chromatic dispersion and other optical channel impairments.
- Channel Selectivity: Facilitates WDM-PON implementation by allowing fine receiver tuning.

The main challenges for CPON are the cost and complexity of coherent transceivers—historically much higher than direct-detection equivalents—and the efficient implementation of DSP, particularly for handling burst-mode upstream signals in TDMA topologies [26]. The standardisation of CPON is currently underway within organisations such as the ITU-T [27].

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3.1.4. WDM-PON

Wavelength Division Multiplexing in PON (WDM-PON) uses multiple wavelengths over the same fibre, assigning one or more dedicated wavelengths to each user (ONU) or group of users/services. This approach enables a significant increase in aggregate capacity and provides logical point-to-point connections over a physical point-to-multipoint infrastructure. In 6G, WDM-PON could be employed to segment traffic, offer differentiated services, or provide ultra-high-capacity connections closer to the network edge [28].

3.2. Exponential Capacity Increase: SDM and New Bands

To scale the capacity of backbone and aggregation networks beyond the limits of conventional Wavelength Division Multiplexing (WDM), new dimensions of multiplexing and spectrum utilisation are being explored.

3.2.1. Spatial Division Multiplexing (SDM)

This technique exploits the spatial dimension within the optical fibre to transmit multiple data channels in parallel, offering a multiplicative increase in the total fibre capacity [12]. It is considered fundamental for avoiding the “capacity crunch” of standard single-mode fibre. Two main approaches are under investigation:

- Multi-Core Fibre (MCF): Integrates multiple cores (light-guiding paths) within a single fibre cladding. Each core behaves as an independent fibre, multiplying total capacity by the number of cores [12]. The main technical challenge lies in inter-core crosstalk, where light leaks from one core into adjacent ones, causing interference. Minimising this crosstalk requires highly precise fibre designs and manufacturing techniques [12].
- Few-Mode Fibre (FMF): Employs a single (or enlarged) core that supports the propagation of multiple spatial modes of light, each carrying an independent data signal [12]. It requires modal multiplexing/demultiplexing techniques (optical MIMO) and Digital Signal Processing (DSP) to separate signals at the receiver. In addition to specialised fibres, SDM demands compatible optical components such as spatial multiplexers/demultiplexers and optical amplifiers capable of simultaneously amplifying signals across all cores or modes [12]. The associated complexity and cost remain significant barriers to large-scale deployment at present.
- New Optical Bands (Beyond C+L): Traditional optical transmission has focused on the C-band (Conventional, ~1530–1565 nm) and L-band (Long, ~1565–1625 nm) due to the availability of Erbium-Doped Fibre Amplifiers (EDFA). To further increase per-fibre capacity, active research is investigating the utilisation of other ITU-T-defined transmission bands: O (Original, ~1260–1360 nm), E (Extended, ~1360–1460 nm), S (Short, ~1460–1530 nm), and U (Ultra-long, ~1625–1675 nm) [29]. Recent experiments have demonstrated the feasibility of ultra-long-haul transmission (>800 km) with aggregate capacities exceeding 100 Tbps by jointly exploiting the C, L, and U bands through innovative techniques such as parametric optical band conversion for U-band amplification [30]. Opening up these new bands could expand the total usable fibre bandwidth beyond 20 THz [30], but this requires the development of new optical components (amplifiers, filters, etc.) and efficient conversion techniques to operate within these spectral regions.

3.3. Drastic Latency Reduction: Hollow-Core Fibre (HCF)

For the most latency-sensitive 6G applications, even the speed of light in silica fibre can become a limiting factor. Hollow-Core Fibre (HCF) is emerging as a disruptive technology.

3.3.1. Operating Principle

HCF guides light through a central hollow channel filled with air or vacuum instead of a solid silica core [31]. Because light travels approximately 50% faster in air than in glass, HCF reduces propagation latency by about 1.54 microseconds per kilometre of fibre, representing a latency improvement of over 30% compared with standard fibre [31].

3.3.2. Additional Benefits

HCF also exhibits significantly lower optical nonlinearity than standard fibre, simplifying or even eliminating the need for nonlinear compensation through complex DSP, particularly at high powers or in dense WDM systems [32]. Designs featuring low chromatic dispersion are also under active investigation.

3.3.3. Status and Advances

Remarkable progress has been achieved in reducing transmission losses in HCF, with reported values as low as 0.11 dB/km—surpassing even the theoretical limit of conventional single-mode fibre [32]. Commercial HCF cable solutions already exist, including terminations with standard connectors and fusion splicing techniques, and pilot deployments have been carried out in active networks [31].

