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ABSTRACT

Optical networks have long played a central role in telecommunication networks, forming the fiber backbone of the Internet. Over time fiber optic systems have evolved and found deployment increasingly closer to the network edge. Today, optical systems extend to the server network interface cards and home access networks. New application areas have emerged such as the use of free space communications using LiFi technologies, space communication networks between satellites and ground stations. Looking ahead, optical systems in many areas will continue to be driven by the need for higher speeds and capacity in order to keep up with traffic demands. In addition to faster interfaces speeds, parallel fiber or spatial division multiplexing will be used for future capacity growth. In several application areas, new functionality is expected such as low latency in Xhaul networks and optical switching and co-packaged optics in data centers. LiFi will become critical for mitigating RF interference for in-building networks. Intense research is underway to develop quantum networks to connect quantum computers. This general trend toward new functionalities for optical systems, moving beyond capacity growth in fiber networks, is driven in large part by the increasing performance and demands of today's user equipment and applications. From the network edge to the data centers, components are reliant on optics. The integration of optics into these new applications and the higher levels of functionality demanded of optics motivate the use of roadmaps to guide research and development and overcome future roadblocks.

Key words:

Optical networks, Xhaul, LiFi, space communications, wavelength division multiplexing, spatial division multiplexing, quantum networks, data center interconnect, data center networks, co-packaged optics.

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INGR ROADMAP

1. INTRODUCTION

Customer expectations of next generation communications solutions include higher speeds, shorter latency, and quicker response times not only for the 5G radio links but also for the full end-to-end network itself. While the optical back-haul network is expected to provide the needed capacity and support, new requirements are expected to be imposed on the front-haul network to support the vision of future networks, from 5G to 6G, and beyond.

5G is designed to support – over a common network infrastructure – a variety of diverse applications spanning across enhanced mobile broadband, massive Internet of Things (IoT), and mission critical ultra-reliable and low latency machine-type communications. New applications that demand low latency will drive a significant change in the architecture of our future networks with integration of cloud processing capabilities even at the edge of these access networks. These key drivers behind the rapid deployment of 5G and emerging requirements of 6G and beyond applications will create new performance expectations and open up market opportunities for optical fiber communications and photonic networking systems.

2. WORKING GROUP VISION

This working group has identified several key trends that form the vision for optical networks in the coming decade. Figure 1 provides a notional model of this future vision, highlighting the key areas under consideration. The evolution of metro networks through increased mesh connectivity and dynamic networking through the integration of reconfigurable optical add-drop multiplexers (ROADMs) and software defined networking (SDN) will continue to support front-/mid-/back-haul (Xhaul) networks for future wireless networks and fixed high speed access networks. Xhaul networks need to evolve to meet the stringent requirements of radio waveform transmission methods and protocols as well as their strict time sensitivity and emerging options to integrate edge cloud architectures within these Xhaul network node locations are important dimensions for these networks. High speed (fixed) access networks for both point-to-point and passive optical network (PON) evolution are expected to provide connectivity at speeds at 100 Gbps and higher, including coherent technologies to achieve even greater data rates. Data center interconnects (DCI) have emerged as a key development in long haul networks including submarine deployments, with emerging applications in metro networks as well. These DCIs are unique point-to-point optical systems between data centers and Internet exchange points or central offices. They are growing rapidly and are expected to grow in importance in the future. Edge cloud computing facilities will rely on disaggregated and open, SDN-based systems, emphasizing advanced functionality and integration with larger wireless and SDN environments. The evolution of optical technologies in data centers will be led by greater use of co-packaged optics (CPO) to overcome the input/output (I/O) challenges for high density processors in both electronic switches and computing processors. Optical switching also has the potential to find use in data center networks, particularly large fiber switches that can flatten the architecture. Networking options for large scale infrastructure and buildings are also expanding to explore new connectivity options. In-building optical networks, which includes visible light communications, will be an important and growing application. As capacity needs to continuously increase together with the requirement to simplify complex connectivity between sites, optical fibers are expected to be deployed increasingly in large cables, potentially evolving to multi-core and other space division multiplexing (SDM) approaches. With the growing challenge of connecting the unconnected, optical technologies are expected to provide high-capacity optical wireless communications to platforms and network nodes in the space (e.g., satellites, high altitude platforms, drones) which are becoming important alternatives towards the delivery of future connectivity. Interest in quantum communications, initially for quantum enhanced security such as quantum key distribution, will continue to grow and expand into distributed quantum computing applications as the photonic technologies for such applications become available.

