Bharat6G Alliance

Bharat 6G Alliance Whitepaper

ROLE OF OPTICAL TECHNOLOGIES FOR 6G

October 2026

Bharat 6G Alliance Whitepaper

Role of Optical Technologies for 6G

\

October 2026

Contents

Executive Summary **7**
1. Introduction and Scope **9**
1.1 Introduction 9
1.2 Scope 10
1.3 Out of scope 10
1.4 Intended audience and structure 10
2. Why Optical is Foundational to 6G: Capacity, Resilience, Scalability and Sustainable Connectivity **11**
2.1 Traffic scale 11
2.2 A converged RF–optical architecture 11
2.3 Reliability and resilience 12
2.4 Communication, sensing, positioning and timing 12
2.5 Energy efficiency and sustainability 12
2.6 Deployment readiness 13
3. Optical Transport for the 6G RAN **15**
3.1 What the RAN asks of transport 15
3.2 Fronthaul 17
3.3 Midhaul and backhaul 18
3.4 Synchronisation and timing 19
3.4.1 What the network has to deliver 19
3.4.2 The GNSS dependency 20
3.4.3 What India has in place 20
3.4.4 Legal time and phase accuracy 20
3.4.5 What 6G adds 20
3.5 Deployment reality in India 21
4. Fibre Access and Fixed-Mobile Convergence — PON Evolution and Slicing **22**
4.1 Evolution from TDM-PON to multi-wavelength PON 22
4.2 Dynamic bandwidth allocation as the basis for service differentiation 23
4.3 Fibre access as a common infrastructure for fixed and mobile networks 23
4.4 PON slicing 24
4.5 Key requirements and research directions 25
5. Optical Wireless — LiFi/VLC, FSO Backhaul, Inter-Satellite Links for NTN, Optical sensing and Hybrid FSO/RF Communications **26**
5.1 LiFi / VLC 27
5.2 Hybrid LiFi–Wi-Fi networks 27
5.3 Terrestrial FSO 29
5.4 Inter-satellite links for NTN 30
5.5 Optical sensing and communication 31
5.6 Hybrid FSO/RF Communication for Resilient 6G Connectivity 32
5.6.1 Motivation and Complementarity of FSO and RF 32
5.6.2 Hybrid FSO/RF Architecture and Link-Selection Principle 33
5.6.3 Analytical Model for an Interference-Limited Hybrid FSO/RF Link 34
5.6.4 Outage and Reliability Characterisation 34
5.6.5 Practical Link-Selection and Monitoring Framework 35
5.6.6 Indian Field Deployment: 5.57-km FSOC/RF Link in Kohima, Nagaland 35
5.6.7 Field Results and Evidence of Resilience 36
5.6.8 Relevance to 6G Deployment in India 37

5.6.9 Potential 6G Deployment Scenarios 37
6. Optical Interconnect for AI-Native Networks **39**
6.1 Data Centre Interconnect: the Foundation of the Digital and AI Economy 39
The Evolution of Data Centre Interconnect 39
Requirements for Modern DCI Networks 39
Optical Technologies Driving DCI 40
Intelligence and Automation in DCI 40
6.2 Multi-Band Optical Line Systems: Scaling Fibre Capacity from C-Band to Super-C+Super-L 41
6.3 Co-packaged optics and optical I/O for AI clusters 45
7. Quantum-Ready Optical Infrastructure: QKD Coexistence over Deployed Fibre and Quantum-Safe Optical Links for Defence, Healthcare and Finance **46**
7.1 QKD over Deployed Optical Fibre 47
7.1.1 Shared-Fibre Quantum–Classical Infrastructure 47
7.2 SDN-Controlled Adaptive Optical Architecture for QKD 47
7.2.1 Dynamic Optical Path Provisioning 48
7.3 Security Monitoring and Adaptive Recovery 49
7.4 QKD, QKMS and Quantum-Safe Cryptography 49
7.5 Applications for 6G and Critical Infrastructure 49
7.6 Recommended monitoring metrics 50
7.7 Standardisation and Interoperability 50
7.8 India's Opportunity for Quantum-Ready 6G Optical Networks 51
7.9 Relevance to 6G 51
8. Standardisation Landscape and Gaps **52**
8.1 Who covers what 52
8.2 Gaps 54
9. India Context: Testbeds, Measured Outcomes, Standards, Intellectual Property and Academia–Industry Translation **56**
9.1 Testbed facilities 56
9.2 Measured outcomes and translation 56
10. Recommendations and Way Forward for India **59**
10.1 R&D priorities 59
10.2 Testbeds and field data 59
10.3 Standardisation 60
10.4 Indigenous manufacturing 60
10.5 Deployment models 60
10.6 Ecosystem development 60
10.7 Priority actions for the next twelve months 61
Conclusion **62**
Annex A. Analytical Model for an Interference-Limited Hybrid FSO/RF Link **63**
A.1 FSO received signal and instantaneous SNR 63
A.2 RF link with co-channel interference 63
A.3 Threshold-based link selection 64
A.4 Outage probability and average symbol error rate 64
Contributors ..... Error! Bookmark not defined.
References **65**

Executive Summary

This white paper argues that the optical layer is a precondition for 6G. Every IMT-2030 usage scenario — immersive, hyper-reliable, massive, ubiquitous, AI-integrated and sensing-integrated communication — places a requirement on fibre, optical wireless or optical timing before it places one on the radio. The paper sets out what those requirements are, which optical technologies meet them today and which are still emerging, where India stands, and what India should build, standardise and protect.

Six findings carry the argument.

- The functional split decides the transport bill. At the O-RAN 7-2x split the fronthaul rate scales with carrier bandwidth and antenna ports or layers: a 5G 64T64R sector needs tens of Gbit/s; a 400 MHz, eight-layer 6G configuration reaches about 117 Gbit/s, and very large arrays extrapolate to terabit class. The 100 µs latency budget keeps fibre reach well under 20 km, and 3GPP has not yet fixed the 6G split, so transport dimensioning stays provisional until Release 21 (Sections 3.1–3.3).

- Timing is now a legal as well as a technical requirement in India. TDD, carrier aggregation and multi-site sensing need phase accuracy from ±1.5 µs down to 65 ns, delivered over fibre with PTP full timing support. From February 2027 the Legal Metrology (IST) Rules add an obligation to take time from IST-traceable sources, with NavIC named — an opportunity to remove GPS as a single point of failure years before 6G (Section 3.4).

- Fibre access is becoming a programmable, sliced fabric. 50G-PON with slice-aware bandwidth and wavelength allocation can carry residential, enterprise and mobile transport traffic on one infrastructure, and Indian work on TWDM-PON and radio-over-fibre scheduling feeds directly into it (Section 4).

- Optical wireless complements RF. LiFi is standardised to 9.6 Gbit/s and hybrid LiFi–Wi-Fi studies report throughput and sum-rate gains above 50 per cent; terrestrial FSO delivers 10–20 Gbit/s over kilometres, and an ERNET India hybrid FSO/RF link in Kohima held availability above 98 per cent through the 2021 monsoon; optical inter-satellite links have reached hundreds of Gbit/s in commercial constellations (Section 5).

- Capacity will grow on fibre already in the ground. C+L and Super-C+Super-L line systems raise usable spectrum to about 12 THz per fibre pair, and the same fibre can carry quantum-key-distribution channels under SDN control. In both cases the differentiator is control software — power-control orchestration and secure path management — where India can build capability rather than import it (Sections 6 and 7).

India's base is real but uneven. Tower fibreisation was around 30 per cent in 2019 against a 70 per cent target; BharatNet is 96.7 per cent service-ready, but a 17-day mean time to restore is incompatible with fronthaul or nanosecond timing. National testbeds at IIT Delhi, IIT Madras, IIIT-Delhi, IIT Guwahati and ERNET India are producing measured results and standards contributions through TSDSI, IEEE and ITU-T (Sections 3.5 and 9).

Seven standardisation gaps recur: the undecided 6G split, metro-reach coherent optics, LEO–LEO inter-satellite links, optical ISAC, hybrid FSO/RF telemetry, multi-band line-system interoperability and QKD/optical control interfaces (Section 8). The recommendations in Section 10 therefore give priority to a restoration-time target and route diversity for fibre serving mobile sites; IST-compliant, NavIC-capable timing before 2027; Indian availability data for FSO; indigenous line-system control and QKD network capability; and a testbed-to-standards pipeline that carries Indian results into ITU-T SG15, IEEE and 3GPP.

1. Introduction and Scope

1.1 Introduction

Work on 6G has so far been dominated by the radio interface: new spectrum, larger antenna arrays, AI-native air interfaces and integrated sensing. The infrastructure that must carry, time and power those radios has received less attention. ITU-R Recommendation M.2160 defines the IMT-2030 framework around six usage scenarios — immersive communication, hyper-reliable and low-latency communication, massive communication, ubiquitous connectivity, AI and communication, and integrated sensing and communication — together with design principles that include sustainability, security and resilience, and ubiquitous connectivity [1]. Every one of these places a requirement on the optical layer before it places one on the radio.

The arithmetic is direct. The performance metrics for IMT-2030 [2] detailed in Section 2.1 elevate bandwidth demands across fronthaul, midhaul, and backhaul links while imposing strict limits on the maximum physical distance between a radio unit and its baseband processing pool. The ION-2030 report published by ITU-T addresses this scaling by establishing target optical transmission rates across fronthaul, aggregation, and core transport segments [3]. Transport is already evolving in step with this scaling. Fronthaul latency budgets are counted in microseconds [4], and phase-synchronised TDD operation, positioning and coherent multi-site sensing depend on timing delivered over fibre to accuracies of ±1.5 μs and tighter [5], [6]. Energy-efficiency objectives, identified as a foundational aspiration in M.2160 [1], push traffic onto the most power-efficient transport available. Optical technology is therefore a precondition for 6G.

This white paper takes optical in its full sense: optical fibre and passive optical access, coherent transport and data-centre interconnect, optical wireless in its several forms (LiFi, FSO, inter-satellite links), optical sensing, and quantum-ready optical infrastructure. These span very different levels of maturity. Fibre access is a mass-market technology and light communications are already standardised [7]; solar-panel optical receivers and reconfigurable optical surfaces remain at laboratory and early-prototype stage. The paper states that distinction explicitly rather than presenting all optical technologies as equally ready, so that recommendations can be acted on with a realistic view of timelines.

India's position adds a second motivation. India has built one of the world's largest fibre footprints and is extending it through BharatNet and National Broadband Mission 2.0 [8], and a national experimental base now sits alongside it. The Department of Telecommunications' Advanced Optical Communication (AOC) Testbed programme, structured as 19 work packages for indigenous, standards-compliant development [9], includes a dedicated optical wireless activity being established at IIT Delhi: a testbed for fully hybrid optical communications, LiFi and FSO, supporting experimental validation of advanced optical systems and modulation techniques in high-precision wireless optical communication, with in-house LiFi transceivers already operating at 100 Mbit/s [10]. Work from this programme is reaching the standards bodies — ITU-T and TSDSI [11]. Indian laboratories at IIIT-Delhi have also produced measurable results in solar-panel optical communication, reflected in TSDSI SI-120, whose Technical Report was accepted and published in November 2025 [12]. India also now has a legal framework for national time traceability, the Legal Metrology (Indian Standard Time) Rules, 2026, which commences in February 2027 and reaches telecom operators from that date [13] — years before 6G — giving Indian networks a nationally sovereign time reference ahead of most. What determines whether this base supports 6G is the reach and availability of

fibre to mobile sites, which Section 3.5 examines against published data. The paper treats these as a single question: what must India build, standardise and protect for the optical foundation of 6G to be in place in time.

1.2 Scope

This document sets out to:

- establish why optical infrastructure is foundational to meeting the IMT-2030 objectives [1], [2], with evidence drawn from deployed networks, published standards and operational systems;
- describe the optical technologies relevant to each domain of the 6G network — transport and synchronisation for the RAN, fixed-mobile convergent access, optical wireless and NTN links, optical interconnect and line-system capacity for AI-native networks, and quantum-ready optical links;
- distinguish mature technology from emerging research at each step, and state the realistic 6G role of each;
- map the Indian capability base: testbeds, measured results, standards contributions, intellectual property and academia–industry translation;
- identify where the relevant standardisation is taking place (ITU-T SG15, ITU-R, IEEE, BBF, O-RAN, 3GPP, TSDSI) and where gaps remain; and
- set out recommendations for India across R&D priorities, testbeds, standardisation, indigenous manufacturing, deployment models and ecosystem development.

1.3 Out of scope

The paper does not specify interfaces, protocols or parameter values; that work belongs in the standards bodies identified in Section 9. It does not evaluate or compare commercial products, and it does not attempt a market forecast. Radio-domain photonics and standalone optical network automation fall outside the scope of this current document. Radio-interface design is treated only where it determines an optical requirement — for example, where the RAN functional split [14] sets the fronthaul bit rate and latency budget. Where a quantitative figure is cited, its source and the assumptions behind it are stated; estimates that depend on unstated assumptions are identified as indicative.

1.4 Intended audience and structure

The paper is addressed to policymakers and programme agencies shaping India's 6G and broadband investments, to operators and equipment vendors planning transport and access evolution, to standardisation delegates, and to the research community.

Sections 2–3 establish the case for optical infrastructure and the transport and synchronisation requirements of the 6G RAN. Sections 4–7 cover the technology domains: fibre access and convergence, optical wireless, optical interconnect for AI-native networks, and quantum-ready optical infrastructure. Section 8 sets out the standardisation landscape and gaps, Section 9 the India context and capability base, and Section 10 the recommendations and way forward. Annex A gives the analytical model behind the hybrid FSO/RF discussion in Section 5.6.

2. Why Optical is Foundational to 6G: Capacity, Resilience, Scalability and Sustainable Connectivity

Section 1 stated the proposition. This section sets out the evidence for it across five dimensions — traffic scale, architecture, resilience, multifunctionality and sustainability — and closes with an assessment of deployment readiness that the rest of the paper builds on.

Meeting the IMT-2030 objectives [1] requires infrastructure that scales across access, transport, edge and cloud computing, sensing, positioning, timing and energy systems. Optical technologies — optical fibre, optical wireless communication (OWC) including LiFi and FSO, optical sensing and optical interconnects — therefore form a complementary infrastructure fabric alongside radio.

2.1 Traffic scale

M.2160 sets out the capabilities of IMT-2030 with indicative target ranges: peak data rates of 50–200 Gbit/s, user-experienced data rates of 300–500 Mbit/s, area traffic capacity of 30–50 Mbit/s/m², connection density of 10^6–10^8 devices/km², over-the-air latency of 0.1–1 ms and reliability up to $1-10^{-7}$, with the applicable values depending on scenario [1]. Transport must scale with the radio access network, and higher radio capacity translates directly into higher aggregation requirements between radio sites, edge computing, core networks and cloud infrastructure.

Today's Internet already shows where that traffic sits. ITU estimates global fixed broadband traffic at approximately 7.3 ZB in 2025 against approximately 1.5 ZB of mobile broadband traffic — fixed networks carry the large majority of Internet traffic even as mobile traffic grows [15]. Fibre carries a growing share of it: OECD data show fibre at approximately 47% of fixed broadband subscriptions across OECD economies at the end of 2024, up from 28% in 2019, with total fibre subscriptions growing nearly 15% annually over that period [16].

The optical layer is responding at the same pace. ITU-T's ION-2030 report identifies target optical line rates of approximately 100 Gbit/s for IMT-2030 fronthaul, 100/400/800–1600 Gbit/s for access, aggregation and core backhaul, and multi-wavelength line capacities reaching tens of terabits per second by 2030 [3]. Section 3 develops what the RAN specifically asks of that transport layer.

2.2 A converged RF–optical architecture

The realistic 6G architecture is not RF versus optical. The two operate at different network layers and complement each other, and optical wireless extends that complementarity into the access layer itself. IEEE 802.11bb-2023 standardises light communications for WLAN operation in the 800–1000 nm range, specifying bidirectional PHY operation from 10 Mbit/s to 9.6 Gbit/s [7] — an indicator of deployment readiness rather than research promise, since a standardised PHY and MAC framework now exists.

LiFi's role is to complement cellular RF coverage where spatial confinement, spectral congestion or RF sensitivity make optical access preferable: high-density indoor spaces, offices and campuses, industrial environments, aircraft and transportation, RF-sensitive locations, and applications requiring high spatial reuse. Section 5 treats hybrid optical–RF access in detail. Figure 2.1 summarises the converged RF–optical infrastructure that this paper covers and the section that treats each element.

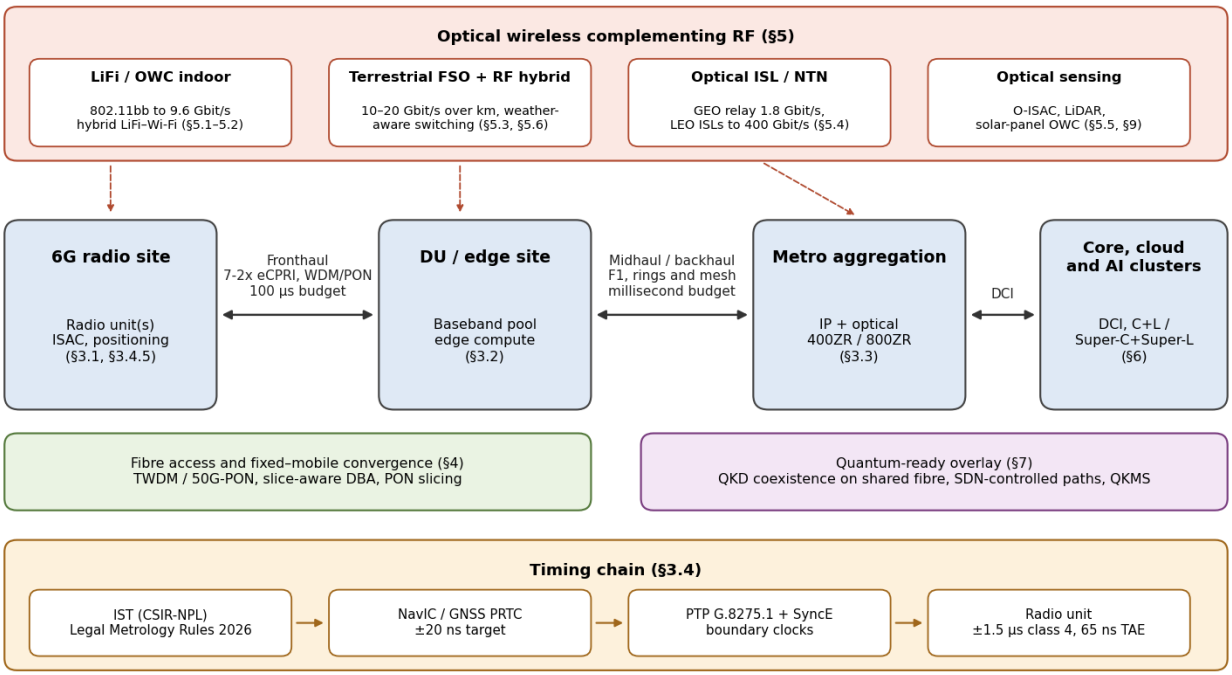

Figure 2.1. The converged RF–optical 6G infrastructure covered in this paper, with the section that treats each element.

2.3 Reliability and resilience

Future networks will carry industrial automation, autonomous systems, transportation, healthcare and public infrastructure, and M.2160 identifies security and resilience alongside ubiquitous connectivity, including connectivity for remote and underserved areas [1]. Optical technologies contribute physically diverse communication paths, and FSO extends the reach of that diversity well beyond terrestrial links. ESA's European Data Relay System has demonstrated operational optical inter-satellite communication at approximately 1.8 Gbit/s over distances exceeding 40,000 km as part of a commercial data-relay infrastructure [17], [18] — evidence that optical wireless is already operational at scale, not confined to the laboratory.

2.4 Communication, sensing, positioning and timing

The IMT-2030 framework places ISAC, high-precision positioning and AI integration among its usage scenarios and capabilities [1]. Optical technology supports this convergence natively: fibre combines transport with distributed sensing and timing distribution; LiFi combines communication with indoor positioning through optical directionality; FSO adds directional sensing; and optical sensors and LiDAR provide sensing and localisation. The consequence is that optical infrastructure can be developed as a multifunctional platform rather than a transport medium alone — a theme taken up for timing in Section 3.4 and for sensing in Section 5.

2.5 Energy efficiency and sustainability

M.2160 calls for future IMT systems to minimise power consumption, improve energy efficiency, reduce environmental impact and use resources efficiently [1]. Optical technology contributes through high-capacity fibre transport, passive optical access, efficient optical interconnects, localised optical wireless connectivity, and optical sensing integrated into existing infrastructure. An emerging extension is solar-enabled optical communication, in which deployed photovoltaic infrastructure performs energy harvesting and optical signal reception simultaneously. This remains at research and prototype stage; experimental results are reported in Section 9.

2.6 Deployment readiness

A credible 6G roadmap must distinguish mature technology from emerging research. Table 2.1 states that distinction, and the maturity assessment carries through the technology sections that follow.

Table 2.1. Maturity of optical technologies and their realistic role in 6G.