3.3.4. Deployment Challenges

Despite these advances, HCF still faces significant practical challenges. Its fabrication process is more complex and costly than that of standard fibre, and production yield remains lower [32]. Fusion splicing of HCF requires more sophisticated and expensive equipment, and splice losses (~0.1 dB) are generally higher than with conventional fibre [32]. Integration with existing fibre infrastructure and long-term compatibility are also areas of active research [32]. Cost remains a major barrier to widespread adoption [33].

3.4. Flexible and Resilient Connectivity: Free-Space Optics (FSO)

Free-Space Optics (FSO) offers a wireless alternative for high-speed data transmission using light beams (laser or LED) propagating through air or space.

3.4.1. Concept and Application in 6G x-Haul

FSO can complement optical fibre infrastructure, particularly in scenarios where fibre deployment is impractical, costly, or time-consuming [34]. Typical 6G use cases include fronthaul/backhaul links for hard-to-reach cell sites, temporary connections for events, rapid network extensions, and potentially links in non-terrestrial networks (satellites, HAPS) [34]. It can also be integrated into hybrid FSO–fibre networks [34].

3.4.2. Advantages

FSO provides very high bandwidth (comparable to fibre), extremely low latency (as light travels almost at the speed of vacuum), rapid deployment, and operation in unlicensed spectrum [34].

3.4.3. Technical Challenges

The main limitation of FSO is its susceptibility to atmospheric conditions [34]. Fog, heavy rain, snow, and smoke can severely attenuate or scatter the optical signal. Atmospheric turbulence—caused by variations in temperature and pressure—induces fluctuations in signal intensity (scintillation) and beam wander, degrading link quality [34]. Maintaining precise alignment between transmitter and receiver (Pointing, Acquisition, and Tracking – PAT) is critical and can be affected by vibration, wind, or thermal expansion of supporting structures [34]. Interference from other light sources (solar or artificial) and link security (potential interception) are also important considerations [34].

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3.4.4. Solutions

Various techniques are being developed to mitigate these challenges: adaptive modulation and coding schemes that adjust transmission parameters according to channel conditions; hybrid RF/FSO systems employing a radio-frequency link (e.g., mmWave) as a backup when the FSO link degrades; adaptive optics to compensate for turbulence; advanced PAT technologies using MEMS mirrors, optical phased arrays (OPA), or liquid crystals; spatial filtering to reduce interference; and secure communication protocols [34].

3.5. Advanced Optical Components: Photonics and Switching

Miniaturisation, energy efficiency, and switching flexibility are essential for the 6G optical network, particularly at the network edge.

3.5.1. Silicon Photonics and PICs (Photonic Integrated Circuits)

This technology enables the integration of multiple optical components and functions (such as lasers, modulators, photodetectors, multiplexers/demultiplexers, and waveguides) into a single silicon chip, using mature and scalable CMOS fabrication processes [35]. The key benefits include:

- Miniaturisation: A drastic reduction in the size and weight of optical components.
- Lower Energy Consumption: Integration reduces losses and the power required for inter-component connections.
- Mass Production and Cost: Leverages the economies of scale of the semiconductor industry.
- Co-Packaged Optics (CPO): Facilitates close integration of optical and electronic components to reduce latency and power consumption at the electro–optical interface.

Silicon photonics and PICs are therefore crucial for developing compact, low-power, and cost-effective optical transceivers, essential for dense 6G edge deployments and for meeting the increasing bandwidth demand of AI-driven data centres [35].

3.5.2. Optical Switching and ROADMs

Reconfigurable Optical Add–Drop Multiplexers (ROADMs) are key nodes in WDM networks that allow the remote and programmable addition, extraction, or passthrough of specific wavelengths without requiring Optical–Electrical–Optical (O–E–O) conversion [18]. In 6G, ROADMs are expected to be deployed closer to the network edge to provide greater flexibility and agility in optical resource allocation [36]. Architectures based on ROADMs combined with packet switches can create reconfigurable x-Haul networks that support heterogeneous interfaces and traffic aggregation in both optical and packet domains [36].

A key challenge lies in balancing optical reconfiguration flexibility with switching times, which must remain compatible with 6G service latency requirements [37]. Ultra-fast and ultra-high-capacity optical switching architectures are under investigation for different network needs [38].

3.6. Second- and Third-Order Perspectives: Technological Synergies and Trade-Offs

The selection and integration of these advanced optical technologies are far from trivial and involve important interdependencies and trade-offs.

First, it is crucial to recognise that no single optical technology can, on its own, solve all the multifaceted challenges of 6G transport. HCF offers the lowest latency but faces cost and splicing-complexity barriers [31]. SDM promises massive capacity but introduces inter-core crosstalk and requires complex components [12]. CPON scales access capacity but increases DSP complexity and transceiver cost [26]. FSO provides deployment flexibility but is vulnerable to atmospheric conditions [34]. PICs are efficient and compact but may have limitations in extreme performance metrics [35].