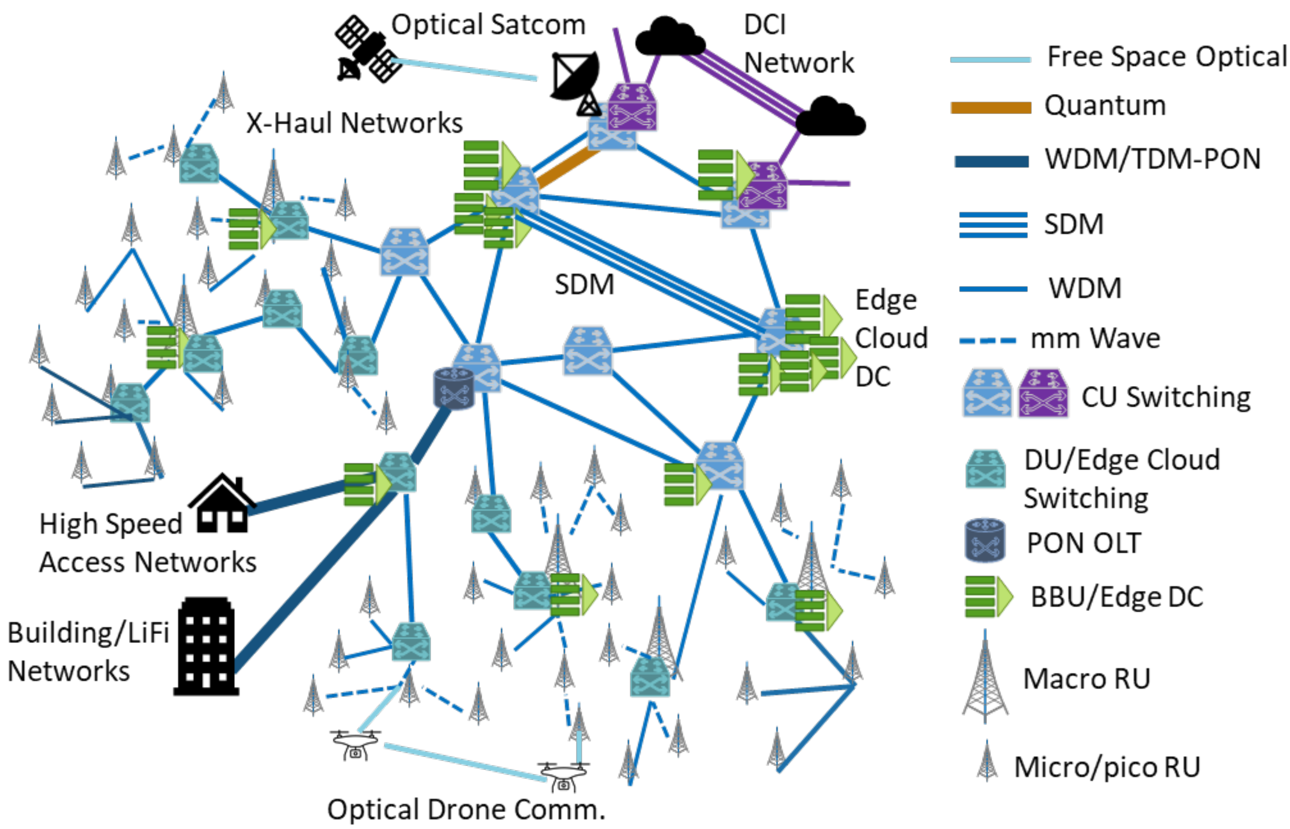


Figure 1. Vision of future optical communication networks.

2.1. Scope of Working Group Effort

The Future Networks Initiative's Optics Working Group (WG) will identify and build roadmaps for key optical technology areas relevant to the INGR. The working group seeks to partner with existing roadmapping initiatives to avoid duplication and collaboratively identify new technology areas in need of roadmapping. This roadmap is intended to bring focus to future technology challenges and track progress toward their solutions as well as guide the development of standards. Emphasis will be placed on new and emerging technologies and network evolution trends that are expected to shape future (optical) networks.

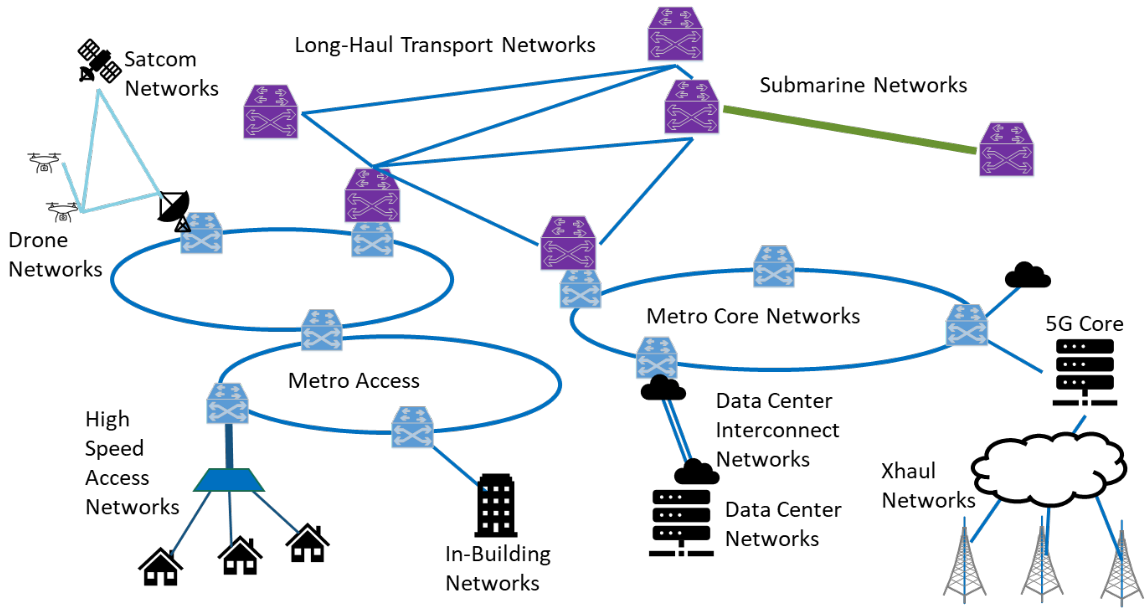


Figure 2. Different types of optical networks.