Optical technology	**Evidence of maturity**	**Realistic 6G role**
Optical fibre	Major broadband technology; 47% of OECD fixed broadband subscriptions in 2024 [16]	Transport, fronthaul, backhaul, edge/cloud
PON / optical access	Widely deployed broadband architecture	High-capacity access and aggregation
Optical data-centre interconnect	Established optical networking ecosystem	AI, cloud and edge interconnect
LiFi / light communications	IEEE 802.11bb standardised, 10 Mbit/s–9.6 Gbit/s PHY [7]	Indoor high-density, RF-complementary access
FSO	Operational terrestrial and space deployments; 1.8 Gbit/s ESA EDRS links [17], [18]	Point-to-point, backhaul, aerial and space links

Optical sensing	Mature fibre sensing ecosystem	ISAC, infrastructure monitoring, positioning
Solar-panel OWC	Experimental / research stage	Rural, remote and energy-constrained infrastructure
OIRS / reconfigurable optical surfaces	Emerging research	Coverage extension, programmable optical environments
Integrated optical communication and energy harvesting	Emerging	Sustainable 6G and IoT infrastructure

A substantial part of the optical foundation of 6G therefore already exists. Fibre carries an increasing share of fixed broadband; fixed networks carry several times more Internet traffic than mobile; light communications are standardised to 9.6 Gbit/s; and operational space systems run multi-gigabit optical links over tens of thousands of kilometres [15]–[18]. The strategic opportunity is to build a converged RF–optical infrastructure in which each technology is used according to its physical and economic advantages: fibre as the scalable transport fabric, LiFi and OWC as complementary access, FSO where fibre or RF is constrained, optical sensing and timing supporting ISAC and positioning, and solar-enabled optical communication as a pathway for energy-constrained environments.

3. Optical Transport for the 6G RAN

Fronthaul, Midhaul, Backhaul and Precise Synchronisation

3.1 What the RAN asks of transport

Where the network is split decides what the transport has to carry. 3GPP TR 38.801 set out eight candidate split points between the radio unit and the baseband [14]. They range from Option 1 (RRC–PDCP), which distributes everything below RRC, to Option 8 (PHY–RF, the CPRI arrangement), which distributes only RF. Option 2 underlies the 3GPP F1 interface and Option 7-2x the O-RAN Open Fronthaul; Table 3.1 summarises the splits that matter for transport.

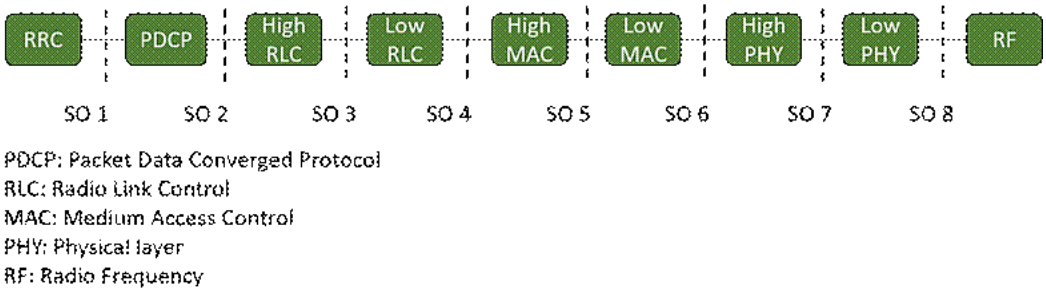

Figure 3.1. Split options in the RAN architecture [14].

For 5G NR, 3GPP has standardised the NG-RAN architecture with the CU/DU split and the F1 interface between gNB-CU and gNB-DU, corresponding to the higher-layer Option 2 split and used for midhaul. 3GPP also studied the wider set of split options in TR 38.801, but it did not standardise an open DU/RU fronthaul interface for Option 7-2x. For 6G, 3GPP standardisation is still in the study and specification-definition phase. Options under consideration include continuing the 5G evolution with a flexible CU/DU/RU placement, refining functional splits to balance coordination gain against fronthaul capacity and latency, supporting cloud-native and more programmable RAN deployments, exposing network capabilities such as sensing, positioning, timing and compute through service interfaces, and introducing AI-native automation for operation and optimisation. Release 20 is developing 6G material, which discusses an evolutionary migration from 5G, programmable networks, AI-native operation and the combination of communication, sensing and compute capabilities, while Release 21 is expected to contain the first normative 6G specifications. In parallel, the O-RAN Alliance standardises open RAN interfaces for 5G deployments, including the Open Fronthaul based on the 7-2x lower-layer split between O-DU and O-RU; O-RAN is also extending its work toward 6G, but specific 6G open-fronthaul choices remain under study rather than finalised. O-RAN currently defines two radio unit categories for 7-2x. A Category A O-RU leaves precoding in the O-DU. A Category B O-RU performs precoding itself [19].

The split therefore has architectural implications not only for radio implementation but also for the transport network. Lower-layer splits enable tighter coordination, pooling and centralised processing, but they also place scheduling and, for some splits, HARQ-related timing across the transport path. Higher-layer splits

reduce capacity and latency pressure and can better reuse an existing packet network, at the cost of moving more processing to the site.

For optical planning, the bit rate follows from what crosses the interface. Option 8 carries time-domain IQ samples for every antenna. A 100 MHz NR carrier at 30 kHz subcarrier spacing is sampled at 122.88 Msps; with 15-bit I and Q samples this gives approximately 3.7 Gbit/s per antenna before line coding and control overhead, and approximately 236 Gbit/s for 64 antennas. Massive MIMO made Option 8 impractical for that reason.

Option 7-2x carries frequency-domain samples, which removes oversampling and guard bands. With a Category A radio unit the stream is per antenna port, after precoding. With Category B it is per spatial layer, before precoding, which keeps the fronthaul rate manageable for arrays with many elements. Block floating point compression reduces the IQ word length further. The resulting rate is set by carrier bandwidth, port or layer count, IQ word length and compression ratio together, and no single figure characterises it; published estimates for a given configuration vary widely with the assumptions made about each, and indicate magnitude only.

6G raises every input to that calculation. Wider carriers and larger arrays increase the 7-2x rate in proportion to bandwidth and to port or layer count. Whether 6G keeps 7-2x or moves the split is still open, and transport cost will weigh on the decision. More recent 6G-oriented estimates illustrate how quickly the requirement can grow. For a 400 MHz radio signal with eight MIMO layers, an Option 7-2 downlink has been estimated at about 117 Gbit/s. If a very large array with 1,024 antenna ports supports 32 or 128 spatial layers, the corresponding rate rises to roughly 0.47 or 1.88 Tbit/s. Option 8 for the same broad class of array can reach the order of 15 Tbit/s because it scales with antenna ports rather than spatial layers. The 117 Gbit/s figure corresponds to the 3GPP TR 38.816 example calculation for Option 7-2 at 400 MHz with eight layers and 32 antenna ports [20]; the larger-array figures are linear extrapolations of that case. These are possible scenarios, not established requirements, but they show how the split selection is critical for the fronthaul capacity.

In addition to fibre propagation impairments that occur at high bit rates, the latency budget sets distance. IEEE 802.1CM Class 1 allows 100 µs of end-to-end, one-way latency between the radio unit and the distributed unit [4]. Light in fibre takes approximately 5 µs per kilometre, so the budget alone would cover 20 km; bridges, queuing and packet delay variation consume part of it, and usable fibre distance is correspondingly shorter. 3GPP does not specify a transport latency limit for F1, and midhaul planning treats it at the millisecond scale — looser than fronthaul by roughly an order of magnitude, with proportionally greater reach.

Table 3.1. Split option against transport segment, payload and latency budget.

Split	**Interface**	**Segment**	**What crosses the interface, and what sets the bit rate**	**One-way latency budget**
Option 2	F1 (3GPP)	Midhaul	PDCP PDUs. Scales with user traffic.	Not specified by 3GPP; millisecond scale in planning practice

Option 6	SCF nFAPI	Fronthaul	MAC transport blocks. Scales with user traffic.	Tighter than F1, set by MAC and PHY timing
Option 7-2x, Category A O-RU	O-RAN Open Fronthaul	Fronthaul	Frequency-domain IQ after precoding. Scales with antenna ports.	100 µs, IEEE 802.1CM Class 1 [4]
Option 7-2x, Category B O-RU	O-RAN Open Fronthaul	Fronthaul	Frequency-domain IQ before precoding. Scales with spatial layers.	100 µs [4]
Option 8	CPRI	Fronthaul	Time-domain IQ. Scales with antenna count and sample rate; approximately 3.7 Gbit/s per antenna for a 100 MHz carrier before line coding.	100 µs [4]

Bit rate depends on carrier bandwidth, port or layer count, IQ word length and compression. The Option 8 per-antenna figure is derived from the sampling arithmetic in the text.

3.2 Fronthaul

Open RAN fronthaul runs eCPRI over Ethernet. The O-RAN control, user and synchronisation planes carry the radio payload and timing, and the management plane handles configuration [19].

Deployed fronthaul links for massive MIMO radio units are typically at 25G, with recent MIMO radios already using 50G. Following the IEEE 802.3 roadmap, 100G, 200G and 400G optics will be introduced as carrier bandwidths grow [21]. However, the optical interface must also remain viable in the outdoor power and thermal envelope of the radio site. Scaling pluggable modules by simply adding lanes or modules increases faceplate area, electrical trace length and heat density. Integrated approaches such as near-package or co-packaged optics may eventually provide higher bandwidth density and lower energy per bit, while short on-board optical links can avoid retimers and equalisation on long electrical traces [22]. However, the maturity, maintainability, environmental qualification and multi-vendor interfaces of these technologies need to be assessed in a RAN context, which poses different requirements compared to the datacom evolution scenarios that triggered the introduction of these technologies.

Potential 6G Impact on Fronthaul

Future 6G systems are expected to employ wider carrier bandwidths and larger antenna arrays than current 5G deployments. Since O-RAN 7-2x transports frequency-domain samples, the fronthaul rate scales approximately with carrier bandwidth and the number of transported antenna ports or spatial layers.

As an illustrative example, a current 5G deployment using a 100 MHz carrier with a 64T64R massive MIMO radio with Option 7-2x typically requires ~25–50 Gbit/s of O-RAN 7-2x fronthaul capacity

depending on the implementation, compression ratio and radio category. If future 6G systems employ a 400 MHz carrier and a 256-element antenna array, the transported information increases approximately fourfold due to bandwidth and up to fourfold due to array scaling. Even after accounting for precoding and compression efficiencies, fronthaul requirements could move into the 200–800 Gbit/s range per sector, with some high-capacity deployments approaching terabit-class fronthaul aggregation.

While distributed RAN over short distances is expected to be mostly deployed over point-to-point fibre links, where fibre count limits deployment more than reach does, wavelength division multiplexing lets several fronthaul links share one fibre. Point-to-point WDM and WDM-PON both apply. ITU-T G.698.4 [23] specifies bidirectional DWDM applications with port-agnostic single-channel interfaces, written primarily for metro. The feature that matters here is self-tuning: the tail-end transmitter sets its own channel frequency from head-end feedback, so wavelengths do not have to be matched port by port at installation.

In addition to WDM or as a standalone option, packet fronthaul [24] is becoming a key enabler for both Cloud RAN and Open RAN by replacing traditional CPRI-based fronthaul with packet-based eCPRI transport. This allows radio units to connect flexibly to physical or virtualised distributed units, making it possible to pool and optimise processing resources across the network rather than tying radios to specific baseband hardware. As radio capacity continues to grow, packet fronthaul helps overcome port-capacity bottlenecks through traffic aggregation and fan-out, improving scalability and resource efficiency. It also increases network resilience by allowing traffic to be redirected to alternative processing resources in case of failures. However, packet fronthaul requires closer collaboration between RAN and transport teams, effectively bridging the two domains.

Use of fibre access infrastructure, such as passive optical networks, for fronthaul is covered in Section 4.

3.3 Midhaul and backhaul

In midhaul and, even more, backhaul, the millisecond-scale latency budget is easier to meet than the fronthaul budget, so it gets less space here.

Potential 6G Impact on Midhaul and Backhaul

Future 6G systems are expected to increase site capacity through wider channel bandwidths, larger antenna arrays and improved spectral efficiency. Current high-capacity 5G macro sectors typically deliver peak throughputs in the range of 3–5 Gbit/s, resulting in site-level traffic of approximately 6–15 Gbit/s for a three-sector macro site. Transport links are normally dimensioned above the expected user throughput to accommodate protocol overheads, aggregation and future growth.

A more significant impact of 6G is likely to appear at aggregation points in the midhaul and backhaul network. While individual sectors may benefit from wider spectrum, advanced MIMO and improved spectral efficiency, the cumulative effect is seen where traffic from tens or hundreds of radio sites converges. Today, a metro aggregation node may collect traffic from dozens of 5G macro sites, resulting in transport requirements of hundreds of gigabits per second. If 6G increases average site throughput by a factor of five to ten, the same aggregation node could require transport capacities in the multi-hundred-gigabit to multi-terabit range. This evolution strengthens the case for 400G, 800G and future 1.6T coherent optical interfaces, as well as greater convergence between IP and optical layers.

Aggregation and metro transport decide cost per bit. The OIF 400ZR implementation agreement put interoperable 400G coherent optics into router-pluggable modules. OIF released the 800ZR implementation agreement in October 2024, specifying an 800G coherent line interface over single-span amplified DWDM links of 80 to 120 km [25]. Both are written for data-centre interconnect reaches, which is worth holding in mind before the same economics are assumed for metro and regional aggregation. The architectural choice that follows is whether to run IP directly over the optical layer or to keep a separate optical transport layer with its own management. That choice sets how far the network can be disaggregated. Optical interconnect between radio access compute and AI clusters is treated in Section 6.

Transport topology is equally important. Fronthaul is commonly dominated by point-to-point or wavelength connections, where deterministic latency and isolation matter more than statistical multiplexing. Midhaul and backhaul can use rings or meshes and obtain greater benefit from packet aggregation. The integration of packet and optical systems combines packet flexibility with the high bandwidth and low latency of optical systems, aiming for a balance between performance, efficiency and functionality, as required by 6G. However, challenges arise when combining packet and optical technologies, such as congestion control in packet networks and efficient integration between the two technologies. Coordinating resources across radio, transport and cloud domains is therefore a must to perform dynamic resource allocation and efficient infrastructure sharing.

3.4 Synchronisation and timing

TDD radio networks depend on phase synchronisation between neighbouring cells. Indian networks now carry a second, independent obligation: from February 2027 the Legal Metrology (IST) Rules, 2026 determine where a network may take its time and what it must record.

3.4.1 What the network has to deliver

Frequency synchronisation keeps oscillators at the same rate. Phase synchronisation aligns the start of frames and symbols across radios. Time synchronisation ties to an absolute timescale such as UTC. FDD macro-operation needs frequency; TDD, carrier aggregation and coordinated multipoint need phase; timestamps for logging and some positioning methods need absolute time [5].

ITU-T G.8271 defines accuracy class 4 as ±1.5 μs, the phase requirement for TDD [5]. ITU-T G.8271.1 divides that budget along the chain [26]. The packet network (including the time source) may contribute a maximum absolute time error of 1100 ns at reference point C. The remainder covers the end application. Relative limits between signals are tighter. 3GPP TS 38.104 clause 6.5.3 specifies time alignment error at the base station, measured between antenna connectors for BS type 1-C and between TAB connectors belonging to different transmitter groups for BS type 1-H. TAE shall not exceed 65 ns for MIMO transmission at each carrier frequency, 260 ns for intra-band contiguous carrier aggregation with or without MIMO, and 3 μs for intra-band non-contiguous and for inter-band carrier aggregation [6]. ITU-T G.8271 separately defines accuracy classes 6C, 6B and 6A at 65 ns, 130 ns and 260 ns [5]. Where those branches sit in different radio units, the transport network has to hold the relative time error between the units inside whichever limit applies.

ITU-T G.8275.1, the full timing support profile, is the standard way to meet class 4 across a multi-hop network. Every node is a telecom boundary clock or a telecom transparent clock, and Synchronous Ethernet supplies physical-layer frequency at each hop [27]. The time error added per hop depends on the boundary

clock performance class defined in ITU-T G.8273.2 and link asymmetry, so class and hop count together set how long a chain can be [28]. ITU-T G.8275.2 with assisted partial timing support can also meet class 4, but it relies on a GNSS receiver at or near the end application [29].

O-RAN describes four fronthaul synchronisation topologies. In LLS-C1 the O-DU synchronises the O-RU over a direct link. In LLS-C2 the O-DU synchronises the O-RU through PTP-aware switches. In LLS-C3 a grandmaster in the fronthaul network synchronises both the O-DU and the O-RU. In LLS-C4 the O-RU takes time from a local GNSS receiver [19].

3.4.2 The GNSS dependency

Most deployed primary reference time clocks take time from GNSS, mostly from GPS. A foreign satellite constellation is therefore a single point of failure for TDD operation, positioning and network timestamps. GNSS signals can be jammed or spoofed, and a spoofed receiver can move network time outside the phase budget before an alarm is raised.

3.4.3 What India has in place

In September 2023, C-DOT and CSIR-NPL signed an agreement under the Telecom Technology Development Fund to develop a NavIC-based, IST-traceable primary reference time clock for the telecom sector. The device is to give telecom and internet service providers direct IST traceability within ±20 ns, with lower GPS dependence as a stated objective [30].

3.4.4 Legal time and phase accuracy

The Rules govern the time a network records and reports — in call detail records, logs, billing and other timestamps — and they decide where the PRTC may take its time. They state no numeric time error limit. What they require is traceability, redundancy and auditability: under Rules 6(4) and 6(5) the end entity carries exclusive responsibility for accuracy, stability and traceability within its own systems, has to monitor deviations, record them in accordance with international standards, and hold auditable data [13]. The phase budget comes from ITU-T and 3GPP, not from the Rules. TDD radios depend on relative phase between neighbouring cells, which is what the ±1.5 µs and time alignment limits describe. A network can meet one requirement and miss the other.

Both requirements reach the operator over the same path. NavIC adds reach and a second source. The sub-microsecond accuracy that fronthaul needs is delivered over fibre, using G.8275.1 across the links that carry the radio payload. The obligation to use IST reaches operators in 2027, years before 6G.

3.4.5 What 6G adds

Positioning and integrated sensing tighten these budgets. Light travels approximately 30 cm in 1 ns, so a positioning method that depends on synchronised base stations needs timing error well below 1 ns for centimetre accuracy. Round-trip time methods remove most of that dependence on network time. Sensing that combines coherent measurements across sites inherits the relative alignment limits above. A positioning accuracy target means little until the method and the timing budget are stated with it. Optical sensing over deployed fibre, which carries the same timing constraints, is developed in Section 5.5.

3.5 Deployment reality in India

The National Broadband Mission of 2019 recorded around 30 per cent of towers as fibre-connected and set a target of at least 70 per cent [8]. National Broadband Mission 2.0 now carries the programme to 2030.

Fibre reach is the principal determinant of how far advanced RAN architectures can be deployed in India. A site without a fronthaul link that meets the numbers in Table 3.1 cannot run a 7-2x split. Short E-band microwave or free-space optical hops can close part of that gap but need to guarantee performance with a given outage probability, which is challenging at high bit rates. Otherwise the site runs a higher split over microwave, with less centralisation, or a self-contained radio. The fibreisation figure therefore sets how much of the Indian network can adopt the architecture the rest of this document assumes.

Availability matters as much as reach. The Comptroller and Auditor General's performance audit of BharatNet, tabled in Parliament on 12 August 2026, found 2.19 lakh gram panchayats service-ready against a revised scope of 2.26 lakh, or 96.70 per cent — a substantial build achievement. The programme is now in its utilisation phase: as of November 2025, 33.20 per cent of service-ready gram panchayats were operational and bandwidth utilisation was 17.91 per cent. Fibre faults caused approximately 48 per cent of non-operational cases, and the mean time to restore was 17 days [31].

These figures describe BharatNet gram panchayat fibre; operator tower fibre runs under separate arrangements. They still bear on 6G, because rural sites beyond operator fibre will depend on BharatNet and on the Amended BharatNet Programme, for which BSNL is the project management agency [31]. A 17-day restoration time cannot support fronthaul, or a phase budget counted in nanoseconds. Ring protection, route diversity and a restoration time target belong in the Indian transport design from the start. Section 10 develops the policy and deployment side.

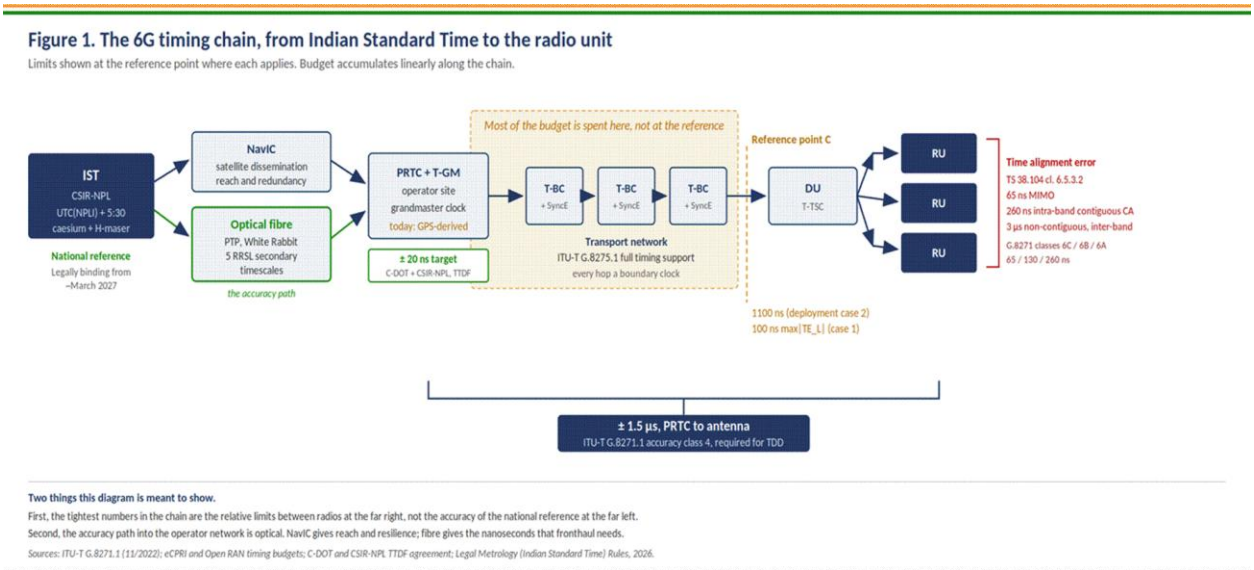

Figure 3.2. The 6G timing chain from Indian Standard Time to the radio unit.