Therefore, the optimal solution for 6G optical infrastructure will likely lie in the synergistic and intelligent combination of multiple technologies. A realistic x-Haul architecture should strategically integrate these technologies, leveraging each where its strengths are most advantageous and its weaknesses can be mitigated—either through complementary technologies or through the inherent intelligence and reconfigurability of the network architecture. For example, HCF could be used for ultra-low-latency critical connections, SDM for high-capacity backbones, CPON for flexible access aggregation, FSO for backup or rapid-deployment links, and PICs for efficient edge transceivers. This heterogeneous integration demands extremely sophisticated network planning, management, and orchestration, likely assisted by AI.

Second, there is an inherent and fundamental tension between the pursuit of extreme performance (Tbps throughput, µs latency, 7–9 "nines" reliability), the technological complexity associated with the solutions that enable it (coherent optics, SDM, HCF, advanced DSP, fast optical switching), and the economic imperative to keep deployment and operational costs (CapEx and OpEx) under control—particularly in the access and edge segments, which are the most geographically extensive. Technologies such as coherent optics [27], SDM [12], and HCF [32] are intrinsically more complex and expensive to manufacture, install, and maintain than more traditional optical technologies (IM/DD, standard single-mode fibre).

While they offer the necessary performance leaps for 6G, their mass and economically viable adoption will critically depend on factors such as global standardisation [39], large-volume production (where PICs play a key role [35]), continuous innovation in materials and processes, and intelligent network architectures that optimise their use (e.g., Open RAN [40], infrastructure sharing [40]). Network operators will need to make careful strategic decisions about where and when to deploy these advanced technologies, evaluating return on investment and considering whether more conventional solutions may suffice for certain segments or less demanding services.

Table 3 summarises the key optical technologies discussed and their potential role in the 6G x-Haul.

Table 3. Key Optical Technologies for 6G x-Haul.

Technology	Key Principle	Main Benefit for 6G x-Haul	Main Challenge	Sources
Evolved PON (>50G) / CPON	Higher speed per λ / Coherent Detection	High Access/Aggregation Capacity; Extended Reach/Split (CPON)	Cost/Complexity (CPON); Burst-Mode DSP (CPON)	[1]
SDM (MCF/FMF)	Spatial Multiplexing (Cores/Modes)	Per-Fibre Capacity Multiplication	Crosstalk (MCF); Complexity (Components, DSP); Cost	[4]
Hollow-Core Fibre (HCF)	Propagation in Air/Vacuum	Ultra-Low Latency (~30% reduction); Low Optical Nonlinearity	Manufacturing/Deployment Cost; Splice Losses; Robustness	[40]
Free-Space Optics (FSO)	Wireless Optical Transmission	Deployment Flexibility; High Bandwidth; Low Latency	Atmospheric Sensitivity; Alignment (PAT); Security	[1]

Silicon Photonics / PICs	On-Chip Optical Integration	Miniaturisation; Low Power Consumption; Cost (High Volume); Co-Packaging	Performance Limitations (vs. Other Materials); Coupling Losses	[35]
ROADMs / Optical Switching	Flexible Wavelength Switching	Network Agility; Reconfigurability; Efficiency (O–E–O Bypass)	Switching Speed vs. Latency; Edge Cost	[15]

4. Intelligent Management and Orchestration of the 6G Optical Network

The inherent complexity of 6G optical architectures and technologies renders traditional network management approaches insufficient. Artificial Intelligence (AI) and advanced automation, enabled by paradigms such as Software-Defined Networking (SDN) and Network Function Virtualisation (NFV), are indispensable.

4.1. The Role of SDN/NFV: Towards Automation and Programmability

Software-Defined Networking (SDN) and Network Function Virtualisation (NFV), which began to be adopted in 5G, become even more critical in 6G to manage the required levels of flexibility and complexity.

4.1.1. SDN (Software-Defined Networking)

By separating the control plane (network intelligence) from the data plane (traffic forwarding), SDN enables centralised and programmatic management of network infrastructure, including optical elements [41]. An SDN controller can dynamically configure optical paths, allocate wavelengths, adjust transceiver parameters, and manage network topology through open interfaces and Application Programming Interfaces (APIs) [42]. This is essential for the dynamic reconfigurability of the 6G x-Haul, allowing the network to adapt to changing service demands and channel conditions [42]. Open-source SDN controllers such as ETSI TeraFlowSDN are evolving to manage complex transport networks that include both optical and packet-based devices [42].

4.1.2. NFV (Network Functions Virtualization)

NFV decouples network functions—such as Centralised Unit (CU) and Distributed Unit (DU) functions in RAN, or Core Network functions—from proprietary hardware, enabling them to operate as software-based Virtual Network Functions (VNFs) or, more recently, Cloud-Native Network Functions (CNFs) on standard IT infrastructure (COTS servers, storage, and switches) [13]. This provides enormous flexibility to deploy, scale, and manage network functions anywhere along the Cloud–Edge continuum, optimising resource utilisation and accelerating the introduction of new services [19].