The Future Networks Initiative's Optics WG is structured to create the space for key stakeholders to discuss the needed optical technologies being developed to meet the needs and goals of future networks. The working group has identified the following topics as relevant. These topics are not intended to exhaustively cover optical technologies and networking, but rather identify areas well suited for roadmapping in terms of their importance for future networks and the potential to describe and track the component technologies for the purpose of the roadmap. Figure 2 illustrates the relevant network domains and their relationships. Aspects of these topics have been identified for roadmapping by the working group and are included in this document:

- Optical Xhaul (front/mid/backhaul) Networks.
- High Speed Optical Access Networks
- Co-packaged Optics / Data Center Networks
- Machine Learning in Optical Networks
- In-Building Optical Networks
- Optical Wireless Technologies for Space Communications Using Satellites or High-Flying Platforms
- Optical Fibers and Spatial Division Multiplexed Networks
- Quantum Communications

2.2. Linkages and Stakeholders

2.2.1. Stakeholders

The working group will convene key experts drawn from stakeholders to discuss the opportunities and challenges of future networks in these domains at different time intervals (3 years, 5 years, and 10 years). The relevant stakeholders include:

- Telco (MNO/MVNO), Satellite Operators, Equipment Providers (Compute, Networking, Storage)
- Cloud/Infrastructure providers (Bare Metal, Private, Public, Hybrid, Multi)
- Standards organizations, alliances, and fora across tele/datacom, computing, and networking.
- Universities, Academic Institutions, Research Organizations and Centers
- Government/Cities (National, State, Province/Districts, City/Town)
- App developers (Domain Specific/Social/Green/Enterprise)
- Consumers & Users (Personal/Family/Workers, Urban, Rural)

2.2.2. Key Supporting Ecosystems

Several engineering and scientific groups and societies in related information and communication technology (ICT) areas are developing roadmaps and/or organizing workshops/conferences to bring the community together, develop whitepapers, and create awareness about future network issues. Relevant contributions from these ecosystems are noted in the technology area descriptions below and the key organizations are listed here:

- IEEE Communications Society (ComSoc), Photonics Society (PS), and Standards Association (SA)
- Optical Society (OSA), Optical Industry Development Associates (OIDA)
- Integrated Photonics Systems Roadmap (IPSR, AIM Photonics)
- International Telecommunications Union – Telecommunications Sector (ITU-T)
- Optical Internetworking Forum (OIF)
- Open Networking Foundation – Open Disaggregated Transport Network (ONF – ODTN)
- European Telecommunications Standards Institute (ETSI)
- Telecom Infra Project (TIP)
- Open Compute Project (OCP)
- Open Radio Access Network Alliance (O-RAN)
- Full-Service Access Network Forum (FSAN)

2.2.3. Linkages to INGR Content

The topics addressed in the Optics WG have linkage to other INGR WGs and technology areas, identified below.

- Test Bed (5G Testbed Optical Network Design and Test harness for Field trials)
- Security (Physical Layer)
- Massive MIMO (Interfacing Over the Air [OTA] Rx/Tx diversity & Beam forming with CPRI/eCPRI)
- Applications and Services (Domain Specific Applications & Innovative services like Adaptive Streaming, ProtoBuffers)
- Connected Open Source & Open Technology Projects (Open Infrastructure, Airship, CORD/Stratum)
- Photonic integration for Computing & Communication Acceleration
- Standards Building Blocks

3. TODAY'S LANDSCAPE

3.1. Current State of Technology and Research

Optical networks widely deployed today (see Figure 3) are architected in a hierarchy of access, metro/regional, and long-haul networks, where long haul can be divided into terrestrial and submarine networks. Access networks include PONs between central offices and enterprise or residential users. Wireless base stations and access points (e.g., Wi-Fi kiosks) are connected with point to point (PtP) connections transporting baseband Ethernet signals over an optical backhaul network. Many cell sites are also connected either through microwave backhaul or directly to the optical backhaul network. Large data centers are located on main long-haul trunk lines and in metro areas are often configured in dual-homed arrangements for redundancy and protection of data. Wavelength division multiplexed (WDM) metro and metro/regional networks connect central office locations through ring networks with connected distribution rings and an increasing number of mesh cross-connecting links. ROADMs are widely used to add and drop WDM traffic within the metro, regional, and long-haul networks. Standards exist for much of the infrastructure and many components in these networks. Emerging technologies frequently use multi-source agreements (MSA) and reference models or architectures developed by individual organizations or large alliances and fora. Long haul and metro transmission systems historically have been proprietary and do not interoperate with other vendors' equipment. However, open and disaggregated systems have been introduced recently and most systems today provide some form of alien wavelength support, admitting signals form other vendors' equipment.