Limits are shown at the reference point where each applies. Sources: [5], [6], [13], [26]–[28], [30].

4. Fibre Access and Fixed-Mobile Convergence — PON Evolution and Slicing

The access network is undergoing a fundamental transition. Traditionally, fixed optical access and mobile access networks have evolved largely independently. Passive optical networks (PONs) have been optimised primarily for fixed broadband, whereas mobile networks have relied on dedicated transport infrastructures for connecting radio sites to the core network. With the densification of mobile networks, increasing deployment of small cells, growth of cloud-based services, and emerging low-latency applications, maintaining separate access infrastructures becomes increasingly inefficient. A common fibre infrastructure capable of simultaneously supporting residential broadband, enterprise connectivity, mobile transport, and emerging services is therefore an attractive direction for future access networks.

In this context, the evolution of PON should not be viewed only as an increase in line rate. The more important transition is from a relatively static access network toward a flexible and dynamically configurable optical access infrastructure, where bandwidth, wavelengths and other network resources can be assigned according to traffic and service requirements.

4.1 Evolution from TDM-PON to multi-wavelength PON

Conventional GPON and EPON systems predominantly use time-division multiplexing (TDM) to share the available capacity among a large number of optical network units (ONUs). This architecture is cost-effective because the fibre and passive distribution network can be shared among many users. However, increasing the capacity of a purely TDM system eventually requires operation at progressively higher line rates and more demanding optical components.

An important evolutionary step is therefore the introduction of wavelength-domain resources in addition to time-domain resources. In time- and wavelength-division multiplexed PONs (TWDM-PONs), multiple wavelengths can operate over the same optical distribution network, while the capacity of each wavelength is further shared in time. Such an architecture combines the statistical multiplexing advantages of TDM with the additional capacity and flexibility offered by WDM [32].

Previous work on flexible TWDM-PON architectures showed that this flexibility is useful not only for increasing capacity but also for improving the utilisation of network resources and reducing energy consumption [32]. If the offered traffic is small, all wavelengths need not remain simultaneously active. Wavelength resources and the corresponding transceivers can be activated according to the network load, whereas additional wavelengths can be enabled as traffic increases. Thus, capacity can be scaled with demand rather than dimensioning the network for its peak requirement at all times.

This principle was investigated further for Super-PON through dynamic bandwidth and wavelength allocation (DBWA). Bin-packing-based wavelength allocation can consolidate traffic on a smaller number of wavelengths when the network load is low, allowing unnecessary transceivers to be switched off, while activating additional wavelengths at higher loads [33], [34]. At the same time, excessive wavelength switching should be avoided because wavelength tuning and switching introduce additional overheads and can increase packet delay. Therefore, future PONs require joint optimisation of bandwidth allocation, wavelength allocation, delay, wavelength switching and energy consumption, rather than independent optimisation of only the transmission capacity.

The standardisation evolution follows a similar capacity trajectory from GPON toward XG-PON/XGS-PON, NG-PON2 and now 50G-PON. The current ITU-T 50G-PON specification supports a nominal 50 Gbit/s downstream rate and, following subsequent amendments, 25 and 50 Gbit/s upstream operation. Importantly, coexistence with earlier PON generations remains an important requirement because upgrading an access network should ideally preserve the already deployed optical distribution infrastructure [35]. Beyond 50 Gbit/s per wavelength, very-high-speed PON technologies are also being studied as a further evolutionary step.

4.2 Dynamic bandwidth allocation as the basis for service differentiation

Increasing the physical-layer capacity alone cannot guarantee the performance required by different services. Since upstream PON capacity is shared by multiple ONUs, the dynamic bandwidth allocation algorithm at the optical line terminal (OLT) becomes a critical element of the network.

Different applications may have significantly different requirements. Best-effort residential traffic can tolerate statistical variations in packet delay, whereas enterprise services, mobile transport, industrial traffic and other time-critical applications may require bounded delay, controlled packet loss and guaranteed bandwidth. Earlier work on SLA-aware DBA demonstrated that resource allocation can be designed to provide differentiated and predictable delay performance to different traffic classes while maintaining high overall channel utilisation [36].

This observation becomes particularly important in a converged network. A single PON may simultaneously carry residential broadband traffic, enterprise traffic and traffic originating from mobile radio units. A resource-allocation mechanism should therefore not simply divide the capacity fairly among ONUs; it should allocate the capacity according to the service-level requirements associated with their traffic.

Consequently, the DBA mechanism evolves naturally from a bandwidth-sharing algorithm into a service-aware scheduler. In a multi-wavelength PON, this scheduler has two dimensions available to it: transmission time and wavelength. These resources can be dynamically distributed among different services, which provides the foundation for implementing logical partitions, or slices, over a common physical PON infrastructure.

4.3 Fibre access as a common infrastructure for fixed and mobile networks

Fixed-mobile convergence is another important driver for the evolution of optical access. Fibre provides enormous transport capacity but no mobility, whereas wireless networks provide mobility but ultimately require a high-capacity transport infrastructure. A converged fibre-wireless network can exploit the complementary properties of the two technologies.

Previous research on radio-over-fibre (RoF) networks considered this problem from both architectural and MAC-layer perspectives [37]. Centralising signal processing and transporting radio signals over fibre allows remote radio units to be simplified while enabling optical resources to be shared among geographically distributed radio cells. More importantly, wavelength and bandwidth resources can be dynamically steered toward those parts of the wireless network where the traffic demand is higher.

This resource flexibility was experimentally investigated for WDM-based RoF fronthaul, where wavelength resources could be allocated according to the traffic requirements of remote radio heads [38]. Similarly, a converged MAC and DBA architecture can jointly perform user identification, polling, bandwidth allocation and wavelength allocation instead of treating optical and wireless resource management as completely independent problems [39].

These ideas become increasingly relevant as fixed and mobile networks converge. A common fibre access network could simultaneously connect homes, enterprises, Wi-Fi access points, small cells and radio units. However, the traffic characteristics of these applications can be very different. Mobile transport, depending upon the functional split being employed, can impose significantly tighter delay and synchronisation constraints than conventional residential broadband. The optical scheduler must therefore be aware of these service differences.

Fixed-mobile convergence should consequently occur not only at the physical infrastructure level but also at the resource-control level. The Broadband Forum's wireless-wireline convergence architecture similarly provides mechanisms for integrating fixed access with the 5G system rather than maintaining completely independent fixed and mobile service architectures [40].

4.4 PON slicing

Network slicing extends this concept further. Instead of constructing a separate physical access network for every service or operator, multiple logical networks can be created over the same PON infrastructure. Each logical network can be assigned a defined set of resources and service characteristics.

A PON slice may be implemented using resources in the time domain, wavelength domain, or a combination of the two. For example, a wavelength or group of wavelengths may be predominantly associated with a particular service, while a more flexible implementation can dynamically allocate transmission windows across shared wavelengths. The latter provides better statistical multiplexing but requires a slice-aware DBA mechanism capable of maintaining the required isolation between different slices.

ITU-T Supplement 74 explicitly considers network slicing in the PON context and identifies use cases including services with different latency requirements, dynamic resource allocation for mobile applications, multi-operator access, multi-service shared networks and industrial PONs. It also identifies slice-aware DBA and control of PON slices as important functions of a sliced optical access network [41].

There is an interesting connection between PON slicing and earlier work on open-access optical networks. Open-access architectures allow multiple network or service providers to share a common fibre infrastructure while providing logical or physical separation between them [42]. PON slicing is not identical to open access; however, both are based on an important architectural principle: ownership of the physical access infrastructure need not imply exclusive use of its resources. Wavelength-level open access provides relatively strong physical separation, whereas software-controlled slicing can provide finer and more dynamic sharing of bandwidth and wavelength resources.

A practical PON slicing architecture can therefore be considered at three levels. At the lowest level is the shared optical infrastructure consisting of the OLT, optical distribution network, wavelengths and ONUs. Above this is a slice-aware MAC and DBA layer that translates slice requirements into bandwidth and

wavelength allocations. At the highest level, an SDN controller or service orchestrator maps end-to-end service requirements onto the appropriate PON resources.

This hierarchy is particularly important for fixed-mobile convergence. An end-to-end mobile-network slice should not terminate when it enters the optical access network. Its latency, bandwidth and isolation requirements need to be translated into appropriate PON scheduling and wavelength-allocation parameters. Conversely, the PON controller should expose information about resource availability and congestion to higher-level orchestration functions.

4.5 Key requirements and research directions

Future fibre access will therefore require more than simply higher transmission rates. Several requirements become important simultaneously.

First, service isolation and predictable QoS are necessary if traffic with very different characteristics shares the same PON. Slice-aware DBA should guarantee minimum or assured resources while retaining statistical multiplexing gains whenever excess capacity is available.

Second, dynamic wavelength allocation will become increasingly important as the number of wavelengths and network capacity increase. The network should be able to consolidate traffic under low load and activate additional wavelength resources under high load, thereby reducing energy consumption without violating latency requirements.

Third, coexistence and incremental upgrade remain essential. A commercially deployable architecture should permit new generations of PON and new services to be introduced without requiring replacement of the existing fibre distribution network.

Fourth, coordination between optical and mobile resource management will be needed. Traffic variations in the radio network should eventually influence resource allocation in the optical access network. This is particularly relevant for dense small-cell deployments in which the traffic distribution can change considerably with time and location.

Finally, slicing requires appropriate control, telemetry and orchestration. Fast information exchange between the OLT, access controller and end-to-end service orchestrator will allow the network to respond dynamically to changes in load, service requirements and failures.

The evolution of PON is thus changing the role of the optical access network. It is no longer only a high-capacity pipe between an OLT and fixed broadband subscribers. Multi-wavelength transmission, dynamic bandwidth and wavelength allocation, open infrastructure sharing and network slicing transform PON into a programmable access fabric. Such a fabric can provide a common infrastructure for fixed broadband, enterprise connectivity and mobile transport, while dynamically assigning optical resources according to service requirements. This convergence of high-capacity fibre, service-aware resource allocation and end-to-end slicing is likely to be a key element of future fixed-mobile networks.

5. Optical Wireless — LiFi/VLC, FSO Backhaul, Inter-Satellite Links for NTN, Optical sensing and Hybrid FSO/RF Communications

The preceding sections discuss how light propagates at high speeds in fibre. Optical waves can also be used for wireless communication — as a complementary technology to radio, as a substitute, or as a completely new network utility beyond communication. From a 6G perspective, LiFi/VLC, which uses LEDs or lasers, can provide gigabit links over a few metres (~10 m) in indoor environments. Terrestrial free-space optical communication (FSO), which uses narrowband infrared lasers, can provide high-speed wireless backhaul links ranging from hundreds of metres to a few kilometres in areas where fibre deployment remains a challenge. Non-terrestrial FSO can provide thousands of kilometres of inter-satellite links (ISLs) for the 6G NTN. Optical sensing can use luminaires, other light sources, or FSO/LiFi links themselves as information sources without disrupting their functioning. Table 5.1 builds on the maturity assessment in Table 2.1 to describe these optical wireless technologies in more detail, followed by Sections 5.1 to 5.6, which discuss each.

Table 5.1. Optical wireless technologies: reach, maturity, and realistic 6G role.

Technology	Reach	Standardised or reported performance	Maturity stage	Realistic 6G role
LiFi / light communication for indoor	A few metres to tens of metres	IEEE 802.11bb standardises 10 Mbit/s–9.6 Gbit/s [7]; ITU-T G.9991 [43] standardises up to 2 Gbit/s. Separately, 70 Gbit/s has been reported over a laser-based (VCSEL) point-to-point optical wireless link with a fibre-coupled receiver [44]; this is a laboratory demonstration, not LiFi in the 802.11bb sense.	Standardised, early commercial (802.11bb, G.9991); the 70 Gbit/s laser link is a laboratory demonstratio n	Dense indoor environments, RF-sensitive sites, positioning
LiFi / OWC for industrial use	Up to 200 m, line of sight	Up to 2.192 Gbit/s as per IEEE 802.15.13 [45].	Standardised (2023)	Factory floors, secure and low-latency links
Terrestrial FSO	Hundreds of metres to a few km	ITU-T G.641 [46] 10 Gbit/s over 2 km, mobile backhaul, SFP+ compatible. 20 Gbit/s over 4.8 km is reported in a favourable climate [47].	Commercial, weather-limited	Point-to-point backhaul or fronthaul, where fibre is impractical.
Optical relay and inter-satellite links	Hundreds to thousands of km	Approximately 1.8 Gbit/s ESA EDRS GEO optical relay links (Section 2.3) [48]. CCSDS 141.10-O-1 [49]: up to 10 Gbit/s over 40,000 km, 1550 nm compatible. Starlink V3 reports 400 Gbit/s inter-satellite links [50].	Operational, mass production	High-reliability NTN backhaul/relay to ground where direct ground contact is limited. Inter-satellite mesh backhaul for NTN.
Optical sensing	Vehicle scale (LiDAR) Few metres	Automotive LiDAR reviewed in [51]. Reflection-based VLC sensing and lighting-integrated	Automotive LiDAR deployed.	ISAC, vehicular perception, infrastructure and

	(VLC/FSO-based ISAC)	ISAC frameworks and link-embedded atmospheric sensing using FSO/ISL [52].	VLC/FSO-based system in early research	environmental monitoring, positioning, gesture sensing

5.1 LiFi / VLC

LiFi/VLC or indoor OWC uses LEDs or laser diodes as transmitters and photodiodes as receivers, employing intensity modulation with direct detection (IM/DD) for communication. The achievable bandwidth is set by the source: visible-light LEDs typically offer a modulation bandwidth on the order of 100 MHz, infrared LEDs somewhat more (up to around 400 MHz), and laser diodes extend into the multi-GHz range.

Two IEEE standards and one ITU-T recommendation define OWC's PHY and MAC layers. IEEE 802.11bb-2023 amends the IEEE 802.11 (Wi-Fi) standard, extending the WLAN PHY architecture into the 800–1000 nm optical band so that existing WLAN chipset designs can be reused, with bidirectional throughput from 10 Mbit/s to 9.6 Gbit/s [7]. ITU-T G.9991 defines the system architecture and PHY and data-link-layer specification for high-speed indoor OWC transceivers, supporting a peak data rate of 2 Gbit/s [43]. For mobile and industrial use, IEEE 802.15.13-2023 standardises OWC for both stationary and mobile devices at ranges up to 200 m, with data rates up to 2.192 Gbit/s [45].

Since light does not pass through walls, LiFi links are inherently confined to a room or line-of-sight cell. This directionality supports high spatial reuse, small-cell densification, and physical-layer security, at the cost of coverage loss under blockage — a trade-off Section 5.2 discusses in detail. The same directionality also enables LiFi to support indoor positioning as an inherent property of the link, something RF systems typically achieve only with additional hardware.

India's AOC Testbed project is directly building experimental capability in this area: IIT Delhi has developed in-house 100 Mbit/s visible-light transceivers, developing both the MAC and PHY layers and the LiFi front ends indigenously [10]. IIT Delhi has filed several patents on the technology, covering optical transceiver lenses [53], [54] and multiplexing methods [55]. For 6G, the realistic role of LiFi/OWC is as a complementary technology at the highest-density, most RF-congested points of the network, such as offices, campuses, factory floors, aircraft cabins, hospitals and other RF-sensitive sites, rather than as a substitute for wide-area cellular coverage.

5.2 Hybrid LiFi–Wi-Fi networks

A key limitation of LiFi is its localised, line-of-sight nature, which can result in coverage holes and performance degradation under blockage. Wi-Fi, in contrast, provides wider coverage but has comparatively limited capacity. This complementarity motivates a hybrid LiFi–Wi-Fi architecture, in which optical and RF links are jointly used rather than treated as competing technologies. Four studies conducted by IIIT-Delhi show a progressive development from hybrid connectivity and link aggregation to mobility management, cross-technology information sharing, and reliability analysis [56]–[59].

The first step is the integration of LiFi and Wi-Fi through link aggregation (LA). Since the two technologies operate in non-overlapping spectrum, a user can receive data concurrently from a LiFi AP and a Wi-Fi AP. This enables the high-capacity characteristics of LiFi to be combined with the broader coverage of Wi-Fi.

In the LA-EQoS framework, a realistic indoor network consisting of four LiFi APs and one Wi-Fi AP in a $5 \times 5 \times 3$ m³ room was considered, with a central controller responsible for network coordination. The proposed LA-EQoS mechanism was designed to improve QoS and average data rate while accounting for LA overhead and adaptive modulation. The simulation results showed 80–100% coverage for more users under predefined QoS requirements, while, for a given outage constraint, the maximum QoS achieved was approximately 1.5 times higher than the compared networks [56].

However, simultaneous use of LiFi and Wi-Fi introduces a new challenge: network management under user mobility. As users move across LiFi coverage regions, conventional systems may trigger frequent handovers between LiFi and Wi-Fi APs. The MARM-HyLiWi framework addresses this issue through mobility-aware link aggregation and dynamic rate allocation. The proposed approach considers the user's data-rate requirement, AP signal quality, backhaul condition, mobility and fairness, and formulates the resource-allocation problem as a multidimensional commodity-flow problem. A relaxed linear-programming formulation followed by rounding is used to obtain a practical solution [57]. The system again considers a $5 \times 5 \times 3$ m³ indoor environment with four LiFi APs and one Wi-Fi AP. The resulting mobility-aware strategy reported a 54% improvement in throughput, while addressing handovers and computational overhead [57].

The next development moves from aggregating user data to using optical connectivity to improve the operation of the RF network itself. The WiLiConnect framework proposes using LiFi APs to communicate the channel-state information (CSI) required by Wi-Fi for spatial multiplexing and MU-MIMO. Conventional Wi-Fi CSI feedback creates overhead because CSI has to be obtained from users through the Wi-Fi channel. The study's motivation experiments showed a sum-rate gap of approximately 65% for 10 users and 56% for 20 users between ideal CSI-known and realistic CSI-feedback operation. WiLiConnect exploits multiple LiFi APs and separate optical uplink/downlink channels to distribute CSI transmission in parallel [58]. The simulations reported approximately 55% improvement in overall Wi-Fi sum rate compared with conventional CSI feedback, while the CSI-sharing scheme incurred only 0.06% overhead for an eight-antenna Wi-Fi AP in terms of total sum rate [58].

The final step in this progression is to establish the reliability benefit of the combined architecture. The 2026 outage-probability study develops an analytical model for link-aggregation-enabled hybrid LiFi–Wi-Fi networks. Unlike simplified approaches, the proposed model incorporates overhead associated with packet reordering and synchronisation in link aggregation and captures interaction between the two links [59]. The resulting analysis reports lower rate-outage probabilities across diverse scenarios compared with standalone LiFi and Wi-Fi systems [59].

Together, these developments show a clear technology progression relevant to 6G: LiFi high-capacity access to hybrid LiFi–Wi-Fi connectivity to simultaneous link aggregation to mobility-aware resource allocation to optical-assisted RF control/CSI sharing to improved throughput, QoS and reliability. The practical use cases include high-density indoor networks, enterprise and campus environments, industrial communication, immersive applications, mobility-intensive indoor scenarios, and environments where RF capacity or spectrum availability is constrained.

The evidence indicates that the practical value of optical wireless is not restricted to its large optical spectrum. Optical links can provide an additional spatial resource, an independent communication medium, parallel connectivity, and an auxiliary channel for network-control information. From a 6G perspective, optical wireless can therefore be integrated as a complementary network layer alongside RF: optical fibre can provide high-capacity transport, while optical wireless provides localised access and heterogeneous

connectivity. The studies collectively show measurable benefits in capacity, QoS, mobility, resource utilisation and reliability, providing a pathway toward intelligent RF–optical networks.

Table 5.2. Evidence from the four hybrid LiFi–Wi-Fi studies.

Development	**Technology / Implementation**	**Objective / Use Case**	**Reported outcome**
Hybrid LiFi–Wi-Fi with LA-EQoS	4 LiFi APs + 1 Wi-Fi AP; 5 × 5 × 3 m³ indoor environment	Improve QoS and coverage through simultaneous LiFi–Wi-Fi transmission	80–100% coverage for more users; ~1.5× higher QoS under outage constraint [56]
MARM-HyLiWi	Mobility-aware LA with dynamic rate allocation considering demand, SINR, backhaul and mobility	Reduce handovers and optimise resources for mobile users	54% throughput improvement [57]
WiLiConnect	LiFi APs used for parallel Wi-Fi CSI transmission	Reduce Wi-Fi CSI-feedback overhead and improve MU-MIMO performance	~55% Wi-Fi sum-rate improvement; 0.06% overhead for 8-antenna AP [58]
LA-HLWN outage analysis	Analytical model incorporating LA packet-reordering/synchronisation overhead	Quantify reliability and rate-outage performance	Lower outage probability across diverse scenarios than standalone LiFi/Wi-Fi [59]

5.3 Terrestrial FSO

Free-space optical (FSO) communication uses narrowband lasers as transmitters, usually in the near-infrared range, from about 780 nm to 1600 nm. The laser beam itself is very narrow and can travel tens of km. But a beam this narrow is hard to keep aligned in a practical scenario. Therefore, the transmitter and receiver are followed by front-end optics that widen the beam — enough to tolerate small movements, but not to penalize the link budget.