4.1.3. Integration SDN/NFV

The combination of SDN and NFV enables automated, end-to-end orchestration of network services [43]. A Management and Network Orchestration (MANO) system can dynamically request both the optical connectivity required (via the SDN controller) and the necessary virtualised network functions (via the NFV Infrastructure Manager – NFVI) to instantiate and manage a complete 6G service, such as a network slice with specific QoS requirements.

4.2. AI/ML Applications in Optical Network Management

Artificial Intelligence (AI) and Machine Learning (ML) are the key tools for enabling intelligence within SDN/NFV-based network management and orchestration.

4.2.1. Intelligent Orchestration and Management

Given the multidimensional complexity of 6G networks — encompassing heterogeneous technologies, services, and resources — AI/ML becomes fundamental for autonomous and optimised decision-making in optical network management [19].

4.2.2. Resource Optimisation

AI/ML algorithms, particularly Reinforcement Learning (RL), can learn optimal policies for the dynamic allocation of resources within the optical network — such as route selection, wavelength assignment, transmission power adjustment, and functional split configuration — in real time, adapting to changing traffic and channel conditions [23]. Multi-Agent Systems (MAS), where distributed AI agents collaborate, represent a promising approach for decentralised and rapid decision-making in complex optical networks [44].

4.2.3. Predictive Maintenance

AI/ML can analyse large volumes of telemetry data collected from the optical network (e.g., optical power, Optical Signal-to-Noise Ratio – OSNR, error rates) to detect subtle patterns, predict imminent component failures (transceivers, amplifiers, fibres), and schedule proactive maintenance activities before service disruptions occur, thereby improving reliability and reducing operational costs [22].

4.2.4. Autonomous Management (Zero-Touch Management – ZSM)

The ultimate goal is to achieve self-managing networks. AI/ML powers the closed-loop automation mechanisms that enable the network to monitor itself, analyse its state, make decisions, and execute corrective actions autonomously (self-configuration, self-optimisation, self-healing) [13]. Intent-Based Networking (IBN) uses AI to translate high-level business or service objectives (the “intent”) into the low-level configurations and actions required in the optical network [19]. Large Language Models (LLMs) are being explored to enable intent specification even in natural language [44].

4.2.5. Security

AI/ML can enhance optical network security through intelligent anomaly detection in traffic or device behaviour that may indicate attacks or intrusions, enabling faster and more accurate responses [45].

4.3. Second- and Third-Order Perspectives: AI as Master Orchestrator and Challenge

The integration of AI/ML into 6G optical network management has implications that extend far beyond simple automation.

First, AI/ML emerges not merely as an optimisation tool but as a fundamental and indispensable enabler for managing the unprecedented complexity introduced by x-Haul convergence, functional split flexibility, distributed edge computing, technological heterogeneity, and the massive scale of 6G optical networks. The combination of FFS, Edge Computing, x-Haul convergence, new technologies such as SDM, HCF, and CPON, along with highly diverse and dynamic service requirements, creates a rapidly evolving multidimensional state and decision space [23]. Traditional manual or algorithmic management methods simply cannot scale or react with the agility and precision required in this environment [43]. The intrinsic ability of AI/ML to learn complex patterns from massive datasets,

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predict future states, and make optimal decisions in real time — particularly through techniques such as RL and MAS [24] — becomes essential for dynamic resource orchestration, adaptive QoS assurance, and the autonomous operation (IBN, ZSM) required by 6G [46]. Without AI, efficient and autonomous management of these networks would be practically unfeasible.

Second, the implementation of AI/ML itself represents a double-edged sword. While it is critical for management, it also introduces new challenges and demands on the optical network itself. AI/ML models require vast amounts of high-quality, low-latency telemetry data extracted from the optical network for both training and inference [44]. Therefore, the optical network must be designed not only to be managed by AI but also to efficiently transport the data required by AI towards computing nodes (at the edge or in the cloud) where the models reside [47].

Moreover, the execution of these AI models — both for inference and distributed training, as in Federated Learning — consumes significant computing and storage resources at the edge, which must be provisioned, managed, and orchestrated jointly with optical communication resources [48]. Finally, to ensure interoperability and avoid ecosystem fragmentation, it is essential to develop and standardise AI-related interfaces and functions within the network architecture — such as the Network Data Analytics Function (NWDAF) defined by 3GPP and its extensions, or the AI interfaces defined in O-RAN for the RAN Intelligent Controllers (RICs).

This includes the standardisation of data collection, AI model lifecycle management (training, deployment, monitoring, retraining), and the exposure of AI capabilities as a service [46]. The need to support AI both as a workload and as a management component adds yet another layer of complexity to the design and operation of 6G optical networks.