The optical network environment shown in Figure 3 has been largely consistent throughout the last decade, 2010-2020. Evolution has primarily occurred through capacity enhancements as the networks evolved from 10 Gbps on-off keyed systems, to systems exploiting advanced modulation formats, e.g. 40 Gbps differential phase shift keying to 100 Gbps coherent polarization multiplexed quadrature phase shift keying (PM-QPSK) and 200 Gbps PM quadrature amplitude modulation (QAM). A variety of other modulation formats and mix-rate systems have also been introduced during this period. Today the evolution of transceiver speeds in WDM networks is continuing to 400, 800, 1000, and 1600 Tb/s and beyond in different steps and formats, as discussed below. Access networks have evolved from 1 Gbps and 2.5 Gbps to 10 Gbps, both for PON and point to point networks, and 50 Gbps PON was recently standardized.

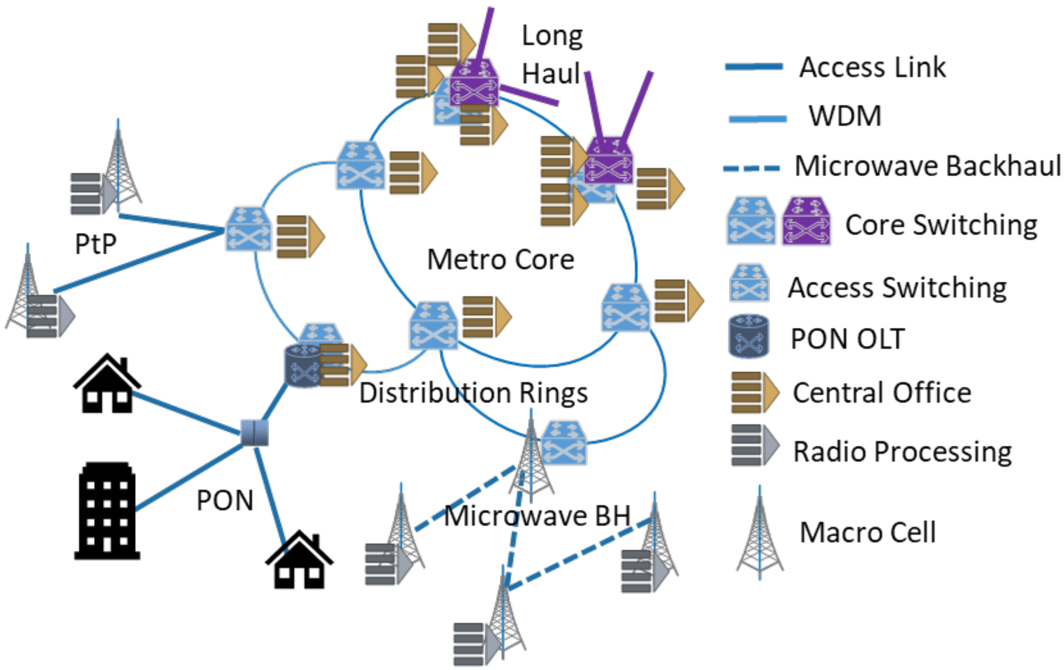


Figure 3. Today's optical networking landscape.

3.2. Drivers and Technology Targets

Optical networks have historically been driven by performance, usually in terms of capacity. Transmission reach was important in the early development when long haul and submarine networks were the main focus. Over time shorter diameter networks such as metro, backhaul, and data center networks, have grown in market size and received greater attention. During the prior decade, total metro-only traffic in North America surpassed long haul traffic for the first time. Capacity or channel data rates, which primarily determine the cost per bit, continues to be a critical business driver. However, new metrics such as power, footprint, and new features such as software defined networking (SDN) support have become important in recent years. Large enterprises such as content providers and hyperscale data center operators started to build or lease their own networks and have contributed to this trend. Data center interconnect (DCI) is a new class of optical system that has emerged to provide very high capacity at low cost and energy between data centers. These networks are forming a new Internet backbone.

Densification of radio access points, primarily built on fiber networks, is a major driver for the development of optical technologies. Radio access network (RAN) architectures such as centralized or cloud RAN make use of a fronthaul or mid-haul (xhaul) network to transport high-capacity digitized radio signals to centralized locations for baseband processing. This saves on power and cost of processing as the number of access points increases, but requires much higher capacity in the optical networks. The need for capacity in RANs is driving cost reductions in high-capacity optical technologies used in metro and long-haul networks, such as coherent optics. Whitebox network elements and system disaggregation has been introduced as a method to drive cost reductions in these technologies, as well as to open the feature set to customization. Other types of optical networks such as satellite networks and in-door and wireless networks, will likely benefit from and follow the technology developments from the high-volume RAN xhaul and data center/DCI systems. Cost pressures associated with the densification of RANs is likely to be the major business driver for the foreseeable future.