Transmit power is the other factor that decides the link budget, and it is limited by eye safety requirements. IEC 60825-1 [60] sets the Maximum Permissible Exposure (MPE) limit for continuous exposure of 10 seconds or more. At 1550 nm, the corneal MPE limit is 100 mW/cm² (1000 W/m²) — about 50 times higher than at 800–850 nm. This is the main reason 1550 nm is so widely used for FSO: it allows much higher transmit power, and it also benefits from mature laser and detector components that were originally developed for fibre-optic systems.

FSO needs no trenching. A link capable of tens of Gbit/s can be set up just by mounting aligned transceivers at each end of a line-of-sight path, a few km apart. Once mounted, alignment usually takes under an hour. This makes FSO useful where laying fibre is not practical, in disaster-response situations where connectivity needs to be restored fast, and in places where RF spectrum is congested.

FSO is standardised in ITU-T G.641 [46], which is compatible with regular fibre SFP+ optics and specifies 10 Gbit/s over 2 km for mobile backhaul. A good real-world example is Google's Project Taara link across

the Congo River, which delivers 20 Gbit/s over 4.8 km with 99.9% availability [47]. It shows both the practical deployment potential of the technology and the growing commercial interest in it.

FSO links can technically work over longer distances in clear weather, but in practice, weather is what limits deployment. Several things affect an FSO link: beam spreading, pointing errors, attenuation from fog and rain, and scintillation caused by turbulence in the air. Fog is by far the biggest problem, because fog droplets are close to the size of the optical wavelength, which causes heavy scattering — this can attenuate the signal by hundreds of dB per km. Rain droplets are much bigger than the wavelength, so they scatter light differently and usually cause only tens of dB per km of loss, even in heavy rain.

This is interesting because optical and RF links exhibit different sensitivities to atmospheric conditions. Fog can significantly affect FSO links, whereas heavy rain can cause substantial attenuation at higher RF frequencies. These complementary propagation characteristics create an opportunity for hybrid RF–FSO architectures, where the two technologies can be combined to further improve link availability and capacity under varying atmospheric conditions. Such hybrid approaches can complement the already mature and reliable multi-band microwave and mmWave backhaul solutions. Given its high capacity, rapid deployment capability and complementary propagation characteristics, FSO can be an important technology component of future 6G-and-beyond networks with large capacities, particularly for mobile fronthaul and backhaul in locations where fibre deployment is difficult or impractical.

The AOC Testbed project, introduced earlier, has also funded work in this area. IIT Delhi has built in-house FSO transceivers tested at 10 Gbit/s over 1.5 km [10], with a 5 km link currently under test. The team also built its own pointing, acquisition and tracking (PAT) system for coarse and fine alignment and holds patents covering LDPC codes for the FSO channel [61], beam engineering [62], a complete FSO system [63], and PAT design [64].

5.4 Inter-satellite links for NTN

Inter-satellite links (ISLs) traditionally use RF to communicate directly in orbit without ground relays, typically operating in Ka-band and higher microwave bands. Due to increasing data demands and regulatory spectrum constraints, RF is approaching its limits. Industry is therefore moving towards optical ISLs, where lasers and photodetectors replace RF antennas. One advantage of optical links (satellite FSO) for ISLs is that the noise is far lower than for terrestrial FSO links, allowing ranges of thousands of km. But optical ISLs require very complex PAT systems, if both endpoints are moving.

From a standardisation point of view, two types of satellite optical link are in focus: GEO optical relay links and GEO-GEO links. GEO optical relay uses a geostationary satellite to store and forward data from LEO satellites that lack direct visibility to earth stations. These links run 36,000–45,000 km between the GEO satellite and the earth stations, and because the GEO node is nearly stationary relative to the earth station, these links do not need complex PAT systems. ESA's EDRS system, operational since 2016 and having completed tens of thousands of GEO optical relay links at approximately 1.8 Gbit/s, is the most mature example and remains in active use for both Earth observation and constellation relay [48].

The Consultative Committee for Space Data Systems (CCSDS) coordinates between the various space agencies, including ISRO, NASA and ESA. It has standardised the data link and physical layers for GEO-LEO and GEO-GEO optical links, building on the operational experience from EDRS, with separate

specifications addressing the high-data-rate, high-photon-efficiency and low-complexity link scenarios [49]. The CCSDS optical physical-layer specifications cover both 1064 nm and 1550 nm operation, with data rates of 3.6 Gbit/s with Reed-Solomon codes and BPSK and up to 10 Gbit/s with QPSK.

For LEO-LEO ISLs, the technology has moved from single demonstration links to a standard part of satellite design. SpaceX's third-generation Starlink (V3) satellites carry six optical inter-satellite links each operating at up to 400 Gbit/s [50] — two orders of magnitude above the GEO relay figure — reflecting how quickly commercial satellites have adopted optical crosslinks once optical terminals became cheap and reliable.

For 6G NTN, the realistic role of ISLs mirrors these two architectures. GEO optical relay offers high-reliability backhaul to the ground where direct ground contact is limited, while LEO-LEO ISLs let a satellite function as an in-orbit backhaul network, reducing how many ground gateways the system needs and extending 6G NTN coverage to areas a single-satellite link could never reach.

5.5 Optical sensing and communication

Integrated sensing and communication (ISAC) is emerging as an important capability of future communication networks. The ITU-R IMT-2030 framework identifies Integrated Sensing and Communication as one of the usage scenarios for IMT-2030 and envisages applications including localisation, object and movement detection, environmental monitoring, imaging, mapping, automated transportation, and digital twins. Although much of the current ISAC research is focused on RF, millimetre-wave and THz systems, optical technologies provide another important opportunity for integrating communication and sensing.

Optical communication systems already employ transmitters, receivers, beam-steering mechanisms and signal-processing functions that can also be used for sensing. Instead of deploying separate communication and sensing infrastructures, the same optical signal and, where appropriate, the same optical hardware can therefore be used for both functions. This can reduce hardware duplication while allowing sensing information to assist communication and communication infrastructure to provide information about the surrounding environment.

The high directionality, large available bandwidth and short wavelength of optical signals are particularly attractive for high-resolution spatial sensing. At the same time, optical wireless technologies such as VLC/LiFi and FSO are already being considered for high-capacity short- and medium-range connectivity. The integration of these communication systems with ranging, localisation, imaging and environmental sensing therefore provides a natural route towards optical integrated sensing and communication (O-ISAC). Recent work has demonstrated optical ISAC using both OFDM-based FSO links and optical phased-array architectures [65], [66], illustrating that communication and sensing functions can be jointly designed rather than implemented as independent systems.

Optical systems offer additional degrees of freedom that can further distinguish optical ISAC from conventional RF-based implementations. Information can be encoded and observed in the spatial distribution, polarisation and phase structure of the optical field in addition to its intensity, frequency and time dependence. Changes in these properties after propagation can contain information about the propagation environment. Structured optical beams can therefore potentially support communication while

simultaneously providing information about beam displacement, rotation, turbulence, scattering or interaction with objects.

Recent work on vectorial optical wireless communication has consequently highlighted the possibility of integrating communication, sensing and imaging through the additional spatial and polarisation degrees of freedom available in optical fields [67]. This represents an interesting longer-term direction. Rather than treating distortions of an optical field only as communication impairments, the distortion itself can be interpreted to obtain information about the environment.

Optical sensing and communication should not necessarily be considered as a replacement for RF-based ISAC. The two technologies have complementary characteristics. RF provides wider coverage and generally greater robustness to blockage, whereas optics can provide very high spatial resolution, narrow beams and large communication bandwidth. A future system can therefore combine sensing information obtained from RF, mmWave, THz, cameras, LiDAR and optical communication links. For example, an RF system may first provide coarse localisation of a mobile terminal. This information can then be used to narrow the acquisition region of a highly directional FSO link. Once the optical link is established, optical sensing can provide more accurate angular or position information for fine beam tracking.

5.6 Hybrid FSO/RF Communication for Resilient 6G Connectivity

Free-space optical (FSO) communication provides a high-capacity wireless transport option where deployment of physical fibre is difficult, slow or costly. Its narrow optical beam, large available optical bandwidth and rapid point-to-point deployment make it relevant to 6G backhaul, fronthaul, temporary connectivity and difficult-terrain deployments. However, terrestrial FSO is sensitive to atmospheric attenuation, turbulence, pointing errors and weather-dependent link outages. A complementary radio-frequency (RF) link can provide connectivity when the optical path is degraded. The resulting hybrid FSO/RF architecture therefore combines the capacity characteristics of FSO with the propagation diversity and coverage characteristics of RF.

For 6G, this relationship should be considered as a multi-bearer resilience mechanism rather than simply an optical link with an emergency RF backup. The optical and RF links experience different impairments, and the RF link itself can be interference-limited. Consequently, link selection can use optical-link quality, RF signal-to-interference conditions, environmental measurements, traffic state and service requirements. This subsection presents an analytical basis for such hybrid operation and an Indian field deployment that demonstrates weather-aware FSO/RF service continuity.

5.6.1 Motivation and Complementarity of FSO and RF

The main deployment challenge for terrestrial FSO is not the absence of optical capacity but the time-varying availability of the atmospheric optical channel. Rain, fog, turbulence and wind-induced pointing or building-sway effects can reduce received optical power and can result in temporary loss of the FSO path. In contrast, an RF path is affected by a different set of propagation and interference mechanisms. This diversity allows an RF path to maintain service when the optical path is temporarily unavailable. The hybrid approach is therefore particularly relevant to hilly, rural, remote and rapid-deployment environments.

Table 5.3. Hybrid FSO and RF Implications.

Characteristic	FSO	RF	Hybrid implication

Capacity	High optical bandwidth and high data-rate potential	Typically lower than the optical bearer for the same deployment	FSO can carry normal high-capacity traffic; RF provides continuity [68]
Weather sensitivity	Sensitive to fog, rain, turbulence and pointing errors	Different atmospheric sensitivity; performance also depends on frequency and interference	Propagation diversity can reduce service interruption
Spectrum	Optical carrier; no conventional RF spectrum allocation	Uses regulated/shared RF spectrum	Hybrid operation can reduce dependence on a single bearer
Interference	Optical channel is not subject to RF co-channel interference	Can be interference-limited	RF SIR should be included in link-selection decisions
Deployment	Rapid point-to-point deployment where line of sight exists	Flexible wireless coverage and fallback	Useful where fibre construction is difficult [69]
6G role	High-capacity backhaul/fronthaul/access extension	Coverage and resilience bearer	Jointly managed multi-bearer connectivity

5.6.2 Hybrid FSO/RF Architecture and Link-Selection Principle

A representative hybrid architecture consists of an FSO transmitter/receiver pair, an RF transmitter/receiver pair, a common traffic interface and a link-selection controller. The FSO link is normally preferred when its instantaneous quality is above a configured operating threshold. When the optical quality falls below the threshold, traffic is transferred to the RF path. For a more advanced 6G implementation, the controller can additionally consider RF interference, latency, packet loss, traffic demand, energy state and environmental measurements.

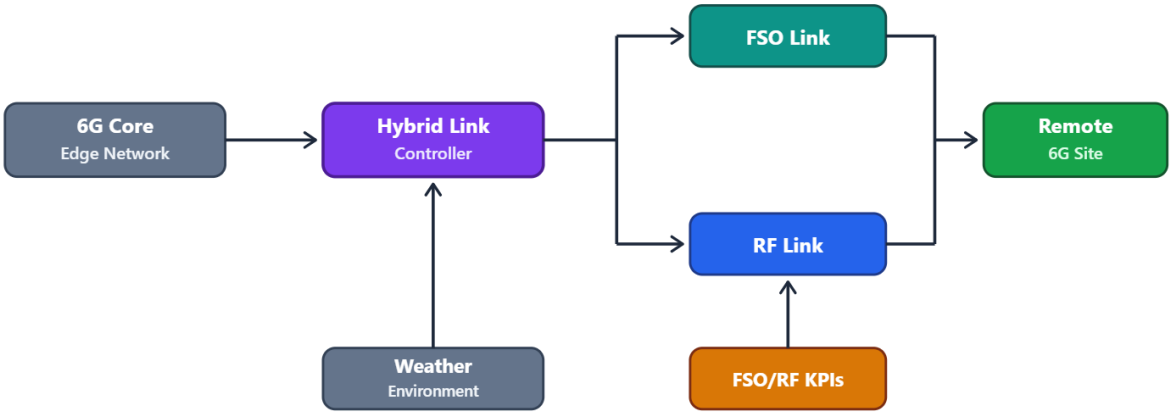

Figure 5.1. Conceptual architecture for hybrid FSO/RF connectivity in a 6G network.

The architecture can be operated in at least three modes: (i) FSO-primary mode under favourable optical conditions, (ii) RF-fallback mode when the FSO bearer becomes unavailable, and (iii) an adaptive hybrid mode in which the controller evaluates both links and service requirements. The third mode is particularly relevant to 6G because it enables the network to treat FSO and RF as complementary resources instead of making a binary availability decision.

5.6.3 Analytical Model for an Interference-Limited Hybrid FSO/RF Link

The analytical model developed in [70] considers a transmitter (TX) and receiver (RX) connected through an FSO link and an RF backup link. The FSO link is selected while its instantaneous SNR is above a predefined threshold Γ_FSO. When the FSO SNR falls below that threshold, the RF link is selected. M-ary phase-shift keying (M-PSK) with subcarrier intensity modulation is considered for the optical link. Atmospheric turbulence and pointing error are represented in the FSO channel, while the RF link is modelled using κ–μ fading with co-channel interference. [70]

Because the RF link is interference-limited, its quality metric is the signal-to-interference ratio (SIR) rather than the SNR. This is relevant to 6G because an RF fallback link cannot be assumed to be interference-free. The signal model, the SNR and SIR expressions and the switching rule are given in Annex A.

The threshold rule provides a simple implementation for an FSO-primary/RF-fallback architecture. For a 6G implementation, the threshold can be extended to a multi-parameter decision policy that also considers RF SIR, packet loss, latency, traffic demand and environmental state. Such an extension is a proposed architectural direction, not a measured result of the source study.

5.6.4 Outage and Reliability Characterisation

For the threshold-based system, a hybrid outage occurs when the FSO path is below its threshold and the RF path is simultaneously below its own service threshold Γ_RF. Under the independent-link assumption used in the analytical model, the hybrid outage probability is

$$P_{\text{out}}^{\text{hyb}} = \mathrm{P}(\gamma_{\text{RF}} < \Gamma_{\text{RF}})\mathrm{P}(\gamma_{\text{FSO}} < \Gamma_{\text{FSO}})$$

This expression makes the resilience mechanism explicit: the hybrid system is unavailable only when both candidate paths are simultaneously below their respective operating thresholds. The source study also derives the average symbol error rate (Annex A).

The analytical results reported in the source study show that co-channel interference increases the error rate and that its impact is particularly significant at lower SNR/SIR conditions; increasing the RF SIR improves hybrid-link performance. [70]

5.6.5 Practical Link-Selection and Monitoring Framework

A practical deployment can combine link-quality telemetry with environmental monitoring. The decision engine need not rely on a single weather parameter. A representative implementation can monitor FSO RSSI/SNR, RF RSSI/SIR, packet loss, latency, throughput, rainfall and wind speed. The selected bearer can then be changed when the measured state indicates that the primary path is no longer able to meet the service requirement.

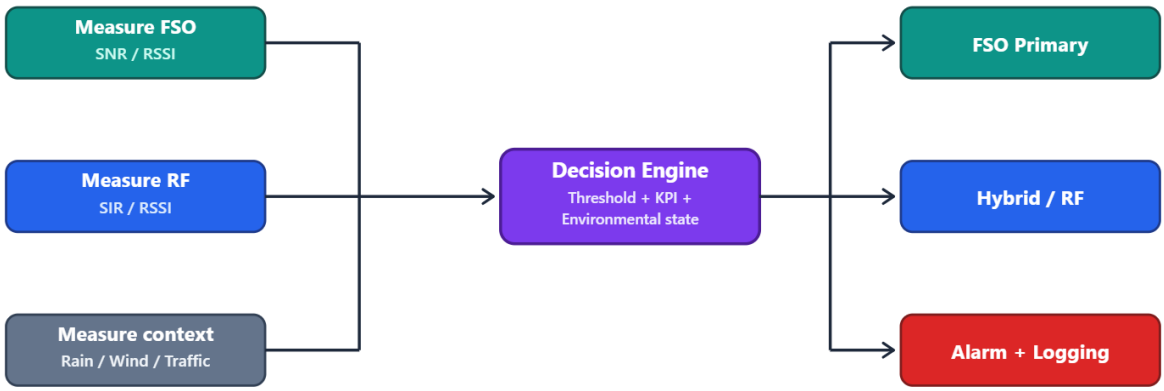

Figure 5.2. Adaptive monitoring and link-selection flow for a hybrid FSO/RF 6G bearer.

Table 5.4. Example Indicators of Adaptive Monitoring.

Input to decision engine	Example indicator	Purpose
FSO link state	RSSI / SNR / optical loss	Detect optical degradation
RF link state	RSSI / SIR	Check fallback quality and interference
Environmental state	Rainfall / wind / fog indicators	Correlate physical impairments with optical degradation
Service state	Latency / PLR / throughput	Protect application-level QoS
Traffic state	Offered load / queue state	Select bearer according to demand
Power state	UPS / solar / equipment status	Distinguish communication failure from power failure

5.6.6 Indian Field Deployment: 5.57-km FSOC/RF Link in Kohima, Nagaland

An ERNET India field deployment provides practical evidence for the hybrid FSO/RF approach in a mountainous and monsoon-dominated environment. A 5.57-km FSOC link was established in 2021 between Kohima Secretariat and Kohima Science College in Nagaland. The deployment used optical transceivers at the two sites, a Layer-2 switching infrastructure, environmental monitoring equipment and an RF failover path. The FSOC system provided a full-duplex optical link, while the RF path was configured to carry user traffic when the optical link became unavailable. [71]

The field architecture was integrated with the State Wide Area Network environment. Weather kits measured parameters including humidity, temperature, rainfall rate, dew point and wind speed, while network monitoring collected link-health and outage information. The deployment therefore provides a useful example of coupling optical-link telemetry with environmental context. [71]

Rain attenuation model

The field study used a rain attenuation formulation based on rain rate. The general empirical relation was $\gamma_{rain} = kR^{\alpha}$ dB/km,

where R is rainfall rate in mm/h and k and α are empirical coefficients. For the parameter values used in the Kohima analysis, k = 1.076 and α = 0.67, giving $\gamma_{rain} = 1.076\ R^{0.67}$ dB/km.

For the reported threshold rainfall rate of 0.27 inch/h (approximately 6.86 mm/h), the specific attenuation was approximately 3.91 dB/km, corresponding to approximately 22 dB over the 5.57-km path. At the reported peak rainfall intensity, the empirical model produced a specific attenuation of about 34 dB/km, which under the same relation corresponds to a rain rate of roughly 170 mm/h. [71]

5.6.7 Field Results and Evidence of Resilience

Table 5.5. Field results of the Kohima FSOC/RF deployment, March–July 2021 [71].

Observed item	**Field result reported in the study**	**Implication**
Observation period	March–July 2021	Covers pre-monsoon and monsoon operating conditions
FSOC path	5.57 km, Kohima, Nagaland	Demonstrates terrestrial optical wireless deployment in hilly terrain
FSOC/RF availability	More than 98% in every observed month	Combined bearer maintained service continuity
Weather-induced outages	Most significant during June and July	Shows the importance of environmental awareness
Rainfall threshold used	0.27 inch/h	Practical trigger used in the field analysis
Wind threshold used	40 mph	Used to classify weather-related degradation
Severe event	738-minute weather-induced outage recorded on 16 June	Illustrates duration of optical disruption

Severe-weather throughput	Fell to approximately 0.2–0.24 Gbit/s during reported periods	Shows the effect of atmospheric degradation on service
Severe-weather PLR/latency	PLR reached 100%; latency approached 100 ms in reported July conditions	Shows rapid QoS degradation under heavy weather
RF role	Traffic switched to RF during FSOC downtime	Provided continuity at reduced capacity

The field study reports that the combined FSOC/RF link maintained availability above 98% in every month of the observation period, reaching 100% in May under relatively favourable weather. Weather accounted for the major share of outage time in June and July, while power-related downtime was much smaller. The study also records a 738-minute weather-induced outage on 16 June, during which latency exceeded 90 ms and throughput fell below 0.2 Gbit/s. During the severe monsoon period, the reported maximum packet-loss rate reached 100% and latency approached 100 ms. The RF failover mechanism maintained connectivity when the FSOC path was unavailable, although at reduced capacity. [71]

5.6.8 Relevance to 6G Deployment in India

The analytical and field evidence together indicate a deployment model in which FSO is used as a high-capacity bearer and RF is retained as a complementary bearer for service continuity. For India, this model is particularly relevant to areas where fibre construction is constrained by terrain, right-of-way, rapid deployment requirements or disaster conditions. The Kohima deployment demonstrates the practical value of this approach in a mountainous region with strong monsoon variability. [71]

For 6G, the architecture can be extended from static FSO-primary/RF-fallback switching toward an intelligent multi-bearer mechanism. The decision engine can combine optical link quality, RF SIR, environmental observations, traffic demand and application-level QoS. Such an approach is consistent with the broader role of optical technologies in 6G as complementary infrastructure rather than a replacement for RF. Sections 2.6 and 5.3 already identify terrestrial FSO as a candidate for point-to-point backhaul and fronthaul where fibre is impractical, and note the complementary propagation behaviour of FSO and RF.