5. Precision Synchronisation in 6G Optical Networks

Precise temporal synchronisation is a fundamental — though often underestimated — requirement for the correct and efficient operation of 6G networks.

5.1. Strict Synchronisation Requirements

6G networks demand unprecedented levels of time and phase synchronisation, achieving accuracies within the nanosecond range [8]. This precision is indispensable for enabling many of the advanced functionalities of the 6G Radio Access Network (RAN), such as:

5.1.1. Coordinated Multi-Point Transmission/Reception (CoMP)

In CoMP, multiple cells or access points collaborate to transmit or receive user signals, requiring highly accurate phase alignment.

5.1.2. Coordinated Massive MIMO and High-Precision Beamforming

To efficiently direct radio-frequency energy and minimise interference, fine synchronisation between multiple antennas and radio units is essential.

5.1.3. Advanced Carrier Aggregation (CA)

The combination of multiple frequency bands requires precise timing alignment.

5.1.4. URLLC/HRLLC Applications

Services such as real-time industrial control, advanced automation, or telesurgery depend on deterministic and ultra-low latency, which in turn requires an extremely accurate temporal base for resource scheduling and signal processing [49]. Round-trip latency requirements below 100 µs for motion control imply the need for extremely tight synchronisation [49].

5.1.5. Integrated Sensing and Communication (ISAC)

Sensing functions that utilise the communication infrastructure may require precise synchronisation to perform accurate distance, velocity, or angle measurements [13]. Synchronisation is regarded as a dedicated functional plane within architectures such as O-RAN (S-Plane), underscoring its critical importance [8].

5.2. Protocols and Techniques: PTP over Fibre

The de facto standard protocol for achieving the high-precision synchronisation required in packet-based networks — including optical transport — is the Precision Time Protocol (PTP).

5.2.1. PTP (IEEE 1588)

PTP is a protocol specifically designed for high-accuracy clock synchronisation in distributed systems over packet networks [45]. It is capable of achieving sub-microsecond and even nanosecond-level precision, particularly when implemented over optical fibre networks due to their low latency and high stability [50].

5.2.2. Hierarchical Architecture

PTP operates under a hierarchical master–slave architecture. A high-precision clock, the Grandmaster Clock (GMC), acts as the primary time reference for a PTP domain. Time is distributed from the GMC through a hierarchy of Boundary Clocks (BCs), which synchronise network segments, to Ordinary Clocks (OCs) or slave clocks in end devices (e.g., RUs, DUs) [50]. Transparent Clocks (TCs) can compensate for delay introduced as messages traverse network equipment [50].

5.2.3. Key Mechanisms

PTP achieves high precision through the following mechanisms

- Precise Timestamping: Accurate time-stamping of PTP messages (Sync, Delay_Req, etc.) at the exact moment of transmission and reception at network interfaces. Hardware-based timestamping is preferred to achieve maximum precision [8].
- Best Master Clock Algorithm (BMCA): A distributed algorithm that automatically selects the best available clock as the master within each network segment, establishing the synchronisation hierarchy and preventing loops [50].
- Delay Measurement: Mechanisms to measure and compensate for the propagation delay of PTP messages across the network, using either End-to-End or Peer-to-Peer methods [50].

5.2.4. ITU-T Profiles for Telecommunications

The ITU-T has defined specific PTP profiles (G.827x series) that set stringent requirements for the performance of telecommunication clocks (T-BC, T-TSC) and the maximum allowable time error accumulated across the transport network, thereby ensuring the synchronisation quality required for mobile applications [8].

5.2.5. Implementation over Optical Fibre

Optical fibre is the ideal medium for carrying PTP signals with high precision due to its inherently low latency, low jitter, and high stability [8]. To maintain nanosecond-level accuracy, it is crucial to minimise packet delay variation (PDV) within the optical network and properly configure PTP parameters, such as high message exchange rates [8].

5.3. Second- and Third-Order Perspectives: Synchronisation as a Critical Service

The requirement for nanosecond-level synchronisation in 6G reveals its fundamental role and the associated challenges within convergent networks.

First, nanosecond-precision synchronisation should not be regarded as an isolated objective but rather as a critical and often "hidden" enabler underlying many of the advanced capabilities that define 6G. Functionalities such as URLLC/HRLLC, advanced RAN coordination (CoMP, coordinated mMIMO), and Integrated Sensing and Communication (ISAC) intrinsically depend on a common and extremely precise temporal reference [49]. Any failure or degradation in synchronisation quality — even by a few nanoseconds — could directly impact the performance of these key functions, compromising the viability of the most demanding 6G services.