4. Future State (2032)

Projecting forward based on current and historical trends, the following observations can be expected to apply:

- Network speeds to and from computers will continue to increase creating further need for optical interfaces at short distances and the bandwidth distance product at which optics becomes the more affordable technology will reduce with further cost reductions in optical technologies; fiber to the home becomes denser and develops into fiber to the room.
- 6G wireless networks will need greater network capacity and flexibility in that capacity, becoming more dependent on optical networking capabilities and integration with optical networks
- Backbone and long-haul networks will continue to serve data centers and exchanges, shifting towards a DCI technology roadmap
- Optical networks in the metro and edge will provide more functionality for cost and energy efficient service delivery, including low latency. This will be accompanied by enhanced software controls and methods such as machine learning.
- Quantum networks will emerge to support distributed quantum computing and novel network functionality such as post-quantum security methods and quantum enhanced time synchronization.

Figure 1 provides a vision for the future state of the network, evolved from the picture in Figure 3. Each of the trends listed above will play a role in moving toward this future vision. One key question in this evolution is the role of satellite networks, particularly low earth orbit networks considered to provide access for users. If these becomes a mainstream access technology then it might disrupt the growth of Xhaul networks. It’s more likely, however, that it would simply add on capacity and coverage and thereby relieve some capacity pressure from xhaul network growth. Whether DCI networks displace traditional long-haul networks over the next decade will be another important trend to watch. Lastly, quantum networks have the potential to drive a new wave of development in telecom or they could prove to be too difficult and expensive to engineer. The applications and technologies involved in quantum networks, however, are largely orthogonal to those used in classical networks, so the impact on the other trends described here will likely be small. Quantum services may become yet another technology platform alongside radio and classical optical.

5. Needs, Challenges, and Enablers and Potential Solutions

5.1. Summary

Key overall needs related to the technologies considered in this roadmap are summarized in Table 1 below. These needs are discussed in more detail in the various technology area descriptions that follow.

Table 1. Overall Needs

Needs	*Description*
Need 1: Flexible and Scalable High Bandwidth Optical Xhaul	Xhaul networks forms the fabric of interconnections between radio units, distributed units and central units of the next generation mobile networks. With the density of cells and the bandwidth offered by such cells increase, future Xhaul networks will need to meet stringent requirements of delay, bandwidth, energy efficiency, latency, synchronization as well as being able to meet the deployment needs of flexibility and scalability. Highspeed optical transceiver technologies will be critical to meet such requirements. In addition, as the network transitions beyond 6G, Xhaul networks needs to accommodate new and emerging networking and deployment approaches.
Need 2: Synchronization, Coordination, and Integration of Optical Xhaul and Wireless Technologies	Packet level transport and optimization of optical Xhaul is essential to ensure future wireless systems and their service requirements are well supported. With the emergence of cell-site routers, the synchronization and packet level coordination between multiple layers within the service delivery will become even more important and optical Xhaul need to meet such requirement while evolving to meet capacity and bandwidth requirements of future deployment scenarios
Need 3: High Capacity, Flexible and Low Latency Optical Access Networks and Technologies	With persistent demand for high bandwidth services, high-capacity optical networks that can offer flexibility and low latency will be required to meet the networking needs of mobile, residential broadband access, business broadband access, edge computing and data center networks. These technologies need to deliver lower latencies, scalable bandwidth options, improved energy efficiencies, variable reach from few kms to few tens of km, and greater flexibility in deployment, operation and management.
Need 4: Highly scalable Data Center Networks and copackaged technologies to meet data center requirements	Data Center Networks have become an important part of networking with a great deal of variation in their architecture, reach and location, thus demanding photonic data center interconnects with highly scalable, ultra-high throughput, ultra-low latency, and very high levels of parallelism. With much of these networks today relying on photonic links to interconnect, future requirements will demand copackaged optics as a technology platform to radically reduce the copper transmission and significantly improve the scalability and throughput of these interconnects.
Need 5: High performance in-building networks using a range of connectivity options and seamless integration with wide area and mobile networks	Last meter connectivity is becoming a major part of the hyperconnected society, and it requires a mix of wireless and wired technologies to meet the evolving requirements. Most importantly, bandwidth of the indoor networks will need to rapidly increase to multiple tens of gigabits per second throughput and needs to seamlessly integrate with mobile and wide area access networks to allow the user an interrupted network connectivity. In addition, a large portion of indoor traffic will involve machine to machine communications and will demand higher degree of flexibility with regard to technologies used to form the network connectivity.

5.2. Optical Xhaul Networks

5.2.1. Current State

Xhaul networks identify the different network segments (fronthaul, midhaul, and backhaul) that are located between a radio unit (RU), a distributed unit (DU), a central unit (CU) and the core mobility network (EPC/5GC) as illustrated in Figure 4 below [1]. The fronthaul networks present the most stringent requirements on network design as they represent the network segment that carries the lower layer split (LLS) traffic with the in-phase and quadrature (IQ) frequency domain data components. More specifically, the delay requirements are at least an order of magnitude more stringent than in midhaul and backhaul networks. More details on services and related delay requirements can be found in O-RAN Xhaul Transport Requirement in Table 3, 5 and 6 of [1].