5.6.9 Potential 6G Deployment Scenarios

Table 5.6. Potential 6G deployment scenarios and the roles of FSO and RF.

Scenario	**Role of FSO**	**Role of RF**	**Hybrid value**
Rural and hilly backhaul	High-capacity point-to-point link	Continuity during optical impairment	Extends high-capacity connectivity without relying exclusively on new fibre [72]
Temporary/disaster connectivity	Rapidly deployable optical bearer where line of sight is available	Rapid fallback/coverage	Improves continuity during changing site conditions

Remote institutional/campus links	Primary high-throughput link	Backup path	Practical alternative to fibre trenching for selected short/medium links
RF-congested environments	High-capacity optical path	Supplementary bearer	Reduces reliance on congested RF spectrum
6G access/edge aggregation	Optical wireless aggregation	Resilient secondary bearer	Supports multi-bearer transport between access and edge sites
Integrated terrestrial/NTN connectivity	Terrestrial FSO can connect difficult sites	RF can provide complementary access	Can form part of a larger multi-domain optical/RF transport fabric

6. Optical Interconnect for AI-Native Networks

6.1 Data Centre Interconnect: the Foundation of the Digital and AI Economy

The rapid growth of cloud computing, artificial intelligence, content delivery platforms, and edge computing is already driving a fundamental transformation in network infrastructure. This is expected to increase further with AI on RAN improvements. Modern digital services are increasingly distributed across multiple edge data centres, creating the need for high-capacity, low-latency, highly reliable Data Centre Interconnect (DCI) networks.

DCI has emerged as the critical layer that enables seamless connectivity between hyperscale data centres, enterprise facilities, cloud regions, internet exchange points, and edge computing sites. As bandwidth demand continues to grow exponentially, optical networking technologies are becoming essential for delivering scalable and sustainable interconnection capabilities. India is seeing the growth of data centres across multiple locations especially near the submarine cable landing locations of Chennai and Mumbai. Additional landing stations are planned in Visakhapatnam.

The Evolution of Data Centre Interconnect

Historically, data centres were deployed as isolated facilities connected through conventional transport networks. This used to be a DWDM link with a few 100 Gbit/s connections between the main and the disaster recovery site. Today, applications operate across geographically distributed infrastructures that require continuous exchange of massive volumes of data.

Several trends are accelerating DCI requirements for higher capacity links:

- Artificial Intelligence (AI) and large-scale GPU clusters
- Multi-cloud and hybrid cloud deployments
- Content Delivery Networks (CDNs)
- Big Data analytics
- Enterprise digital transformation
- 5G and future 6G core networks
- Edge computing and distributed applications

Requirements for Modern DCI Networks

Modern DCI solutions must address several critical requirements.

1. **Massive Scalability:** Data centre traffic growth continues to outpace enterprise traffic growth. Network operators require architectures capable of scaling from hundreds of gigabits per second to multiple terabits per second without requiring major changes to the underlying fibre infrastructure. Many are built on a build-as-you-grow model, in which the DCI links have to scale without additional fibre being laid.

2. **Low Latency:** Applications such as AI training, financial transactions, cloud gaming, and distributed databases are highly sensitive to latency. DCI architectures must minimise packet processing delays and provide deterministic transport characteristics. This is especially relevant as AI models are increasingly deployed for stock and commodity trading, which also requires edge data centres near exchanges for faster access to live market information.

3. **High Availability:** Downtime can result in significant business impact. Modern DCI networks therefore incorporate redundancy, fast restoration mechanisms, and automated fault recovery to ensure service continuity. Whether five or six nines of availability is needed depends on the industries the data centres serve.

4. **Operational Simplicity:** As networks grow in scale, manual provisioning and troubleshooting become increasingly impractical. Automation and analytics are necessary to reduce operational complexity and improve service delivery times.

Optical Technologies Driving DCI

Optical networking has become the preferred transport medium for DCI due to its capacity and efficiency.

High-Speed Coherent Optical Transmission

Advances in coherent optical technology have enabled a progression from 100G wavelengths to 400G, 800G, and emerging multi-terabit optical channels. These technologies significantly increase network capacity while maximising utilisation of existing fibre assets.

Optical Transport Networks (OTN)

OTN technology provides efficient grooming and aggregation of client services onto high-capacity optical wavelengths. This improves bandwidth utilisation, simplifies network management, and enables scalable service delivery.

Reconfigurable Optical Networking

Modern optical networks increasingly use Reconfigurable Optical Add-Drop Multiplexers (ROADMs) and flexible optical switching architectures, allowing wavelengths to be dynamically routed across the network without manual intervention.

Flexible Spectrum Management

Flex-grid technologies enable optical spectrum allocation based on actual service requirements, improving spectral efficiency and accommodating higher-capacity transmission technologies.

Intelligence and Automation in DCI

As DCI environments increase in scale and complexity, automation is becoming a fundamental requirement rather than an optional capability.

Telemetry-Driven Visibility

Modern DCI platforms collect extensive operational data, including:

- Performance metrics
- Optical impairments
- Network alarms
- Configuration states
- Traffic statistics
- System logs

This information provides detailed visibility into network behaviour and operational health.

Predictive Operations

Advanced analytics and machine learning enable proactive identification of:

- Traffic growth patterns
- Potential failures
- Capacity bottlenecks
- Service degradations

This shift from reactive to predictive operations improves service reliability and reduces operational costs.

Closed-Loop Automation

Automated workflows can continuously monitor network conditions, recommend corrective actions, and in some cases implement optimisations automatically. This capability reduces mean time to repair (MTTR) and improves network efficiency.

Zero-Touch Provisioning

Automated deployment and provisioning facilitate rapid service activation while minimising configuration errors and operational effort.

6.2 Multi-Band Optical Line Systems: Scaling Fibre Capacity from C-Band to Super-C+Super-L

From per-channel gains to spectral scaling

Section 3 and Section 6.1 established two pillars of the 6G optical foundation: the transport and synchronisation the radio access network demands, and the optical interconnect that stitches together AI-native data-centre infrastructure. Both rest on the same premise — that the optical layer can keep scaling in capacity. The IMT-2030 framework and ITU-T's ION-2030 optical targets project line rates and aggregate per-fibre capacities that rise steeply through 2030 [3], as 6G pushes higher radio capacity into fronthaul, midhaul and backhaul, concentrates traffic at edge and cloud sites, and adds AI workloads that

place unprecedented demands on the links between sites. The capacity of the optical line system is therefore a precondition for 6G as well as a data-centre concern.

This section takes a different vantage point from the preceding one: where the interconnect techniques already discussed raise the capacity carried by each individual wavelength, the lever examined here is the *spectrum itself* — how much of the fibre's usable optical band is lit. The two are complementary, and both are now needed, because raising per-wavelength capacity alone has run into physics: modern coherent transponders operate close to the Shannon limit of the optical channel, so squeezing more bits onto one wavelength yields diminishing returns and, at the higher orders, shorter reach. Once that per-wavelength efficiency is largely exhausted, the way to keep growing the capacity of an installed fibre is to widen and add optical bands on the cable that is already in the ground — a spectral lever that is decisive wherever new fibre cannot be built quickly, from 6G transport to the busiest inter-site links.

The C-band and the limit of a single band

Conventional DWDM operates in the C-band (approximately 1529–1568 nm, the extended C-band), which sits at the fibre's loss minimum (~0.2 dB/km near 1550 nm) and is served by mature, low-noise Erbium-Doped Fibre Amplifiers (EDFAs) [73],[74]. A C-band system offers on the order of 4.8 THz of usable spectrum. With flexible-grid channel plans [73] and high-order coherent modulation, this translates to a few tens of terabits per second per fibre pair — indicatively ~30–50 Tbit/s over typical DCI reaches, depending on modulation format and distance. The difficulty is that a fully loaded C-band system has essentially *no spare spectrum*. Further growth then requires either lighting new fibre — capital-intensive and slow, particularly across metro rights-of-way and at coastal cable-landing hubs — or finding additional spectrum on the same fibre. The latter is the premise of multi-band operation.

Widening the band: Super-C

The least disruptive step is to widen the amplification and filtering window of the existing band. Super-C extends the usable range to approximately 1524–1572 nm — about 6.1 THz, roughly 1.27× the classic C-band, adding on the order of 1.3 THz of spectrum. It is an in-band upgrade: the same fibre and the same architecture, with extended-range amplifiers and wider filtering, delivering roughly a quarter more capacity without a second band.

Lighting the second band: C+L

The decisive step is to light the adjacent L-band (approximately 1569–1610 nm) alongside the C-band on the *same fibre pair*. Combined, C+L provides on the order of 9.6 THz — roughly double the usable spectrum and, on the same indicative basis as the C-band estimate above, ~60–100 Tbit/s per fibre pair. Because it reuses the installed plant rather than requiring new cables, C+L offers the lowest cost-per-bit path to capacity growth, an economic advantage that aligns directly with the demands of DCI. C+L line systems are commercially mature and constitute the mainstream choice for high-capacity inter-data-centre links today.

The current frontier: Super-C+Super-L

Applying the widening technique to both bands yields Super-C+Super-L — Super-C at approximately 1524–1572 nm (above) together with Super-L at approximately 1574–1626 nm — providing approximately

6.1 THz in each band for a combined ~12.2 THz per fibre pair — roughly 2.5× the original C-band. It represents the present frontier of terrestrial multi-band line systems.

The operating challenges of a C+L line system

Operating a second band is not without cost. The two bands share one strand of glass, and the physics of that shared medium couples them together. The dominant effect — and the defining operational challenge of C+L — is Stimulated Raman Scattering (SRS): as light propagates, energy transfers from shorter (C-band) to longer (L-band) wavelengths [75], [76]. Over a span the C-band loses power while the L-band gains it, producing a growing spectral tilt of several decibels; the effect scales with the total launched power and the span length. In steady state this is readily compensated: the amplifier chain applies an equal-and-opposite tilt tuned for the current load, and the spectrum arrives flat. The difficulty is that the C and L bands *cannot be operated independently*: any change in loading breaks that balance.

- Loading transients. An add, drop, resize or failure on either band instantly changes the integrated power, so the SRS transfer re-tilts at the speed of light — while the amplifiers' tilt correction, still set for the old load, catches up only over seconds. In that gap, surviving channels on *both* bands see an abrupt power step that can push traffic outside its operating window.
- Amplifier and noise effects. Cascaded EDFA gain ripples and accumulated amplified-spontaneous-emission (ASE) noise compound along the line, and dual-band mesh express paths add interdependencies between segments.

The unifying risk can be stated concisely: *a spectral hole or an abrupt change in loading* is what triggers a transient on traffic already in service.

Ensuring dependable C+L operation: a high-level view of the solution

Modern line systems render multi-band operation robust through a small set of cooperating optical power-control disciplines. None requires the operator to reason about the underlying physics; the system enforces one guiding principle automatically — keep the optical line in a stable, uniformly loaded condition, and manage any change to it in a controlled way. Two complementary strategies deliver this. The one approach among several: other line-system suppliers meet the same stability objectives by different means, and none is yet standardised (Section 8.2).

Maintaining a stable spectral load (ASE management)

Optical amplifiers respond to the total power and spectral occupancy presented to them, so a partially filled band is inherently harder to keep stable than a fully occupied one. C+L line systems therefore maintain a consistent, uniformly loaded spectral profile at all times — independent of how many revenue-bearing channels happen to be active — by occupying otherwise-unused spectrum with benign, non-traffic-bearing light (broadly, managed amplified spontaneous emission). Because the line always presents a stable, uniform load, the amplifiers hold a steady operating point and do not need to react as channels are added, removed or lost, leaving surviving traffic undisturbed. The specific means of achieving this are an implementation matter for the line system; the concept is simply that the spectrum is kept continuously and uniformly loaded.

Orchestrating change and synchronising the optical power controls

The second strategy concerns how the spectrum is allowed to change and how the automatic power-control loops behave while it does. Rather than letting loading changes and the power controls act independently — where they could work against one another and let a power excursion propagate — the line system orchestrates changes across the network elements along the path and synchronises them with the automatic power controls, so that the two act in concert. Managed together as a single strategy, this orchestration and synchronisation keeps the optical line within a stable operating regime throughout any change, so the power controls only ever experience gradual, controlled variation and the cross-band SRS coupling that C+L would otherwise amplify is never presented with an abrupt disturbance to react to. How this is carried out is specific to the line-system implementation; the concept is that spectral change and power control are managed together, not separately.

Beyond C+L: the emerging S-band frontier

The same reasoning that motivates C+L points to a further step: lighting the S-band (roughly 1460–1530 nm) below the C-band to form triple-band S+C+L operation and pushing the total lit spectrum into the ultra-wideband regime. Laboratory and field trials have already carried well over 100 Tbit/s across a single fibre pair this way, and even wider band combinations have been demonstrated [77]. The appeal is unchanged — still more capacity drawn from fibre that is already installed. In practice, however, S+C+L remains at the research and early-trial stage rather than in volume deployment, for a few reasons. The S-band has no direct equivalent of the mature, efficient EDFA that serves the C-band; it depends instead on thulium-doped fibre amplifiers or distributed Raman amplification [78], which today are markedly less power-efficient and add cost and complexity. The wider the total spectrum, the stronger the cross-band Raman power transfer becomes — with the shortest (S-band) wavelengths giving up power to the longer bands — so the tilt- and power-management challenge described earlier grows correspondingly harder and generally calls for careful launch-power shaping and Raman pumping. Component maturity across amplifiers, wavelength-selective switches and transceivers, together with overall energy consumption, remain the principal gating factors. For network planners the takeaway is that S+C+L is a credible next increment on the multi-band trajectory, but one whose economics and operational maturity are still being established.

Maturity and relevance for India

In line with this document's mature-versus-emerging discipline: C-band is ubiquitous, Super-C and C+L are commercially deployed, Super-C+Super-L is the emerging frontier now reaching scale, and S+C+L (above) stands as a future possibility once its amplification and component maturity are established. For India, the implication is direct: the metro, long-haul and inter-site optical backbone that 6G transport and AI workloads will load must grow largely on the fibre already deployed, and multi-band operation is what allows that. The strategic point, however, is that the differentiator is the operational intelligence — keeping the spectrum stably loaded and managing change in a coordinated, synchronised way — that makes multi-band capacity dependable in live networks. Building indigenous capability in these line-system control disciplines, and contributing to the relevant ITU-T and IEEE standards, is therefore as strategically important to India's optical foundation for 6G as the transmission optics themselves.

6.3 Co-packaged optics and optical I/O for AI clusters

Inside the data centre, the interconnect between accelerators and switches is moving the same way as fronthaul optics (Section 3.2): from pluggable modules at the faceplate towards optics placed next to, or in the same package as, the switch or accelerator silicon. Pluggable optics scale by adding lanes and modules, which raises faceplate area, electrical trace length and energy per bit; at the 51.2 Tbit/s and 102.4 Tbit/s switch generations the electrical link from ASIC to module becomes the limiting element. Co-packaged optics (CPO) shortens that link to millimetres, while near-package optics and linear-drive pluggable optics offer intermediate steps that keep the module serviceable. OIF's Co-Packaging Framework Implementation Agreement sets out the target applications and their electrical, optical, thermal, mechanical, reliability and management requirements, and launched follow-on projects on a 3.2T co-packaged module and an external-laser small-form-factor pluggable [22]. The Ethernet Alliance roadmap places 1.6 Tbit/s interfaces, 200 Gbit/s-per-lane signalling and linear pluggable optics on the near-term path for AI fabrics [21].

For 6G the relevance is twofold. Edge and regional sites that host RAN compute alongside AI inference will inherit data-centre interconnect technology, and the energy-per-bit case for integrated optics is strongest exactly where 6G adds AI workloads. At the same time, Section 3.2 shows that the outdoor radio site imposes thermal, power and maintainability constraints that data-centre CPO was not designed for, so adoption in the RAN will lag the data centre and needs its own qualification. Optical I/O for chip-to-chip links — silicon-photonics transceivers integrated at the package or die — is at demonstrator stage and is treated here as emerging, in line with Table 2.1.

7. Quantum-Ready Optical Infrastructure: QKD Coexistence over Deployed Fibre and Quantum-Safe Optical Links for Defence, Healthcare and Finance

The evolution towards 6G will increase dependence on high-capacity optical networks for transport, synchronisation, cloud and edge connectivity, and critical services. The same optical infrastructure can also support quantum-secure key distribution. Quantum Key Distribution (QKD) introduces a quantum channel alongside classical communication and imposes requirements on loss, noise, synchronisation, monitoring and key management that differ from conventional optical networking.

The TSDSI TR 6062 V1.0.0 proposes a protocol-agnostic, SDN-based optical architecture in which an SDN controller dynamically provisions optical paths for QKD, monitors quantum and classical channel conditions, and initiates alternate-path recovery when degradation, failure or a security-related anomaly is detected. The architecture includes QKD endpoints, optical switches/ROADMs, trusted relay nodes and a Quantum Key Management System (QKMS). [79]

For the 6G optical foundation, the relevant transition is therefore from isolated point-to-point QKD links towards programmable, monitored and interoperable quantum-ready optical networks. The focus of this section is the optical-networking role of QKD rather than a detailed description of individual QKD protocols.

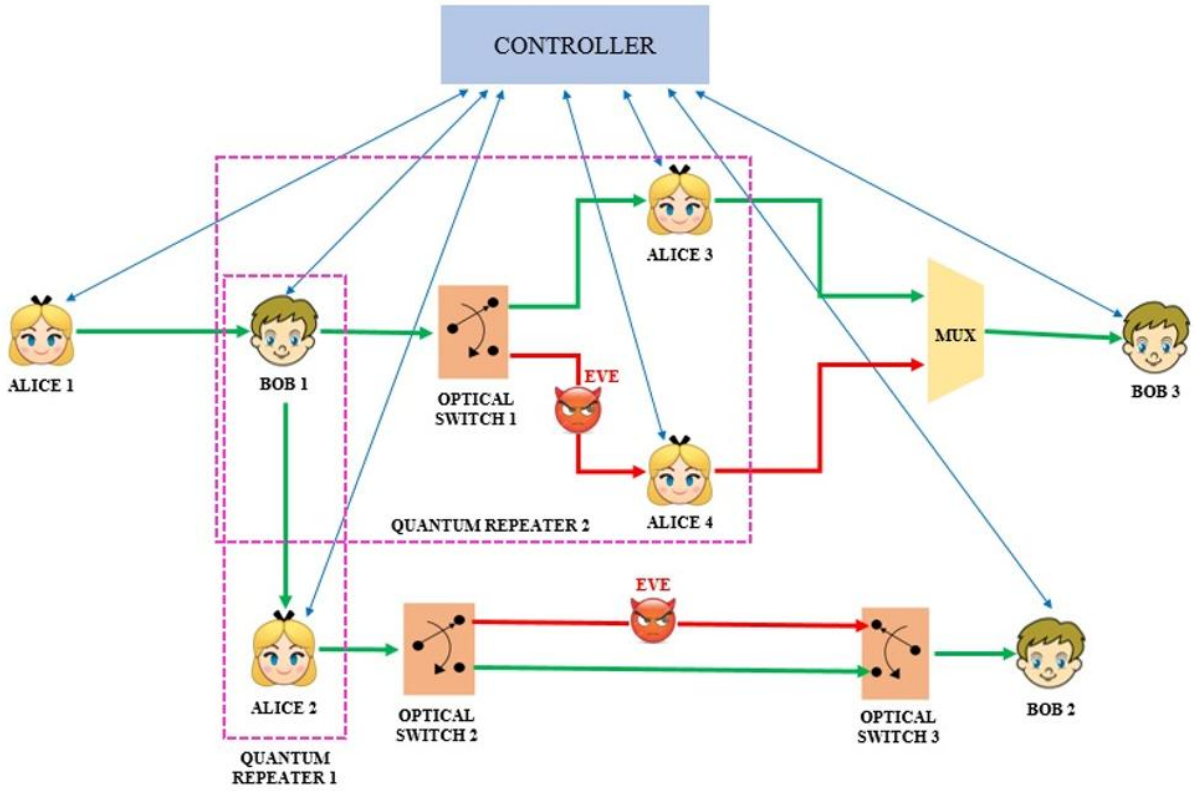

Figure 7.1. SDN-based optical network for QKD.

The architecture illustrates an SDN controller coordinating QKD endpoints, optical switching elements and alternate paths. The intermediate nodes labelled as quantum repeaters in the source report represent trusted relay nodes in the proposed architecture. The architecture is intended to support dynamic path reconfiguration while quantum and classical channels are managed in parallel. [79]

7.1 QKD over Deployed Optical Fibre

A practical quantum-ready network should make use of deployed optical fibre wherever the physical loss, channel isolation and operational conditions permit. QKD does not simply replace classical optical transport; it adds a quantum channel and associated classical processing to the existing optical environment.

The TSDSI architecture considers coexistence of quantum and classical communication over shared optical infrastructure. The quantum channel carries the quantum states required for key generation, while classical channels support synchronisation, sifting, error correction, privacy amplification and control signalling. Optical switches and ROADMs provide programmable path control, allowing the infrastructure to be reconfigured without requiring a separate physical network for every secure service. [79]

7.1.1 Shared-Fibre Quantum–Classical Infrastructure

The coexistence model can be viewed as three coordinated functions:

- Quantum channel — carries the quantum states used for QKD.
- Classical channel — supports synchronisation, sifting, error correction, privacy amplification and control.
- Optical control infrastructure — manages wavelengths, switching, routing and alternate-path provisioning.