For instance, coordinated beamforming requires that signals from multiple RUs arrive at the user in perfect phase alignment, necessitating very fine temporal synchronisation among those RUs [8]. URLLC applications, with microsecond-level latency targets, require precise timing for radio resource allocation and signal processing within very short time windows [49]. Therefore, the 6G optical transport network must be explicitly designed to carry PTP synchronisation signals with minimal degradation (low PDV). In addition, optical network equipment (switches, routers, ROADMs) must be PTP-compliant — operating as high-precision Boundary Clocks (BCs) or Transparent Clocks (TCs) — to preserve and regenerate timing signal quality across the entire x-Haul chain [50].

Second, ensuring and maintaining nanosecond-level, end-to-end synchronisation across convergent and heterogeneous 6G networks — integrating optical fibre, FSO, satellite links, and non-3GPP networks such as Wi-Fi — represents a major technical and management challenge. PTP was originally designed with wired Ethernet networks in mind [50]. Extending its nanosecond precision across wireless links (such as FSO or satellite), which inherently exhibit greater latency variability and jitter, is complex and requires advanced compensation techniques [8].

The coexistence of different PTP profiles (e.g., the telecom G.827x profile, the TSN industrial profile) and the need to synchronise diverse technological domains (3GPP RAN, Core, Edge Computing, industrial OT networks) within a single physical infrastructure demand careful synchronisation architecture planning, meticulous clock configuration, and continuous performance monitoring of the synchronisation chain. The standardisation of robust PTP profiles for such convergent scenarios and ensuring interoperability between equipment from different vendors are therefore crucial for successful synchronisation in 6G [49].

6. Implementation and Standardisation Challenges

The transition towards a 6G-ready optical infrastructure, although technologically promising, faces significant practical challenges in terms of cost, complexity, energy consumption, and the need for global standardisation and interoperability.

6.1. Cost and Complexity Analysis

Upgrading optical infrastructure to meet 6G requirements entails significant investment and increased operational complexity.

6.1.1. Infrastructure Investment

Deployment requires substantial investments in

- New Fibres: Potential deployment of advanced fibres such as HCF or MCF/FMF in critical network segments, although their manufacturing and deployment costs remain high [40].
- Equipment Upgrades: Replacement or modernisation of optical transceivers (towards high-speed coherent types), ROADMs (more flexible and faster, deployed closer to the edge), and Ethernet switches (with TSN and high-precision PTP support) [50].
- Network Densification: Increasing the number of cell sites and optical access points to improve coverage and capacity, particularly when operating at higher frequencies [40].
- Technological and Operational Complexity: The integration of multiple novel technologies (CPON, SDM, HCF, FSO, PICs, AI/ML, SDN/NFV) into a cohesive network significantly

increases design, implementation, management, and maintenance complexity [40]. Highly skilled personnel are required to operate and optimise such advanced networks [40]. Managing heterogeneous and distributed networks, with virtualised functions and software-defined control, introduces new operational challenges.

- Cost Mitigation Strategies: To make the transition viable, various strategies are being explored:

1. Reusing 5G Infrastructure: Maximising the use of existing fibre and cell site infrastructure [40].
2. Adopting Open RAN: Encouraging vendor competition and the use of COTS (Commercial Off-The-Shelf) hardware to reduce equipment costs [40].
3. Infrastructure Sharing: Collaborative models where multiple operators share passive (fibre, towers) or even active network elements to reduce CapEx and OpEx [40].
4. Virtualisation and Automation: NFV and SDN, combined with AI-driven automation, can reduce long-term operational costs by optimising resource usage and simplifying management [40].

6.1.2. Energy Consumption and Sustainability

Sustainability has become a core consideration for 6G, encompassing energy efficiency, environmental impact, and social responsibility.

- Energy Challenge: Although 6G aspires to achieve significantly higher energy efficiency per bit transmitted (a key KPI), the expected exponential growth in data traffic, massive proliferation of connected devices, and the energy required for new functionalities (edge computing, AI model training and inference) could lead to a net increase in total network energy consumption [9]. This poses both economic (operational cost) and environmental (carbon footprint) challenges. Equipment lifecycle issues — including manufacturing and electronic waste (e-waste) — also raise sustainability concerns [9].
- Solutions for Energy-Efficient Optical Networks:
- Low-Power Components: Development and adoption of inherently more efficient optical components, such as silicon photonics-based PICs, integrating multiple functions on a single chip to reduce losses and power use [35].
- Energy-Efficient Optical Transceivers: Design of high-speed (Tbps) transceivers that minimise energy consumption per transmitted bit [19].
- Optimised Optical Architectures: Network architectures designed to minimise unnecessary O–E–O conversions, favouring direct optical switching (optical bypass) and eliminating intermediate layers (e.g., IP-over-optical flattening) to reduce overall energy consumption [19].
- Low-Power Modes: Implementation of sleep or low-power modes for network components (transceivers, amplifiers, switches) during low-traffic periods [51].
- Intelligent Energy Management: Use of AI/ML and SDN to monitor energy consumption in real time and dynamically optimise network configurations (e.g., selectively powering down elements, routing traffic through efficient paths) to minimise energy expenditure without compromising QoS [9].
- Renewable Energy Sources: Powering network nodes and data centres with renewable energy [9].