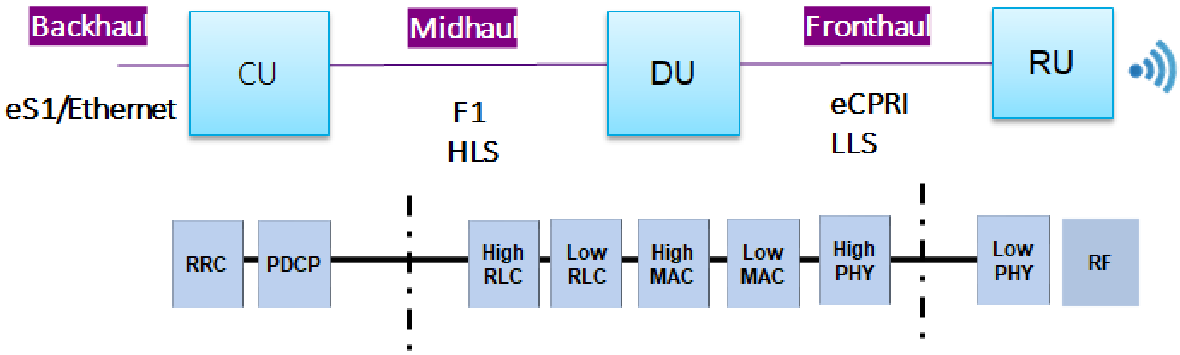


Figure 4. Xhaul Network; processing functions shown in grey boxes below the corresponding node types at which they are executed; dot-dashed lines indicate split locations.

Beyond delay, the throughput constitutes the next category of requirements defining the Xhaul transport networks. They are determined by the type of service, number of antenna ports and number of mobile users. The O-RAN Xhaul Transport requirement document [1] (Annex A, Nov 2020) includes several tables providing throughput requirements that are dependent on service bandwidth, numbers of multiple-input multiple output (MIMO) layers, and number of frequency carriers.

The current state of the art in Xhaul transport networks is given by the following technologies in fronthaul networks:

- 10 Gbps (SFP+) or 25 Gbps (SFP28) interface as the mainstream transceiver technology with 4 x 10 Gbps/25 Gbps (QSFP+/QSP28) starting to emerge at radio units (Rus)
- Dark fiber deployments in short-range applications (< 100m)
- Coarse WDM (CWDM) and dense WDM (DWDM) for centralized radio access network (CRAN) applications
- Optical transceivers range from short range (SR) to long range (LR). They may support single wavelength, multiple wavelength (e.g., LR-4) or multiple fiber (SR-4 with MPO connectors).
- The maximum theoretical distance is 20 km, although most operators plan to limit the maximum distance to 10 km for some margins to be available in their network for insertion of WDM and packet based (routers) in fronthaul networks.

Midhaul and backhaul networks are less constrained by delay requirements and can be designed with distances in 10s of km. Central unit (CUs) and core network equipment can be placed in data centers far away from distributed units. This placement advantage delivers an immense benefit to operators in terms of capital expenses and operational expenses.

5.2.2. Challenges

As indicated above the current optical technologies are determined based on current demands of 4G and emerging 5G networks. The throughput requirements are mainly determined by the number of antennas and the service bandwidth. The number of antennas is determined by the density of users and the environmental limitations. The service bandwidth is dependent on the type of broadband service offered by the mobile operators. The penetration of 5G users is very small in most countries. A majority of service offerings are limited to bandwidths below 100 MHz

Both the density of users and the service bandwidth are expected to grow significantly within the next few years. As a result of these projections researchers and developers are working on next generation technologies that enable the transport of much larger bandwidth (at least an order of magnitude). Some of these technologies are available for low-volume deployments in core networks, but are not economical for mass deployments especially in fronthaul networks; examples include:

- 50 Gbps, 200 Gbps [2]
- 400 Gbps [3]
- Single wavelength 100 Gbps transceivers
- More economical DWDM and higher density CWDM (e.g., MWDM) wavelength multiplexing technologies.

As the density of cell sites increase with future high-capacity networks of 5G and beyond exploiting millimeter wave frequency bands and beyond, it may be possible to realize photonic fronthaul links exploiting analog radio over fiber transmission to achieve greater energy efficiency and latency while ensuring all the network functionalities are retained by digital management of such analog radio over fiber front haul links between the DUs and CUs [4]. These approaches will require suitable transceiver technologies integrating photonic and millimeter-wave systems, photonic layer support of beam forming, software defined networking interfaces to manage the resource allocations as well as supporting remote management of cell sites. However, such developments need to compete with rapidly developing digital photonic transceiver technologies. With the emerging vision of 6G, new ways of deploying front ends of such networks in cell free architectures can be considered. Such architectures may demand more interconnections between such wireless front ends and a dynamic optical mesh network to meet the future Xhaul needs.