Because quantum signals are sensitive to optical loss and noise, wavelength assignment, channel isolation, optical power management and continuous monitoring are important in shared-fibre deployments. The report therefore positions SDN as a means of coordinating quantum and classical resources rather than treating them as independent networks. [79]

7.2 SDN-Controlled Adaptive Optical Architecture for QKD

Static point-to-point QKD links have limited ability to respond automatically to changing network conditions. A link failure, excessive QBER, abnormal optical loss, synchronisation failure or suspected security event can interrupt key generation. The proposed SDN architecture separates network control from the optical/QKD data plane so that path selection and recovery can be automated.

1. Application layer — requests secure communication services and obtains keys through QKMS.
2. Control layer — maintains topology, QKD resource and link-status information and makes path decisions.
3. Device/data layer — includes Alice, Bob, QKD modules, optical switches/ROADMs, monitoring functions and trusted relay nodes.

The controller can use parameters such as QBER, secret key rate (SKR), key availability, link state and topology information to select or reconfigure a secure path. The protocol-agnostic approach described in TR 6062 is intended to avoid coupling the control architecture to a single QKD protocol or vendor. [79]

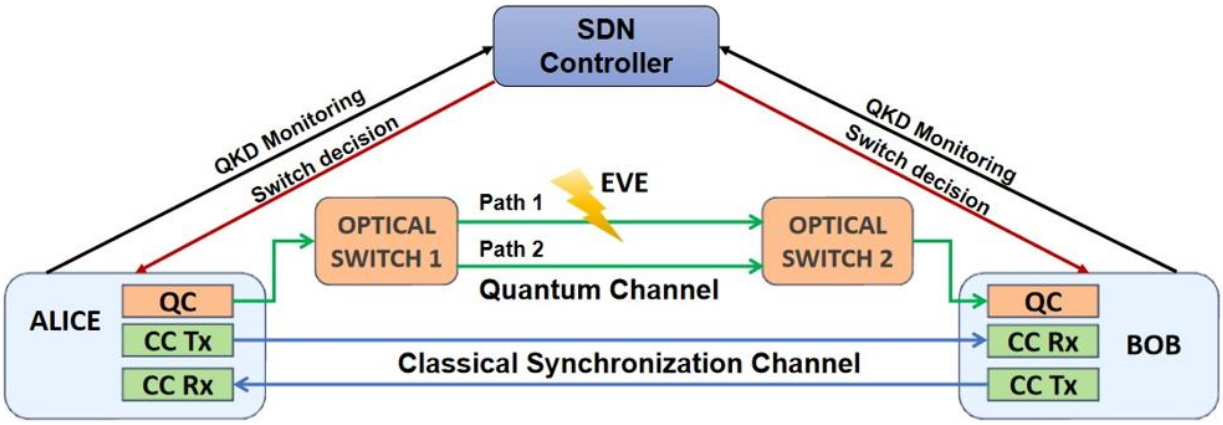

Figure 7.2. SDN-based threat detection and adaptive recovery.

The source architecture shows the controller receiving QKD monitoring information and issuing switching decisions. Path 1 and Path 2 provide alternate quantum paths, while a classical synchronisation channel supports the QKD endpoints. This provides the basis for security-aware optical path recovery. [79][80]

7.2.1 Dynamic Optical Path Provisioning

When the active QKD path becomes unsuitable, the controller can determine an alternate path and configure the relevant optical switching elements. The recovery process is intended to minimise interruption while preserving the security state of the QKD system. For multi-hop networks, trusted relay nodes can extend connectivity between endpoints that do not have a direct quantum path. [79]

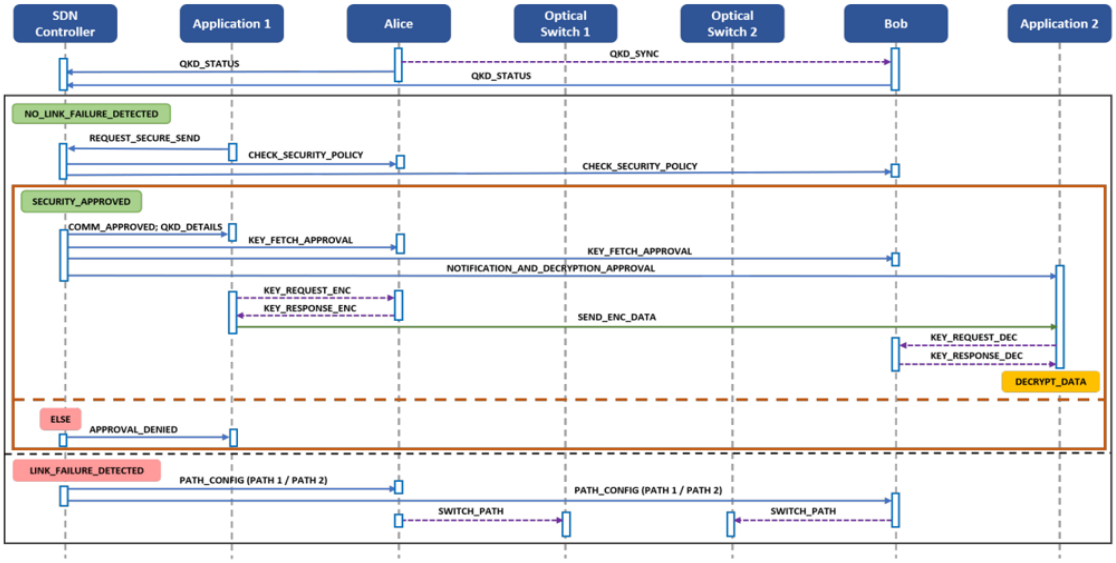

Figure 7.3. System interaction sequence for SDN-enabled QKD path provisioning

The sequence illustrates QKD status monitoring, security-policy checking, key retrieval and encrypted communication, followed by PATH_CONFIG and SWITCH_PATH actions when a link failure is detected. It is useful as the operational reference for a closed-loop 6G quantum-security workflow. [79]

7.3 Security Monitoring and Adaptive Recovery

A quantum-ready optical network needs visibility into both conventional optical performance and quantum-specific parameters. The TSDSI architecture describes continuous monitoring of QBER, optical signal loss, channel latency and related QKD indicators. Deviations from predefined conditions can trigger a security or recovery action. [79],[81]

The operational loop can be summarised as:

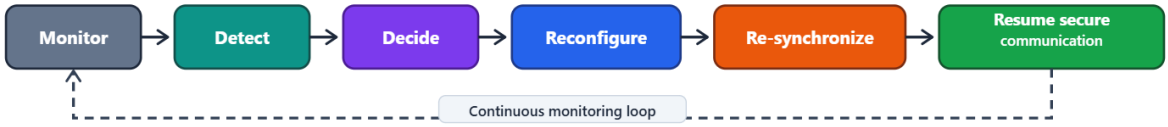

Figure 7.4. Operational monitoring and recovery loop for QKD over SDN-controlled optical paths [79].

- Continuous monitoring of quantum and classical channels.
- Detection of abnormal QBER, loss, synchronisation or link conditions.
- Controller decision based on topology, resource and security state.
- Reconfiguration of optical switches/ROADMs to an alternate path.
- Re-synchronisation and re-initialisation of QKD endpoints.
- Resumption of secure key generation after acceptable conditions are restored.

7.4 QKD, QKMS and Quantum-Safe Cryptography

QKD produces secret key material but does not by itself provide the complete end-to-end cryptographic service. The source report identifies QKMS as the bridge between QKD infrastructure and higher-layer applications such as VPNs, secure voice and encrypted data services. The QKMS stores, refreshes and distributes generated keys, while the SDN layer provides the supporting network connectivity and path resilience. [79]

The report also describes coexistence of QKD and post-quantum cryptography (PQC) during the migration to quantum-safe communications. This permits existing cryptographic mechanisms to evolve while QKD is introduced for selected high-value links and services. [79]

A practical 6G security stack can therefore be represented as:

Classical security + PQC + QKD + QKMS + Adaptive optical-network control

7.5 Applications for 6G and Critical Infrastructure

Table 7.1. Application domains for quantum-ready optical links.

Application domain	Potential role

Government and strategic communications	Quantum-secure key distribution for selected high-value links, with adaptive path provisioning and recovery.
Financial networks	Integration with secure optical data-centre and inter-site connectivity where high-value information requires additional quantum-safe keying.
Healthcare	Protection of sensitive information exchanged among geographically distributed hospitals, research institutions and data centres.
Energy and critical infrastructure	Secure communications for operational technology and critical control systems, with optical-path resilience.
6G transport and edge networks	Quantum-ready optical links between central cloud, regional edge, access and control locations.

7.6 Recommended monitoring metrics

Table 7.2. Monitoring metrics for a quantum-ready optical network.

Metric	Purpose
QBER	Quantum-channel quality and anomaly/security indication
SKR	Effective secure-key generation capability
Optical loss	Physical link condition and path suitability
Path-switching time	Speed of adaptive optical recovery
Key-pool availability	Balance between key generation and consumption
Synchronisation status	Ability of Alice and Bob to resume QKD
Controller reaction time	Control-plane responsiveness
Cross-channel interference	Impact of coexisting classical channels

7.7 Standardisation and Interoperability

Moving from experimental QKD links to operational quantum-ready optical networks requires interoperability across QKD equipment, optical networking equipment, SDN controllers and key-management systems. TR 6062 positions its architecture with respect to the ITU-T Y.3800 series [80]–[85] and discusses coordination with ITU-T and ETSI activities. [79]

1. Application layer — interfaces between applications and QKMS, key retrieval and security-service requests.
2. Control plane — SDN interfaces, QKD status reporting, path computation, resource management and multi-domain orchestration.
3. Optical/device layer — QKD/SDN integration, optical switching, wavelength management and trusted-node operation.

For B6GA, the important standardisation objective is not to prescribe a single implementation, but to establish interoperable control, management and device interfaces that permit quantum-secure services to be introduced progressively into multi-vendor optical networks.

7.8 India's Opportunity for Quantum-Ready 6G Optical Networks

India can evolve quantum-ready optical capability incrementally by combining existing fibre infrastructure, QKD testbeds, programmable optical switching and software-defined control. The implementation pathway described in TR 6062 starts from laboratory validation and progresses through multi-hop/trusted-node operation, quantum–classical coexistence, attack simulation, interoperability testing and metro/data-centre pilots [79]. This pathway is consistent with the objectives of the National Quantum Mission [86].

1. Laboratory QKD validation
2. QKD over deployed optical fibre
3. SDN-controlled QKD
4. Multi-hop/trusted-node operation
5. Quantum–classical coexistence
6. Multi-vendor interoperability
7. Metro/backbone and inter-data-centre quantum-secure services

This staged approach avoids requiring an immediate nationwide quantum network. Instead, quantum-secure capability can be introduced where security requirements, optical conditions and operational readiness justify it.

7.9 Relevance to 6G

Quantum-ready optical infrastructure can be treated as an additional security capability of the 6G optical transport layer. Its relevance follows from four complementary functions:

1. Optical transport provides the physical infrastructure over which QKD can operate.
2. SDN provides programmability for dynamic provisioning and recovery.
3. QKMS integrates generated key material with communication applications.
4. QKD and PQC can coexist as complementary mechanisms during the transition to quantum-safe communications.

The resulting architecture moves beyond static point-to-point QKD towards monitored, programmable and interoperable quantum-ready optical networking, aligned with the broader 6G objective of resilient and software-controlled infrastructure.

8. Standardisation Landscape and Gaps

The preceding sections drew on standards from six bodies working in parallel: ITU-T SG15 on the optical layer, IEEE on optical wireless and Ethernet interfaces, 3GPP on the radio access architecture that sets transport requirements, O-RAN on open fronthaul, BBF on fixed-mobile convergence, and TSDSI on India-specific study items feeding into the bodies above. Three further reference points matter without being named in that list: CCSDS for optical inter-satellite links, IEC for laser eye safety, and a fast-emerging quantum-networking track spanning ITU-T and ETSI. This section sets out what each body covers for optical-6G and closes by identifying where the coverage runs out — either because 6G work has not reached that body yet, or because two bodies' outputs do not yet meet at the interface between them.

8.1 Who covers what

- **ITU-T SG15** underpins the optical-layer standards used throughout this paper: transport network equipment and applications (G.698.4 [23], G.9804.3 [35]), PON slicing (G Suppl. 74 [41]), indoor optical wireless (G.9991 [43]), terrestrial FSO (G.641 [46]), and the full timing and synchronisation stack (G.8271 [5], G.8271.1 [26], G.8273.2 [28], G.8275.1 [27], G.8275.2 [29]). SG15's GSTR-ION-2030 report sets the optical line-rate and multi-wavelength capacity targets explicitly against the 2030 horizon, and it anchors the traffic and transport arithmetic in this paper [3]. This SG15 portfolio is mature and interoperable at the level of individual Recommendations; what it does not yet cover is multi-vendor interoperability of C+L and Super-C+Super-L operation, where the actual differentiator — coordinated ASE management and synchronised power-control orchestration across a shared C+L line — remains a matter of proprietary vendor engineering rather than a published Recommendation.
- **IEEE** covers two distinct layers. At the optical-wireless access layer, 802.11bb-2023 [7] and 802.15.13-2023 [45] standardise LiFi/OWC PHY and MAC operation for WLAN-style and industrial/mobile use respectively. At the transport layer, 802.1CM [4] sets the Class 1 fronthaul latency budget, and the 802.3 roadmap [87] sets the pluggable-optics generations (25G/50G/100G/400G) assumed for fronthaul scaling. A newer item, IEEE P1962 on broadband connectivity using solar panels as optical receivers, is still in development [88].
- **3GPP** sets the radio-network side of every optical transport requirement. TR 38.801 [14] defines the split-option taxonomy; TS 38.104 clause 6.5.3 [6] sets the time-alignment-error limits; and the F1 interface (Option 2, CU/DU) is the only split 3GPP has standardised end-to-end for 5G. For 6G, 3GPP is still working this out: split selection, synchronisation and service-interface exposure are part of Release 20 (study), with Release 21 expected to bring the first normative 6G specifications. Until that split is decided, the number that fronthaul capacity depends on remains open.
- **O-RAN** Alliance standardises the open fronthaul interface — control, user and synchronisation planes (O-RAN.WG4.CUS [19]) — the 7-2x lower-layer split with its Category A/B radio-unit distinction, and the four fronthaul synchronisation topologies (LLS-C1–C4). As with 3GPP, O-RAN's work is extending toward 6G rather than having settled 6G-specific choices: whether 7-2x, defined for 5G, carries forward into 6G at all is explicitly unresolved.
- **BBF (Broadband Forum)** contributes TR-470 [40], the wireless-wireline convergence architecture — the one standard here that formally bridges fixed and mobile access. TR-470 is written for 5G; PON slicing (ITU-T Suppl. 74 [41]) is the mechanism by which such convergence would extend to 6G-era service differentiation, but the two are not yet formally linked in a single standard.
- **TSDSI**, India's telecom standards development society, is the vehicle through which most Indian-originated telecom research reaches the international bodies above, working alongside the

Telecommunication Engineering Centre (TEC), which coordinates India's National Working Groups against each ITU-T Study Group (NWG-15 against SG15, and so on) and has itself landed contributions directly as ITU-T Recommendations — the Indian proposal for a fibre optic network terminal box, contributed by the Ministry of Communications and Sterlite Technologies, was approved as ITU-T L.209 in February 2022 [89]. TSDSI's own footprint at ITU-T SG15 is long-standing: TSDSI founded an Optical Access and Transport study group that developed the CPRI Fronthaul standard later carried into 3GPP and O-RAN work [90], and Indian delegates from member companies have contributed directly to core SG15 Recommendations including G.8032 (Ethernet Ring Protection Switching) and the MPLS-TP standards [90]. TSDSI's more recent optical-specific study items are SI-120 on solar-panel-based optical wireless communication, whose Technical Report was accepted and published in November 2025 [12]; SI-128 on ISAC channel modelling in the FR3/THz band [91]; NI-424 on LiFi/Wi-Fi internetworking [92]; and, most recently, TR 6062 V1.0.0 on SDN-based QKD coexistence over deployed fibre, published June 2026 [79]. TSDSI's role is to formalise this India-originated work — testbed results, field trials and study items alike — into a form that can subsequently be proposed at ITU-T, ITU-R WP5D or IEEE, as the SI-120 contribution to IEEE P1962 already illustrates [88], [12].

- **CCSDS (Consultative Committee for Space Data Systems)** is the relevant body for optical NTN links. It coordinates ISRO, NASA, ESA and other space agencies, and has standardised the datalink and physical layers for GEO-LEO and GEO-GEO optical links (CCSDS 141.10-O-1 [49]), building on ESA EDRS operational experience. LEO-LEO inter-satellite links — the architecture Starlink V3 has deployed at scale — remain outside CCSDS's standardised scope.
- Quantum-network standardisation is the newest addition to this landscape. TSDSI TR 6062 positions its SDN-based QKD architecture against the ITU-T Y.3800 series (Y.3800 [80], Y.3801 [81], Y.3802 [82], Y.3810 [83]) and ETSI's GS QKD component and API specifications (GS QKD 011 [84], GS QKD 012 [85]). This is presently a technical-report-level contribution rather than an approved multi-body standard. The near-term standardisation objective is not a single implementation, but interoperable control, management and device interfaces across QKD equipment, optical networking equipment, SDN controllers and key-management systems from different vendors.
- **IEC 60825-1** [60], though a product-safety standard rather than a telecommunication one, is a binding constraint on every optical-wireless link discussed in this paper. It is IEC 60825-1's Maximum Permissible Exposure limits, not any telecom standard, that fix the achievable transmit power — and therefore a substantial part of the achievable link budget — for LiFi, FSO and satellite optical terminals alike.

Table 8.1. Standards and technical-report coverage of the optical-6G stack, by body.

Domain	Body / document	Status for 6G
Optical transport, PON, sync	ITU-T SG15 (G.698.4 [23], G.9804.3 [35], G.8271-series [46], [80]–[83])	Mature for current generations; ION-2030 [3] sets 2030-horizon targets, not 6G-specific interfaces
Multi-band line systems (C+L, Super-C+L)	Vendor implementation; no ITU-T interoperability standard	Commercially deployed; multi-vendor power-control/orchestration interoperability not standardised
Coherent pluggables for aggregation	OIF 400ZR / 800ZR [25]	Written for DCI reach (80–120 km); not written for metro/regional aggregation reach

Split options and RAN architecture	3GPP TR 38.801 [14], Release 20/21	5G splits (Option 2/F1) standardised; 6G split selection still in study
Open fronthaul	O-RAN WG4 (7-2x, LLS-C1–C4) [19]	Standardised for 5G; extension to 6G under study, not finalised
Fixed-mobile convergence	BBF TR-470 [40]	Written for 5G; PON-slicing link to 6G service differentiation not yet formalised
Indoor/industrial OWC	IEEE 802.11bb [7], 802.15.13 [45]; ITU-T G.9991 [43]	Standardised, commercially available
Terrestrial FSO	ITU-T G.641 [46]	Standardised for SFP+-compatible short-reach mobile backhaul; no standard for weather-adaptive FSO/RF bearer switching (Section 5.6)
Laser eye safety	IEC 60825-1 [60]	Mature, binding on transmit-power budgets for all optical-wireless links
Solar-panel OWC	IEEE P1962 (draft) [88]; TSDSI SI-120 [12]	Pre-standardisation; TR published, IEEE work in progress
Optical ISAC	—	No dedicated standards track; TSDSI SI-128 [91] covers FR3/THz, not the optical band
Optical ISL / NTN	CCSDS 141.10-O-1 [49]	Standardised for GEO relay; LEO-LEO ISLs remains proprietary
QKD-integrated optical networks	TSDSI TR 6062 [79]; ITU-T Y.3800 series [80]–[83]; ETSI GS QKD [84], [85]	Technical-report stage; multi-vendor interoperability of SDN/QKD/optical control interfaces not yet standardised
Legal time source	Legal Metrology (IST) Rules, 2026 [13]	India-specific regulatory instrument, not an SDO output; sets traceability and auditability, not phase accuracy

8.2 Gaps

Seven gaps recur across the sections above.

1. The 6G fronthaul split is undecided. Section 3.1's bit-rate projections — from roughly 117 Gbit/s to several Tbit/s per sector, depending on array size and split — all depend on whether 3GPP and O-RAN retain 7-2x or move to a different split for 6G. Until Release 21 settles this, transport dimensioning for 6G fronthaul stays provisional, and the choice between pluggable and co-packaged optical interfaces (Section 3.2) cannot be finalised either.
2. Metro-reach coherent optics have no dedicated implementation agreement. OIF's 400ZR and 800ZR [25] are written for data-centre interconnect reach (Sections 3.3 and 6.1). The midhaul and backhaul aggregation growth Section 3.3 projects — multi-hundred-gigabit to multi-terabit aggregation nodes — will need coherent optics engineered and standardised for metro and regional reach, not simply DCI-reach modules deployed further than they were specified for.
3. LEO-LEO inter-satellite links remain outside CCSDS scope. Section 5.4 notes that CCSDS 141.10-O-1 [49] standardises GEO relay and GEO-GEO links, building on ESA's EDRS experience, but that

LEO-LEO ISLs — the architecture Starlink V3 has now deployed at scale — are proprietary to individual satellite operators. For 6G NTN designs that assume interoperable, multi-operator satellite mesh backhaul, this is an open standardisation question rather than a solved one.