6.1.3. Interoperability and Standardisation

The global nature and technological complexity of 6G make standardisation and interoperability absolutely crucial to its success.

- Critical Need: To create a vibrant global market, foster competition, reduce costs through economies of scale, and ensure a seamless user experience (including international roaming), it is essential that equipment and solutions from different vendors interoperate smoothly. Global harmonised standardisation of interfaces, protocols, and architectures is the key to achieving such interoperability [34].

- Key Standardisation Bodies (SDOs): Several international organisations play fundamental and often complementary roles in defining 6G standards, including those relevant to optical transport:

1. ITU-R (International Telecommunication Union – Radiocommunication Sector): Leads the global vision for IMT-2030 (6G), defining use scenarios, performance requirements, and evaluation criteria for radio interface technologies [34].
2. ITU-T (Telecommunication Standardisation Sector): Focuses on the standardisation of fixed networks, including optical transport (OTN), access networks (PON – Study Group 15, SG15), Ethernet, synchronisation (G.827x), and network management and control (e.g., YANG models) [11].
3. IEEE (Institute of Electrical and Electronics Engineers): Develops fundamental standards for networking technologies such as Ethernet (IEEE 802.3), local wireless networks (Wi-Fi, IEEE 802.11), Time-Sensitive Networking (TSN, within IEEE 802.1), and PTP (IEEE 1588). It also defines high-speed optical interfaces (e.g., 800G, 1.6T) [44].
4. 3GPP (3rd Generation Partnership Project): The main body responsible for the standardisation of mobile cellular systems (RAN and Core Network). Defines architectures, interfaces (including eCPRI for fronthaul), protocols, and functionalities, including AI/ML integration (e.g., NWDAF). Releases 20 and 21 will mark the beginning of specific normative work for 6G [13].
5. O-RAN Alliance: Focuses on defining open and disaggregated RAN interfaces to promote multi-vendor interoperability and AI-driven intelligence through RAN Intelligent Controllers (RICs) [52].
6. ETSI (European Telecommunications Standards Institute): Plays a key role in transposing 3GPP standards into European norms and works in complementary areas such as MEC, NFV, ZSM (Zero-Touch Service Management), and SDN controllers such as TeraFlowSDN [42].
7. Other Forums and Alliances: Organisations such as OIF (Optical Internetworking Forum), CableLabs, and MOPA (Mobile Optical Pluggable Alliance) also contribute to the standardisation of specific optical interfaces and components [17].

- Inter-Organisational Coordination: Given the convergence of fixed and mobile, wired and wireless, and communication and computing technologies in 6G, effective collaboration and alignment among these various standardisation bodies are more crucial than ever to avoid fragmentation and to ensure a coherent and globally harmonised standards framework [53].

6.1.4. Second- and Third-Order Perspectives: The 6G Ecosystem

Implementation and standardisation challenges reflect the complexity of the ecosystem required to realise 6G and the growing emphasis on sustainability.

First, achieving 6G is not merely a technical challenge for individual network operators but a complex and multifaceted ecosystem challenge. It involves an intricate network of interdependent actors: network equipment manufacturers, optical component and semiconductor suppliers (developing PICs, HCF, DSP chips, etc.), cloud service providers (supporting the Cloud–Edge continuum), software and AI algorithm developers, the various standardisation bodies that must coordinate efforts, and government regulators managing spectrum and policy frameworks [53].

No single entity possesses all the pieces of the 6G puzzle. Operators depend on manufacturers [56], who in turn rely on the component supply chain [35]. AI and cloud integration demand close collaboration with technology giants [23]. Global standardisation requires difficult consensus among multiple SDOs with sometimes divergent interests [40]. Spectrum policies are critical enablers [45]. Therefore, the success and pace of 6G implementation will fundamentally depend on the ability of this complex ecosystem to collaborate effectively, align visions, overcome shared technical and economic barriers, and establish truly open and interoperable standards [34]. Lack of coordination or fragmentation in any of these areas could significantly delay the fulfilment of the 6G promise.

Second, sustainability — environmental, economic, and social — is emerging as an integral and fundamental design requirement for 6G, not as a secondary consideration or an afterthought. The increasing energy consumption of communication networks is a global concern, both for its environmental impact (carbon footprint) and for its operational costs [9]. The need for massive infrastructure deployments and constant technological upgrades raises issues of investment cost and electronic waste (e-waste) management [9].