Table 2. Challenges Associated with Optical Xhaul Networks

Near-term Challenges: 2022-2025	*Description*
50GE Transceiver	Provide adequate 50GE transceivers for radio applications such as they meet their cost and environment goals
Mid-term Challenges: 2026-2027	*Description*
200GE Transceiver	Provide adequate 200GE transceivers for radio applications such as they meet their cost and environment goals
Optical Fronthaul supporting Beamforming	As large antenna arrays and beamforming becoming important, how to achieve beam forming in such situations becomes a major challenge. Optical fronthaul approaches compatible with beamforming may make it easier to realize scalable and flexible fronthaul that is based on radio over fiber approaches. However, cost-effective transceivers and ability to manage such approaches like the way digital transceivers can be managed remain as major challenges.
Long-term Challenges: 2028-2032	*Description*
400GE Transceiver	Provide adequate 400GE transceivers for radio applications such as they meet their cost and environment goals
Optical Fronthaul supporting Beamforming	Photonic integrated circuits and solutions to manage future requirements of MIMO based radio frontends
Dynamically Managed Optical Networks	With the introduction of cell-free networking and much more interconnected DUs and RUs, it will become important to consider future Xhaul optical networks as highly meshed architectures with the need to dynamically manage the networks through a range of wavelength and time domain resource allocation and provisioning and management approaches including protection and restoration capabilities.

5.2.1. Packet, Synchronization, PON and Wireless technologies in Xhaul

The current and future state of the Xhaul in this document focuses on the optical layer. Xhaul networks also include packet and synchronization functions that are not discussed here in detail but should be mentioned in summary as those functions are critical for a scalable Xhaul network that meets the stringent synchronization requirements of 5G services.

While the initial 5G deployments are characterized by the use of dark fiber or WDM technologies, the use of packet-layer network elements is essential for a scalable Xhaul that covers dozens or more radio units. Cell site routers are being planned for use in fronthaul networks. The introduction of routers drives the need for proper synchronization planning, since routers can inherently impact packet-based synchronization technologies such as PTP/IEEE 1588v2 [5], or Synchronous Ethernet [6].

The 5G services not only introduce the need for larger bandwidth, but also much more stringent synchronization requirements. Carrier aggregation and MIMO transmit a diversity of features that demand time alignment error (TAE) limits that are 5-10 times more stringent than those in conventional LTE networks [7]. Meeting these tight TAE limits necessitates the use of routers with higher class (Class C, Class D) Telecom Boundary Clock (T-BC) time error limits and the use of enhanced Primary Reference Timing Clock (ePRTC) equipment.

Finally, other transport technologies are being designed and optimized for fronthaul networks. They include the next generation PON (NG-PON) with dynamic bandwidth allocation (DBA) supporting Cooperative Transport Interface (CTI) (see section 4 below) and wireless methods using millimeter wave technologies. While NG-PON DBA/CTI [8] is designed with the intent to optimize the latency requirements of available PON technologies, the millimeter wave technologies address the need of fronthaul networks to transport a much larger volume of traffic compared to traditional microwave backhaul networks.

Table 3. Challenges Associated with Packet, Syncronization, PON, and Wireless Technologies in Xhaul

Near-term Challenges: 2022-2025	*Description*
Meeting demand time alignment requirements through higher class routers (Class D-T-BC)	5G services demand stringent timing requirements that far exceed the timing requirements for switches and routers. Optical Xhaul networks need to deliver more mature and lower-Class D Boundary Clocks for cost-effective Deployments in the field.
Mid-term Challenges: 2026-2027	*Description*
Meeting demand time alignment requirements through higher class routers (Class D-T-BC)	5G services demand stringent timing requirements that far exceed the timing requirements for switches and routers. Optical Xhaul networks need to deliver more mature and lower-Class D Boundary Clocks for cost-effective Deployments in the field
Long-term Challenges: 2028-2032	*Description*
Optimizing Optical Xhaul with strict timing and latency requirements	With the emergence of greater bandwidth of millimeter wave frequency bands, the optical Xhaul networks need to offer even greater control of timing and latency.

5.2.2. Potential Solutions

Future deployments will demand highly optimized, flexible, and scalable optical Xhaul that can be well integrated into wireless and radio systems. This will require the parallel development of highspeed optical transceivers be leveraged and optimized to meet the stringent requirements arising from latency, bandwidth, energy efficiency, synchronization, and flexibility in the operation and management of such Xhaul networks. In addition, as the networks move to a cell free network architecture, it will require a dynamic networking approach to manage the interconnection in such architectures. As millimeter wave frequencies are exploited as part of NR deployment and vision for 6G, optical Xhaul needs to support beamforming as well as higher density MIMO antenna implementations. In such situation, new optical fronthaul approaches may need to be devised and requires high level of integration of optical transceiver technologies along with radio and baseband processing hardware supporting different functional splits. Optical Xhaul networks in future needs to deal with a variety of interface standards and specifications as well as a fully interconnected network, demanding new approaches in design, deployment and management of such networks. In this section, we summarize the solutions that have become possible with the associated roadmap of the optical access networks, leaving the discussion of the detailed roadmap of high-speed optical access networks to the next section. In addition, there has been considerable research in to photonic fronthaul and photonic beamforming and more recently on integration of such technologies to achieve cost effectiveness. A combination of these and yet to be defined approaches may provide cost-effective and scalable solutions that can coexist seamlessly with maturing highspeed digital optical Xhaul transceiver technologies to meet the challenge of providing photonic fronthaul.