4. Optical ISAC has no standards home yet. Section 5.5 notes that RF, mmWave and THz ISAC sit within the IMT-2030 usage-scenario framework, with corresponding 3GPP and ITU-R study activity; optical ISAC — VLC/FSO-based sensing, structured-beam sensing — has no equivalent track. TSDSI's SI-128 [91] addresses ISAC channel modelling in FR3/THz but not the optical band specifically, leaving the O-ISAC work in Section 5.5 without a clear path to standardisation.
5. Hybrid FSO/RF link selection has no interoperability standard. Section 5.6 presents both an analytical outage model and field evidence from a 5.57-km ERNET India deployment in Kohima showing that a weather-aware FSO/RF switching architecture, backed by environmental telemetry, can hold availability above 98% through a monsoon season. What Section 5.6 also makes clear is that this switching logic — threshold-based today, and proposed as a multi-parameter policy for 6G — runs on vendor-specific controller and telemetry interfaces. Unlike LiFi (802.11bb [7], 802.15.13 [45]) or FSO point-to-point links (G.641 [46]), there is no standard defining a common telemetry or controller interface for hybrid FSO/RF bearer selection, which would be needed before such systems could interoperate across vendors or be integrated into a common SDN/automation platform, as the recommendations in Section 10.3 call for.
6. Multi-band optical line systems lack a multi-vendor interoperability standard. Section 6.2 describes C+L and Super-C+Super-L operation as commercially mature but dependent on proprietary power-control and orchestration mechanisms to stay stable under loading transients. No ITU-T Recommendation yet standardises the ASE-management and change-orchestration behaviour Section 6.2 identifies as the actual differentiator between line systems — a gap in the SG15 portfolio, and one where Indian participation would build capability rather than merely adopt a finished standard.
7. QKD-integrated optical network interfaces are still at the technical-report stage. Section 7 describes an SDN-based architecture (TSDSI TR 6062 [79]) that coordinates QKD endpoints, optical switches/ROADMs, trusted relay nodes and a key-management system, and positions itself against the ITU-T Y.3800 series [80]–[83] and ETSI GS QKD specifications [84], [85]. This is a coherent architectural proposal, but it is not yet a ratified interoperability standard. Section 7.7 gives priority to interoperable control, management and device interfaces across a multi-vendor QKD/optical ecosystem rather than to a single implementation. That priority is itself evidence that this standardisation work has not yet happened at ITU-T or ETSI.

Taken together, these gaps describe a landscape where individual technology layers — fibre access, transport, timing, optical wireless, DCI, quantum-ready optics — are each reasonably well standardised on their own terms, but the connective interfaces are where the open work remains: between 5G-era standards and 6G requirements (split selection, metro-reach coherent optics), between adjacent optical domains that have grown up separately (multi-band interoperability, optical ISAC, hybrid FSO/RF telemetry), and between optical networking and an entirely new domain now entering the optical layer (QKD/SDN interoperability). Section 10 returns to this in setting out where Indian standardisation effort, through TSDSI and direct participation in ITU-T, IEEE and 3GPP, would be best placed.

9. India Context: Testbeds, Measured Outcomes, Standards, Intellectual Property and Academia–Industry Translation

India's 6G capability can be strengthened by linking indigenous research, experimental testbeds, standardisation, intellectual property, skills and industry translation into one innovation pipeline. Optical wireless research at IIIT-Delhi provides a concrete example of this approach: hybrid LiFi–Wi-Fi studies address capacity, mobility, control information and reliability [56]–[59], while solar-panel optical communication extends the concept toward sustainable and infrastructure-constrained connectivity [98]–[101]. The evidence is particularly relevant because the work spans algorithms, analogue electronics, optical components, real communication equipment and application-specific demonstrations.

9.1 Testbed facilities

India's optical testbed base has three layers: the Advanced Optical Communication (AOC) Testbed funded by the Department of Telecommunications under the Telecom Technology Development Fund and its partner laboratories, institutional facilities that pre-date it, and field deployments run by ERNET India. The AOC Testbed was sanctioned in July 2023. Its consortium spans IIT Madras, IIT Delhi, IIIT-Delhi, ERNET India and industry partners including Sterlite Technologies, Tejas Networks, Signalchip, Signaltron, SASMOS, SFO Technologies, Nav Wireless and Quanfluence [9], [94].

9.2 Measured outcomes and translation

The hybrid LiFi–Wi-Fi studies are described in Section 5.2 and Table 5.2. They are system-level simulation and analytical studies built on a common $5 \times 5 \times 3$ m³ indoor model with four LiFi APs and one Wi-Fi AP, and they complement the hardware testbed results below [56]–[59].

A parallel indigenous testbed pathway has been developed around commercially available solar modules as optical receivers. The broadband solar-module platform uses a bandwidth-enhancement circuit (BEC), 16-QAM OFDM, white LEDs equipped with TIR lenses, and a polycrystalline Si solar module. In the reported experimental configuration, the setup achieved 18.85 Mbit/s over 330 cm, with a measured 3-dB bandwidth of 3.27 MHz [98]. An earlier IR-LED platform used four IR LEDs with TIR lenses, a solar-panel receiver and a BEC; experiments were conducted at 2 m under 350-lux ambient lighting, with 100 mW analogue-circuit power consumption and 8 W LED-panel power consumption, achieving 10.7 Mbit/s at 1 m [99]. These are direct hardware testbed results rather than purely simulated claims: the papers describe the AWG, LED driver, TIR optics, receiver circuitry, DSO/USRP-based processing and measured waveforms.

The application scope has also been extended beyond a fixed indoor link. For vehicular platooning, a solar-panel receiver with an analogue bandwidth-enhancement circuit was experimentally evaluated at a 2 m inter-vehicle distance. The study reports maintained communication under approximately ±50° receiver misalignment and connectivity when 90% of the solar-panel area was blocked; near-IR LEDs were used to reduce glare and outdoor attenuation effects [100]. A separate mirror-assisted NLOS prototype uses a 650-nm laser, mirror-reflected optical path, solar-panel receiver, high-pass filtering and audio recovery, demonstrating communication when the direct optical path is obstructed [101]. Together with ongoing OIRS/MIRS research, these demonstrations show a progression from point-to-point optical links toward blockage-resilient, mobility-aware and reconfigurable optical infrastructure.

IIT Delhi's AOC Testbed work (Sections 5.1 and 5.3) adds field and laboratory results in terrestrial FSO and LiFi [10]. On FSO, an in-house prototype has been operated over a 2.5 km link on the IIT Delhi campus in varied weather, including rain and winter fog. This prototype does not yet include the turbulence-mitigation and tracking features described next, which are to be integrated in forthcoming field tests. The target specification for the complete system is 10 Gbit/s over 20 km in clear weather, with reliability above 99%.

Turbulence-induced scintillation can call for up to 30 dB of additional power margin at a bit error rate of 10^{-3}, and two techniques are used to reduce that penalty. Beam engineering propagates the $\ell = 0$ and $\ell = 1$ orbital-angular-momentum states collinearly, so that their complementary diffraction patterns add to a more concentrated central spot after turbulence. In simulation it lowers the SNR needed for a target outage probability by 10–20 dB, depending on turbulence strength; at $C_n^2 = 10^{-15}$ $m^{-2/3}$ and an outage probability of 10^{-3}, the engineered beam needs about 10 dB against 20 dB for a Gaussian beam. Laboratory experiments have confirmed the benefit [62]. Channel-assisted coding (CAC) addresses the slow-fading nature of the FSO channel: with a coherence time of 10 ms to several seconds, a whole code block can fall within one fade. CAC matches the LDPC degree distribution to the channel parameters in combination with spatial multiplexing, and simulations under strong turbulence show gains of up to 20 dB over conventional LDPC coding [61]; an FPGA implementation is under way. For link set-up, coarse alignment is automated using a GNSS-aided attitude and heading reference system (AHRS), with a fine-tracking stage for stability [64]; the target is link set-up in under 30 minutes.

On LiFi, the IIT Delhi testbed uses white LEDs, so that communication shares the illumination source. The transmitter and receiver serve a 1 m² cell at 3 m with a downstream rate of 100 Mbit/s, support time-division multiplexing of users on one transmitter, and keep a mobile receiver connected as it moves within the cell; an in-house receiver lens widens the mobility region [53]. The testbed has been demonstrated at IMC 2019, IEEE ANTS 2020 and IMC 2022. Patents cover the LiFi receiver front-end, system and multiplexing [53]–[55], and the FSO coding, beam-engineering, system and tracking designs [61]–[64].

Table 9.1. Indian testbeds and capabilities in optical wireless.

Indian testbed / capability	Implementation and measured evidence	6G relevance
Hybrid LiFi–Wi-Fi	Simulation and analytical studies; 4 LiFi + 1 Wi-Fi AP in a 5 × 5 × 3 m³ room; LA, mobility and CSI sharing (Section 5.2) [56]–[59].	Heterogeneous access, mobility and reliability.
Solar-panel OWC	BEC + poly-Si solar module + TIR optics; 16-QAM OFDM; 18.85 Mbit/s at 330 cm and 3.27 MHz BW [98].	Sustainable dual-use communication infrastructure.
Outdoor / vehicular OWC	IR-LED/TIR testbed; 2 m link; 350 lux; 10.7 Mbit/s at 1 m; ±50° misalignment and 90% blockage evaluated [99], [100].	ITS, roadside and infrastructure-constrained links.
NLOS / optical surfaces	650-nm laser + mirror-reflected path + solar receiver; successful audio recovery over NLOS [101]; extends toward OIRS/MIRS.	Blockage mitigation and reconfigurable optical paths.
Terrestrial FSO (IIT Delhi)	In-house prototype; 2.5 km campus link operated in rain and winter fog; beam engineering (10–20 dB simulated SNR reduction, laboratory-validated) and CAC (up to 20 dB simulated gain) being integrated; target 10 Gbit/s over 20 km [61]–[64].	Rapidly deployable backhaul where fibre is impractical.
LiFi (IIT Delhi)	White-LED transmitter and receiver; 100 Mbit/s over 3 m to a 1 m² cell; TDM multi-user access; receiver mobility within the cell [53]–[55].	Dense indoor and RF-sensitive access.

The next step for India is to connect such testbeds to standardisation and technology translation. Research contributions have supported IEEE P1962 on broadband connectivity using solar panels as optical communication receivers and TSDSI SI-120 on Solar Panel Based Optical Wireless Communication, whose

Technical Report was accepted and published in November 2025 [88], [12]. Additional TSDSI contributions address ISAC channel modelling in FR3/THz (SI-128) and Li-Fi/Wi-Fi internetworking (NI-424) [91], [92]. The ecosystem is also generating protected technology through patents on LiFi bandwidth enhancement, LiFi-assisted CSI sharing and LED power allocation [102]–[104]. This combination of measurable testbed performance, standards participation, IP creation, multidisciplinary skill development and academia–industry interaction provides a practical model for moving Indian 6G research from laboratory validation toward interoperable and field-oriented optical systems.

10. Recommendations and Way Forward for India

The recommendations below draw together the findings of Sections 3 to 9. They are grouped under the headings agreed in the terms of reference — R&D priorities, testbeds and field data, standardisation, indigenous manufacturing, deployment models and ecosystem development — and each item names the section that supports it.

10.1 R&D priorities

- Fronthaul for 6G arrays: model 7-2x and alternative splits against Indian spectrum and array assumptions, including compression, so that transport dimensioning is ready when 3GPP settles the split (Sections 3.1 and 8.2).

- Optical interfaces within the radio-site envelope: evaluate near-package and co-packaged optics against outdoor power, thermal and maintainability constraints before assuming that datacom roadmaps apply (Section 3.2).

- Slice-aware PON control: joint bandwidth and wavelength allocation, PON–RAN resource coordination and open-access sharing for converged access (Sections 4.2–4.5).

- Weather- and interference-aware hybrid FSO/RF link selection, and optical ISAC on structured optical beams (Sections 5.5 and 5.6).

- Multi-band line-system control: ASE management and change orchestration for C+L and Super-C+Super-L operation (Section 6.2).

- SDN-controlled QKD over shared fibre, QKMS integration and QKD–PQC coexistence (Section 7).

10.2 Testbeds and field data

- Extend the AOC Testbed and institutional testbeds from link demonstrations to end-to-end validation: fronthaul over WDM and PON, timing chains from an IST-traceable PRTC to the radio unit, and hybrid LiFi–Wi-Fi access (Sections 3, 4 and 5).

- Build region-specific optical availability datasets for FSO — winter fog in northern India, monsoon rain in the north-east and coastal regions — before FSO is planned for fronthaul or backhaul (Sections 5.3 and 5.6).

- Progress quantum-ready testing through the staged pathway in Section 7.8: deployed fibre, SDN control, trusted nodes, coexistence, interoperability and metro pilots.

- Report results in a form that standards bodies can use — measured link budgets, timing error, availability and interoperability — not only peak rates (Section 9).

10.3 Standardisation

- Work through TSDSI, and through direct participation in ITU-T SG15, IEEE and 3GPP, on the seven gaps in Section 8.2, giving priority to the 6G split and fronthaul dimensioning, metro-reach coherent optics, and interoperable control interfaces for multi-band line systems and QKD networks.

- Bring hybrid FSO/RF telemetry and controller interfaces, and optical ISAC, to TSDSI as study items so that Indian field results define the initial scope (Sections 5.5 and 5.6).

- Carry SI-120 and IEEE P1962 through to publication and use the same route for NI-424 and TR 6062 (Sections 8.1 and 9).

10.4 Indigenous manufacturing

- Prioritise the components and subsystems where this paper identifies control and integration as the differentiator: fronthaul optics and gateways, PTP-aware transport with IST-traceable PRTCs, multi-band line-system control, FSO transceivers with pointing, acquisition and tracking, and QKD/optical switching integration (Sections 3, 5.3, 6.2 and 7).

- Align qualification with the standards named in Section 8 — the ITU-T G-series, IEEE 802.3, O-RAN WG4 and IEC 60825-1 — so that indigenous products are interoperable at first release.

10.5 Deployment models

- Set a restoration-time target, and require ring protection and route diversity, for BharatNet and any fibre that will serve mobile sites; a 17-day restore time cannot support fronthaul or nanosecond timing (Section 3.5).

- Align operator primary reference time clocks with the Legal Metrology (IST) Rules — IST traceability through NavIC or another authorised source, with compliant holdover — ahead of February 2027 (Section 3.4).

- Plan converged fibre access so that one PON carries residential, enterprise and mobile transport traffic with slice-level isolation (Section 4).

- Use hybrid FSO/RF and, where justified, optical NTN links as resilience bearers in hilly, remote and disaster-prone areas rather than as substitutes for fibre (Sections 5.4 and 5.6).

- Grow backbone and DCI capacity on installed fibre through multi-band operation before laying new cable (Section 6).

10.6 Ecosystem development

- Fund academia–industry translation to show the pipeline from laboratory result to patent, study item and technology transfer (Section 9).

- Develop skills in optical transport, timing and photonics alongside radio, since the constraints identified in this paper fall on transport engineers as much as on RAN designers.

- Coordinate B6GA working groups with the National Quantum Mission and the National Broadband Mission so that quantum-ready and fibreisation programmes share targets and timelines (Sections 3.5 and 7).

10.7 Priority actions for the next twelve months

Of the recommendations above, four can start now and do not depend on 3GPP decisions:

- Adopt a restoration-time target and a route-diversity requirement for fibre that serves mobile sites, starting with the Amended BharatNet Programme (Section 3.5).

- Publish a B6GA position on IST-traceable, NavIC-capable timing for operators ahead of the February 2027 commencement of the Legal Metrology (IST) Rules (Section 3.4).

- Open the AOC Testbed facilities to enable an end-to-end fronthaul and timing validation programme with operators and vendors (Sections 3 and 9.1).

- Launch TSDSI study items on hybrid FSO/RF telemetry interfaces and on optical ISAC to enable the role of optical technologies in 6G.

Conclusion

Optical technologies are foundational to 6G because they provide the infrastructure required to scale, transport, localise, sense, synchronise and sustain next-generation connectivity. The evidence already exists across several layers: fibre accounts for an increasing share of fixed broadband; global fixed networks carry several times more Internet traffic than mobile networks; IEEE has standardised light communications up to 9.6 Gbit/s; and operational space systems have demonstrated multi-gigabit optical links over tens of thousands of kilometres [7], [15]–[18].

The strategic opportunity for 6G is therefore to build a converged RF–optical infrastructure in which each technology is used according to its physical and economic advantages.

Fibre provides the scalable transport fabric; LiFi and OWC provide complementary access; FSO extends connectivity where fibre or RF is constrained; optical technologies support sensing, positioning and timing; and solar-enabled optical communication offers a pathway toward sustainable connectivity in energy-constrained environments.

Sections 3 to 7 trace that infrastructure from the radio site inward: fronthaul whose bit rate is set by the functional split and whose reach is set by a 100 μs budget; timing that Indian networks must, from February 2027, take from IST-traceable sources; a PON layer that is becoming a programmable, sliced access fabric; optical wireless that is standardised indoors, field-proven for hybrid FSO/RF backhaul in monsoon conditions and deployed at scale in orbit; multi-band line systems that keep capacity growing on installed fibre; and an SDN-controlled path to quantum-secure links over that same fibre.

For India the sequence is clear. Most of the fibre is in the ground, the testbeds in Section 9 are producing measured results, and the legal timing framework arrives in February 2027. What remains is connective work rather than new technology: deciding the 6G split, standardising the interfaces where adjacent optical domains meet, restoring BharatNet fibre in hours rather than weeks, and carrying Indian testbed results into ITU-T SG15, IEEE and 3GPP through TSDSI. Section 10 sets out the recommendations, and Section 10.7 the four actions to start first.

The conclusion of this paper is therefore not that optical is one 6G technology among many, but that it is the layer on which the others depend. India's position in 6G will be decided as much by fibre reach, timing and control software as by the radio interface, and the decisions that set that position fall due before the first 6G specification is published.

Annex A. Analytical Model for an Interference-Limited Hybrid FSO/RF Link

This annex sets out the signal model and the expressions behind Sections 5.6.3 and 5.6.4, following the analysis in [70].

A.1 FSO received signal and instantaneous SNR

For the FSO path, the received baseband symbol can be represented as

$$y_{\mathrm{FSO}} = P_{\mathrm{FSO}}\xi I_{\mathrm{FSO}} + n_{\mathrm{FSO}}$$

where P_FSO is the transmitted optical power, ξ is the detector responsivity, n_FSO represents additive noise, and I_FSO is the composite optical channel irradiance. The irradiance is the product of the atmospheric-turbulence (I_a), pointing-error (I_p) and path-loss (I_l) terms:

$$I_{\mathrm{FSO}} = I_a I_p I_l$$

With heterodyne detection, the instantaneous FSO SNR is

$$\gamma_{\mathrm{FSO}} = \frac{P_{\mathrm{FSO}}\xi I_{\mathrm{FSO}}}{\sigma^2_{\mathrm{FSO}}}$$

where σ²_FSO is the noise variance. The source study models atmospheric turbulence using a Gamma–Gamma distribution and includes pointing error through a dimensionless coefficient ζ. The average electrical SNR is expressed as

$$\bar{\gamma}_{\mathrm{FSO}} = \frac{\delta A_0 I_l P_{\mathrm{FSO}}\xi}{\sigma^2_{\mathrm{FSO}}}$$

where A_0 is the power fraction collected by the receiver aperture and δ is the pointing-error term. The pointing-error coefficient is related to the equivalent beam waist and the jitter standard deviation through $\zeta = \frac{w_{L_{\mathrm{eq}}}}{2\sigma_s}$, as used in the source analysis [70].

A.2 RF link with co-channel interference

For the RF backup path, the received complex baseband signal is represented by a desired RF signal, multiple interfering signals and receiver noise:

$$y_{\mathrm{RF}} = \sqrt{P_{\mathrm{RF}}}h_{\mathrm{RF}}s + \sum_{i=1}^{L}\sqrt{P_i}h_i s_i + n_{\mathrm{RF}}$$

where s and s_i are the desired and interfering symbols, h_RF and h_i the corresponding channel coefficients, and P_RF and P_i the corresponding transmit powers. Because the link is interference-limited, the instantaneous RF quality metric is the signal-to-interference ratio (SIR):

$$\gamma_{\mathrm{RF}} = \frac{P_{\mathrm{RF}}|h_{\mathrm{RF}}|^2}{\sum_{i=1}^{L} P_i|h_i|^2}$$

The desired RF signal is modelled using a κ–μ distribution. The analytical study considers L mutually independent interferers and derives the resulting SIR distribution [70].

A.3 Threshold-based link selection

The basic switching rule in [70] is

$$\gamma = \begin{cases} \gamma_{\mathrm{FSO}}, & \text{if } \gamma_{\mathrm{FSO}} > \Gamma_{\mathrm{FSO}} \\ \gamma_{\mathrm{RF}}, & \text{if } \gamma_{\mathrm{FSO}} \le \Gamma_{\mathrm{FSO}} \end{cases}$$

A.4 Outage probability and average symbol error rate

Under the independent-link assumption, the hybrid outage probability of Section 5.6.4 can be written in terms of the cumulative distribution functions F of the RF SIR and the FSO SNR:

$$P_{\mathrm{out}}^{\mathrm{hyb}} = \mathrm{P}(\gamma_{\mathrm{RF}} < \Gamma_{\mathrm{RF}})\mathrm{P}(\gamma_{\mathrm{FSO}} < \Gamma_{\mathrm{FSO}}) = F_{\gamma_{\mathrm{RF}}}(\Gamma_{\mathrm{RF}})F_{\gamma_{\mathrm{FSO}}}(\Gamma_{\mathrm{FSO}})$$

The average symbol error rate is obtained by integrating the conditional error probability over the FSO and RF channel distributions. For M-PSK, the conditional error expression used in the analysis is

$$\mathrm{P}(e|\gamma) = (A/2)\mathrm{erfc}\left(\sqrt{B\gamma}\right)$$

where A and B depend on the modulation order [70].