Moreover, ensuring that the benefits of 6G are accessible and affordable to all — bridging the digital divide — is a key social consideration [3]. Consequently, decisions regarding which optical technologies to implement (e.g., prioritising the energy efficiency of PICs [35] or evaluating the full lifecycle of HCF [33]), how to design network architectures (e.g., promoting infrastructure sharing [40] or adopting circular economy principles), and how to operate the network (e.g., optimising energy consumption through AI [9]) will increasingly be influenced by sustainability criteria that complement traditional technical performance KPIs [11].

The long-term viability of 6G will therefore depend on its ability to be not only powerful but also sustainable.

7. Conclusions and Recommendations

7.1. Clave Summary of Key Findings

The advent of 6G promises to revolutionise connectivity, enabling a future of ubiquitous intelligence and the seamless fusion of the physical and digital worlds. However, this vision imposes unprecedented demands on the optical transport infrastructure, requiring terabit-per-second data rates, microsecond-level latency, extreme reliability, and nanosecond precision synchronisation—capabilities that far exceed those of current 5G networks.

To meet these demands, the optical network architecture must evolve towards a convergent, flexible, open, and natively intelligent x-Haul model, deeply integrating communication with distributed computing at the edge (Edge Computing). This requires the adoption and synergistic combination of advanced optical technologies, including ultra-high-speed PON (potentially based on Coherent Optics – CPON), Spatial Division Multiplexing (SDM) using multi-core or few-mode fibres, Hollow-Core Fibre (HCF) for ultra-low-latency links, Free-Space Optics (FSO) for deployment flexibility, and Photonic Integrated Circuits (PICs) for compact, energy-efficient components at the network edge. Reconfigurable Optical Add–Drop Multiplexers (ROADMs) extended to the edge will play a key role in network agility.

The management of this complex, heterogeneous, and distributed infrastructure is unfeasible without advanced automation powered by Software-Defined Networking (SDN), Network Function Virtualisation (NFV), and, fundamentally, Artificial Intelligence (AI) and Machine Learning (ML). AI/ML will be essential for dynamic resource optimisation, predictive maintenance, autonomous management (Zero-Touch, IBN), and enhanced security. Likewise, nanosecond-level synchronisation, enabled by protocols such as PTP over optical fibre, is a critical underlying requirement for many advanced 6G functions.

Nevertheless, the implementation of this vision faces significant challenges related to high investment costs, technological and operational complexity, increasing energy consumption, and the imperative for coordinated global standardisation to ensure interoperability within a complex and multifaceted ecosystem. Sustainability emerges as a transversal design requirement.

7.2. Strategic Recommendations

To navigate the transition towards 6G optical infrastructure successfully and sustainably, the following strategic recommendations are proposed for the telecommunications ecosystem — including operators, manufacturers, researchers, standardisation bodies, and regulators:

7.2.1. Prioritise Strategic R&D Investment

Focus research and development efforts on maturing and reducing the cost of key optical technologies identified — CPON, SDM, HCF, high-performance PICs, components for new optical bands, and robust FSO systems. Promote innovation in low-power Digital Signal Processing (DSP) and efficient AI/ML algorithms for optical network management.

7.2.2. Adopt Flexible, Open, and Programmable Architectures

Actively embrace the principles of O-RAN, SDN, and NFV in the design of 6G x-Haul networks. Develop and implement architectures that inherently support Flexible Functional Splits (FFS) and x-Haul convergence to maximise adaptability and resource efficiency.

7.2.3. Design for Native Intelligence (AI-Native)

Integrate AI/ML capabilities into the optical network architecture from the earliest design stages. Develop and standardise platforms, interfaces (APIs), and data models for telemetry collection, distributed AI model training/inference, and intelligent orchestration of optical and computing resources.

7.2.4. Embed Sustainability as a Core Criterion

Evaluate technologies and architectures not only by their performance but also by their energy efficiency, environmental impact (lifecycle, e-waste), and total cost of ownership (TCO). Actively promote infrastructure sharing, renewable energy usage, and circular economy principles in 6G deployments.

7.2.5. Strengthen Global Collaboration and Standardisation

Foster closer collaboration and strategic alignment among standardisation bodies (ITU-T, ITU-R, IEEE, 3GPP, ETSI, O-RAN, OIF, etc.) to develop a coherent and globally harmonised set of 6G standards for optical transport. Active participation from all ecosystem stakeholders is crucial to ensuring interoperability and achieving economies of scale.

7.2.6. Develop Gradual Migration and Coexistence Plans

Define clear roadmaps for the evolution from existing 5G networks to 6G, enabling the coexistence of multiple generations of technologies and a progressive migration that protects existing investments and minimises service disruption.

Addressing these challenges and following these recommendations will be essential to unlocking the full transformative potential of 6G — ensuring that optical fibre infrastructure becomes not a bottleneck but a key enabler for the next era of intelligent and ubiquitous connectivity.

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