Contributors

Chair and editor: Dr. Sonali Garg, VC-WG Technology, HFCL Limited

Below are the list of authors for the paper

Organization	Co-author names	Primary contribution
HFCL Limited	Sonali Garg	Sections 1, 2, 6, 9 and 10; overall editing
IIT Delhi	Prof. Abhishek Dixit	Sections 4, 5, 8, 9 and 10
IIIT-Delhi	Prof. Vivek Bohara and Rahul	Sections 5 and 9, 10
Ericsson	Fabio Cavaliere	Sections 2 and 3
ERNET India	S. Kirubakaran	Sections 5 and 7
Tech Mahindra	Rajat Agarwal	Section 3
Advaya Networks	Aditya Chaudhary	Initial draft of Section 3
Tejas Networks	Jishnu Aravindkashn	Section 6 a
Nokia	Nikhil Satyarthi, Baranidhar Ramanathan	Section 6 b

Acknowledgements: We thank Dr. Sendil Devar, Mr. Aditya Chaudhary and Prof. Abhishek Dixit for their reviews and suggestions during the review process.

References

[1] ITU-R, Recommendation ITU-R M.2160-0, Framework and overall objectives of the future development of IMT for 2030 and beyond, Nov. 2023.
[2] ITU, "IMT-2030: Technical requirements for the 6G future," 18 Mar. 2026. https://www.itu.int/hub/2026/03/imt-2030-technical-requirements-for-the-6g-future/ (draft new ITU-R Report, adopted by WP 5D February 2026; submitted to ITU-R Study Group 5 for approval, December 2026).
[3] ITU-T, GSTR-ION-2030, Technical Report on International Optical Networks towards 2030 and beyond, 2025.
[4] IEEE Std 802.1CM-2018, Time-Sensitive Networking for Fronthaul, Class 1 latency requirements.
[5] Recommendation ITU-T G.8271/Y.1366, Time and phase synchronization aspects of telecommunication networks. https://www.itu.int/rec/T-REC-G.8271
[6] 3GPP TS 38.104 V20.0.0, NR; Base Station (BS) radio transmission and reception, clause 6.5.3, Time alignment error.
[7] IEEE Std 802.11bb-2023, IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN MAC and PHY Specifications—Amendment 6: Light Communications, 2023.
[8] Department of Telecommunications, National Broadband Mission booklet. https://dot.gov.in/sites/default/files/National%20Broadband%20Mission%20-%20Booklet_0.pdf
[9] Advanced Optical Communication (AOC) Testbed, Department of Telecommunications, Government of India. https://www.aoctestbed.in/
[10] AOC Testbed, Facilities at IIT Delhi, Department of Telecommunications, Government of India. https://www.aoctestbed.in/facilities-at-iitdelhi-aoc-testbed
[11] AOC Testbed, Patents Filed and Standardizations. https://www.aoctestbed.in/patents-filed-and-standardizations
[12] TSDSI, Solar Panel Based Optical Wireless Communication, Study Item SI-120; Technical Report accepted and published, Nov. 2025.
[13] Legal Metrology (Indian Standard Time) Rules, 2026, G.S.R. 761(E), Gazette of India, Extraordinary, Part II Section 3(i), No. 695, 27 Aug. 2026.
[14] 3GPP TR 38.801, Study on new radio access technology: Radio access architecture and interfaces, clause 11.
[15] ITU, Facts and Figures / Internet Traffic, 2025.
[16] OECD, "Fibre and 5G drive OECD digital transformation as broadband markets mature," Oct. 2025.
[17] European Space Agency, "First SpaceDataHighway laser relay in orbit," 2016.
[18] European Space Agency, "EDRS space network ready to go ahead," 2012.
[19] O-RAN Alliance, O-RAN.WG4.CUS, Control, User and Synchronization Plane Specification.
[20] 3GPP TR 38.816, Study on Central Unit (CU) – Distributed Unit (DU) lower layer split for NR, Annex A, Fronthaul bandwidth.
[21] Ethernet Alliance, 2026 Ethernet Roadmap, Dec. 2025. https://ethernetalliance.org/
[22] Optical Internetworking Forum, OIF-Co-Packaging-FD-01.0, Co-Packaging Framework Document, Implementation Agreement, 3 Feb. 2022.
[23] Recommendation ITU-T G.698.4, Multichannel bi-directional DWDM applications with port agnostic single-channel optical interfaces. https://www.itu.int/rec/T-REC-G.698.4
[24] Ericsson, "Packet fronthaul – design choices towards versatile RAN deployments," White Paper EAB-21:006051 Uen, Jan. 2026.
[25] Optical Internetworking Forum, 400ZR Implementation Agreement, and 800ZR Implementation Agreement, 30 Oct. 2024. https://www.oiforum.com/technical-work/hot-topics/800g-coherent/
[26] Recommendation ITU-T G.8271.1/Y.1366.1 (11/2022), Network limits for time synchronization in packet networks.
[27] Recommendation ITU-T G.8275.1/Y.1369.1, Precision time protocol telecom profile for phase/time synchronization with full timing support. https://www.itu.int/rec/T-REC-G.8275.1
[28] Recommendation ITU-T G.8273.2/Y.1368.2, Timing characteristics of telecom boundary clocks and telecom time slave clocks. https://www.itu.int/rec/T-REC-G.8273.2

[29] Recommendation ITU-T G.8275.2/Y.1369.2, Precision time protocol telecom profile for phase/time synchronization with partial timing support. https://www.itu.int/rec/T-REC-G.8275.2
[30] Press Information Bureau, C-DOT and CSIR-NPL sign agreement for development of NavIC based IST traceable Primary Reference Time Clock for telecom sector, 20 Sep. 2023. https://pib.gov.in/PressReleasePage.aspx?PRID=1959133
[31] Comptroller and Auditor General of India, Report No. 19 of 2026, Performance Audit of BharatNet. https://cag.gov.in/webroot/uploads/download_audit_report/2026/19-of-2026-UG-Eng-06a7c90aa5f2901.29659974.pdf
[32] A. Dixit et al., "Flexible TDMA/WDMA passive optical network: Energy efficient next-generation optical access solution," Optical Switching and Networking, vol. 10, no. 4, pp. 491–506, 2013.
[33] S. Garg and A. Dixit, "Bin-packing based offline dynamic bandwidth and wavelength allocation algorithms for power efficiency in Super-PON," OSA Continuum, vol. 4, no. 8, pp. 2091–2107, 2021.
[34] S. Garg and A. Dixit, "Bin-Packing-Based Online Dynamic Bandwidth and Wavelength Allocation Algorithm in Super-PON," IEEE Access, vol. 9, pp. 139379–139392, 2021.
[35] Recommendation ITU-T G.9804.3, 50-Gigabit-capable Passive Optical Networks (50G-PON): Physical Media Dependent (PMD) Layer Specification, including Amendment 3, Feb. 2026.
[36] A. Dixit et al., "Dynamic Bandwidth Allocation With SLA Awareness for QoS in Ethernet Passive Optical Networks," Journal of Optical Communications and Networking, vol. 5, no. 3, pp. 240–253, 2013.
[37] A. Dixit, "Architectures and Algorithms for Radio-Over-Fiber Networks," Journal of Optical Communications and Networking, vol. 10, no. 5, pp. 535–544, 2018.
[38] G. Pandey, A. Choudhary and A. Dixit, "Wavelength Division Multiplexed Radio Over Fiber Links for 5G Fronthaul Networks," IEEE Journal on Selected Areas in Communications, vol. 39, no. 9, pp. 2789–2803, 2021.
[39] K. Singh, A. Dixit and V. K. Jain, "Converged Medium Access Control and Dynamic Bandwidth Allocation for Radio-Over-Fiber Networks," IEEE Access, vol. 9, pp. 55165–55178, 2021.
[40] Broadband Forum, TR-470 Issue 2, 5G Wireless Wireline Convergence Architecture, Mar. 2022.
[41] ITU-T, Network Slicing in a Passive Optical Network Context, Series G Supplement 74, Dec. 2021.
[42] A. Dixit et al., "Fiber and wavelength Open Access in WDM and TWDM passive optical networks," IEEE Network, vol. 28, no. 6, pp. 74–82, 2014.
[43] Recommendation ITU-T G.9991 (03/2019), High-speed indoor visible light communication transceiver – System architecture, physical layer and data link layer specification, with Amd. 1 (07/2020), Cor. 1 (10/2020) and Amd. 2 (04/2021).
[44] H. Kazemi et al., "Achieving 70 Gb/s Over a VCSEL-Based Optical Wireless Link Using a Multi-Mode Fiber-Coupled Receiver," J. Lightwave Technol., vol. 43, no. 24, pp. 10986–10994, 2025.
[45] IEEE Std 802.15.13-2023, IEEE Standard for Multi-Gigabit per Second Optical Wireless Communications (OWC), with Ranges up to 200 m, for Both Stationary and Mobile Devices, 2023.
[46] Recommendation ITU-T G.641, Terrestrial free-space optics for mobile backhaul with short reach interfaces, International Telecommunication Union, Geneva, Nov. 2025.
[47] B. Erkmen, "Beaming broadband across the Congo River," X (Taara) blog, 16 Sep. 2021. https://x.company/blog/posts/taara-beaming-broadband-across-congo/
[48] M. Gregory, F. Heine, A. Brzoska et al., "Status on laser communication activities at Tesat-Spacecom," in Proc. SPIE 12877, Free-Space Laser Communications XXXVI, San Francisco, CA, USA, Mar. 2024, Art. no. 1287704.
[49] Optical High Data Rate (HDR) Communication—1550 nm, CCSDS 141.10-O-1 (Orange Book), Jun. 2022.
[50] "Starlink Version 3 Satellites," Starlink Updates. https://starlink.com/updates/starlink-version-3-satellites [Accessed: 22 Sep. 2026].
[51] Y. Li and J. Ibanez-Guzman, "Lidar for autonomous driving: The principles, challenges, and trends for automotive lidar and perception systems," IEEE Signal Process. Mag., vol. 37, no. 4, pp. 50–61, Jul. 2020.
[52] F. Liu et al., "Integrated Sensing and Communications: Toward Dual-Functional Wireless Networks for 6G and Beyond," IEEE Journal on Selected Areas in Communications, vol. 40, no. 6, pp. 1728–1767, Jun. 2022.
[53] A. Dixit, Ruchi, A. Prakash, V. Singh and A. Gupta, "Optical receiver front-end device for optical wireless communication," filed 14.02.2025, Indian Patent No. 571069 (granted).
[54] A. Dixit, Ruchi, A. Gupta, V. Singh and A. Prakash, "An optical wireless communication system," filed 08.01.2026, Indian Patent Application No. 202611002329.
[55] A. Dixit and R. Anwesh, "Multi-code Walsh multiplexing for high spectral efficiency in Li-Fi networks," filed 16.10.2025, Indian Patent Application No. 202511100407.
[56] N. M. Karoti, S. Paramita, R. Ahmad, V. A. Bohara and A. Srivastava, "Improving the Performance of Heterogeneous LiFi-WiFi Network Using a Novel Link Aggregation Framework," Proc. IEEE WCNC, 2022, pp. 2322–2327.

[57] S. Paramita, R. Mondal, A. Bhattacharya, V. A. Bohara and A. Srivastava, "MARM-HyLiWi: Mobility-Aware Rate Maximization in Link Aggregation Enabled Hybrid Li-Fi/Wi-Fi Networks," Proc. IEEE COMSNETS, 2025, Poster Track, pp. 891–894, doi: 10.1109/COMSNETS63942.2025.10885587.
[58] S. Paramita, A. Bhattacharya, V. A. Bohara and A. Srivastava, "WiLiConnect: A Novel CSI Sharing Technique in Hybrid WiFi/LiFi Networks," Proc. IEEE VTC2024-Spring, 2024, doi: 10.1109/VTC2024-SPRING62846.2024.10683067.
[59] S. Paramita, V. A. Bohara, A. Bhattacharya and A. Srivastava, "Outage Probability Analysis for Link Aggregation-Enabled Hybrid LiFi-WiFi Network," IEEE Communications Letters, vol. 30, pp. 1588–1590, 2026, doi: 10.1109/LCOMM.2026.3674993.
[60] IEC 60825-1:2014, Safety of laser products – Part 1: Equipment classification and requirements, 2014.
[61] A. Dixit and S. Garg, "A method for allocating channels for LDPC codes and a system thereof," filed 05.10.2021, Indian Patent No. 565729 (granted).
[62] A. Dixit and S. Dubey, "A system and a method for generating an engineered beam for speckle reduction," filed 09.12.2025, Indian Patent Application No. 202511124354.
[63] A. Dixit, A. Sharma, V. Bhatt, A. Sharma, A. Malik and S. Dubey, "Free-space optical communication (FSOC) system," filed 09.02.2026, Indian Patent Application No. 202611013798.
[64] A. Dixit, S. Dubey, A. Sharma, V. Bhatt, A. Sharma and A. Malik, "System and method for tracking and alignment of free space optical communication transceivers," filed 09.02.2026, Indian Patent Application No. 202611014036.
[65] Y. Wen, F. Yang, J. Song and Z. Han, "Free Space Optical Integrated Sensing and Communication Based on DCO-OFDM: Performance Metrics and Resource Allocation," arXiv:2312.13654, Dec. 2023.
[66] X. Su et al., "Optical Integrated Sensing and Communication: From Theory to Practice," Tsinghua Science and Technology, 2025, doi: 10.26599/TST.2025.9010099.
[67] I. Nape, K. Singh, A. Klug et al., "Revealing the invariance of vectorial structured light in complex media," Nature Photonics, vol. 16, pp. 538–546, 2022, doi: 10.1038/s41566-022-01023-w.
[68] M. Siddharth, S. Shah, N. Vishwakarma and R. Swaminathan, "Performance analysis of adaptive combining based hybrid FSO/RF terrestrial communication," IET Communications, vol. 14, 2021, doi: 10.1049/iet-com.2020.0598.
[69] C. Dath and N. A. B. Faye, "Resilience of long range FSO link under a tropical weather effects," Scientific African, vol. 7, e00243, 2019, doi: 10.1016/j.sciaf.2019.e00243.
[70] S. Kirubakaran and M. D. Selvaraj, "Performance Analysis of Interference Limited Hybrid FSO/RF Systems," in Proc. 2022 IEEE International Conference on Signal Processing and Communications (SPCOM), Bangalore, India, 2022, pp. 1–5, doi: 10.1109/SPCOM55316.2022.9840786.
[71] S. Kirubakaran, A. Ashok, H. K. Atluri, N. Choudhary, K. Lala, A. Paventhan and G. Pimparkar, "Performance Analysis of FSO Deployment in the North-East India," in Proc. 2025 IEEE 9th International Conference on Information and Communication Technology (CICT), 2025, doi: 10.1109/CICT67193.2025.11399033.
[72] H. Hassan, S. Althunibat, A. Al-Mbaideen, M. Hasna and K. A. Qaraqe, "A Survey on Hybrid Free Space Optical and Radio Frequency Systems: Classification, Progress, Observations, and Challenges," IEEE Access, vol. 13, pp. 63994–64060, 2025.
[73] Recommendation ITU-T G.694.1, Spectral grids for WDM applications: DWDM frequency grid (flexible grid).
[74] Recommendation ITU-T G.652, Characteristics of a single-mode optical fibre and cable.
[75] M. Cantono, R. Schmogrow, M. Newland, V. Vusirikala and T. Hofmeister, "Opportunities and Challenges of C+L Transmission Systems," IEEE Journal of Lightwave Technology, vol. 38, no. 5, pp. 1050–1060, 2020.
[76] N. Deng, L. Zong, H. Jiang, Y. Duan and K. Zhang, "Challenges and Enabling Technologies for Multi-Band WDM Optical Networks," IEEE Journal of Lightwave Technology, vol. 40, no. 11, pp. 3385–3394, 2022.
[77] T. Hoshida, V. Curri, L. Galdino, D. T. Neilson, W. Forysiak, J. K. Fischer, T. Kato and P. Poggiolini, "Ultrawideband Systems and Networks: Beyond C+L-Band," Proceedings of the IEEE, vol. 110, no. 11, pp. 1725–1741, 2022.
[78] Recommendation ITU-T G.665, Generic characteristics of Raman amplifiers and Raman amplified subsystems.
[79] TSDSI, "SDN-Based Optical Network for QKD: Secure and Adaptive Architecture," TSDSI TR 6062 V1.0.0, Jun. 2026.
[80] Recommendation ITU-T Y.3800, Overview on networks supporting quantum key distribution.
[81] Recommendation ITU-T Y.3801, Functional architecture for quantum key distribution networks.
[82] Recommendation ITU-T Y.3802, Quantum key distribution networks – Control and management.
[83] Recommendation ITU-T Y.3810, Architectures for multi-hop quantum key distribution networks.
[84] ETSI GS QKD 011, Quantum Key Distribution (QKD); Components and internal interfaces.
[85] ETSI GS QKD 012, Quantum Key Distribution (QKD); Protocol and data format for QKD key delivery API.

[86] Government of India, Department of Science and Technology, National Quantum Mission.
[87] IEEE Std 802.3ba-2010, 802.3bs-2017 and 802.3df-2024, Ethernet physical-layer amendments for 100G, 400G and 800G operation.
[88] IEEE Standards Association, IEEE P1962, Standard for Providing Broadband Connectivity to Rural Infrastructure by Utilizing Solar Panels as Optical Communication Receivers (draft).
[89] Recommendation ITU-T L.209 (02/2022), Requirements for fibre optic network terminal box (FONT); draft contributed by the Ministry of Communications (India) and Sterlite Technologies, ITU-T SG15 Contribution 1585, Jan. 2020.
[90] TSDSI, Optical Access and Transport Study Group: fronthaul specification work and member contributions to ITU-T SG15 Recommendations G.8032 (Ethernet Ring Protection Switching) and MPLS-TP.
[91] TSDSI, Study of the Channel Model for Integrated Sensing and Communication Network in FR3 and THz Band, Study Item SI-128, Dec. 2025.
[92] TSDSI, Study of Internetworking of Li-Fi & Wi-Fi Network, Study Item NI-424, Dec. 2025.
[93] AOC Testbed, Facilities at IIT Madras, Department of Telecommunications, Government of India. https://www.aoctestbed.in/facilities-at-iitmadras-aoc-testbed
[94] Press Information Bureau, DoT launches Bharat 6G Alliance to drive innovation and collaboration in next-generation wireless technology, 3 Jul. 2023 (TTDF agreements for the 6G THz Testbed and the Advanced Optical Communication Testbed, ₹240.51 crore).
[95] Indian Institute of Technology Guwahati, "IIT Guwahati transfers novel free-space optical communication technology to telecom industry," press release, 13 Feb. 2023. https://iitg.ac.in/iitg_press_details?p=36%2Fiit-guwahati-transfers-novel-free-space-optical-communication-technology-to-telecom-industry
[96] Ministry of Communications, Secretary (Telecom) inaugurates Centre of Excellence on "Classical and Quantum Communications for 6G" at IIT Madras Research Park, Chennai, Jul. 2024.
[97] Indian Institute of Technology Madras, National Hub for Quantum Communication (IITM–C-DOT Samgnya Technologies Foundation) inaugurated under the National Quantum Mission, Dec. 2025.
[98] Rahul, A. Srivastava, V. A. Bohara, D. Solanki and A. Mitra, "Demonstration of Broadband Data Link over off-the-shelf Solar Module with White LED," IEEE Journal of Lightwave Technology, vol. 43, no. 10, pp. 4564–4572, May 2025, doi: 10.1109/JLT.2025.3541831.
[99] Rahul, V. A. Bohara, A. Mitra, D. Solanki and A. Srivastava, "Sunlight to Signals: Solar Panel as Active Data Receiver," Proc. IEEE COMSNETS, 2024.
[100] Rahul, V. A. Bohara, A. Srivastava, D. Solanki and A. Mitra, "Dead Zone Mitigation in Vehicular Platoon via Solar Panel as a Communication Receiver," IEEE Transactions on Intelligent Transportation Systems, 2025.
[101] Rahul et al., "Mirror-Assisted Non-Line-of-Sight Voice Communication Over Solar Panels as Receivers for Long-Range Low-Power Links," Proc. IEEE COMSNETS, 2026, Demo Track.
[102] Rahul, A. Mitra, D. Solanki, A. Srivastava and V. A. Bohara, "A System to Amplify Bandwidth Capacity in a Li-Fi Network System," Indian Patent 557160, granted 31 Dec. 2024.
[103] S. Paramita, A. Bhattacharya, V. A. Bohara and A. Srivastava, "Utilizing LiFi for Sending Channel Feedback in a Hybrid Wi-Fi/Li-Fi Network," Indian Patent 578625, granted 20 Jan. 2026.
[104] A. Singh, A. Srivastava, V. A. Bohara and A. K. Jagadeesan, "System and Method to Optimize a Light Emitting Diode Power Allocation Framework," U.S. Patent US12075547, granted 27 Aug. 2024.

Bharat6G Alliance

Bharat 6G Alliance
2nd Floor, C DoT Campus,
Mandi Road, Mehrauli,
New Delhi- 110030 (INDIA)

info@bharat6galliance.com

www.bharat6galliance.com