Table 4. Potential Solutions for Optical Xhaul Networks

Near-term Challenges: 2022-2025	*Potential Solutions to Near-Term Challenges*
50 Gbps Transceivers	Optimize transceiver design for outdoor applications, improve manufacturing process to reduce costs
Class D T-BC	Optimize cost of highly stable oscillators. Enable logical design of lower cost solutions with highest time stamping accuracy and low packet jitter capabilities
Mid-term Challenges: 2026-2027	*Potential Solutions to Mid-term Challenges*
200 Gbps Transceivers	Optimize transceiver design for outdoor applications, improve manufacturing process to reduce costs
Class D T-BC	Optimize cost of highly stable oscillators. Enable logical design of lower cost solutions with highest time stamping accuracy and low packet jitter capabilities
Long-term Challenges: 2028-2032	*Potential Solutions to Long-term Challenges*
400 Gbps Transceivers	Optimize transceiver design for outdoor applications, improve manufacturing process to reduce costs

The solutions associated with each challenge should be described in each of the sections below:

5.2.2.1. Digital Optical Xhaul Transceivers

With the roadmap of highspeed optical transceivers discussed in the next section, it is clear that there are multiple and parallel industry sectors that will keep driving the development of digital optical transceivers to provide 50 GBPS, 200 GBPS and 400 GBPS and eventually 1 TBE to ensure optical ethernet as a viable transport technology for future optical Xhaul needs. Details of these solutions are also discussed in the next section.

5.2.2.2. Class C and D routers with improved boundary clocks

With popular trend of optical ethernet as the dominant form of optical Xhaul transport method, synchronization needs to main the higher specifications of time alignment errors. In addition, future technology improvements in oscillators as well as design of low jitter and high precision logic will not only need to deliver performance improvements but also demonstrate cost reduction to meet operational and capital expenditure requirements of future deployments.

5.3. High Speed Optical Access Networks

5.3.1. Challenges

Optical access is a segment of network providing broadband services to mobile, residential, business users within typically a distance of 20 km. Fig 5 shows PON technology evolution and standard trends, which has been mostly standardized in ITU-T and IEEE [9]. The PON technologies have mainly evolved to increase the speed per wavelength based on cost-effective optics and the use of non-return-to-zero (NRZ) modulation format. 10G-PONs such as XGS-PON and 10G-EPON support symmetric downstream and upstream transmission are being testbed by various network operators in preparation for commercial deployments. The NG-PON2 standard was developed by ITU-T and provides a total network throughput of 40 Gbps, corresponding to up to 10 Gbps symmetric upstream/downstream speeds available at each subscriber. The use of a tunable transceiver in the subscriber side equipment resolved the inventory problem, whereas it also led to the need to find technologies that satisfy both price and performance. The development of new PON standards was also started for beyond 10 Gbps per wavelength. The 50G-EPON by IEEE supports one or two wavelengths of 25 Gbps, and aggregated capacity reaches 50 Gbps by channel bonding. The 25GS-PON MSA group has published a specification for 25 Gbps symmetric PON. Its optical specification is based on the 25G EPON standard, and a transmission convergence (TC) layer is an extension of XGS-PON. Meanwhile, ITU-T is working on the TDM-PON standard with 50 Gbps per single wavelength with NRZ modulation and digital signal processing. Unlike the 10 Gbps based PON, higher speed PONs such as 50G E-PON, 25GS-PON, 50G HSP utilize O-band for both upstream and downstream transmission to avoid the dispersion induced penalty. In addition, the NRZ modulation format was adopted due to its simplicity as well as nonlinearity tolerance.

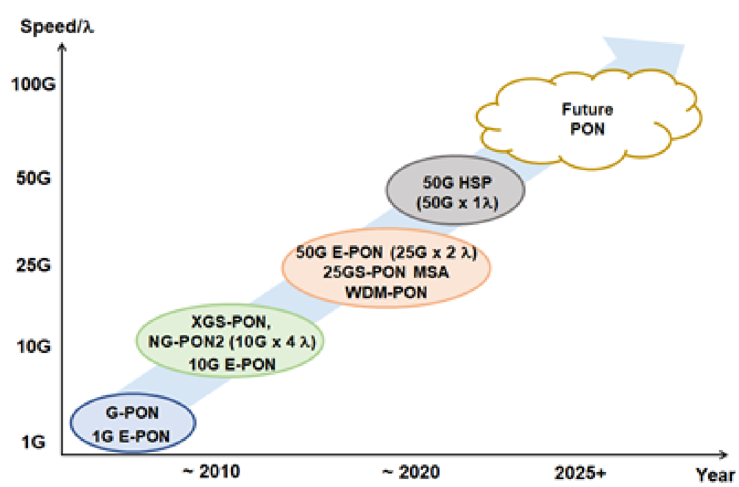


Figure 5. PON technologies evolution and standard trends.

Optical access network continuously evolved into higher speed systems providing broadband services to residential users (FTTH: Fiber-to-the-Home), and recently has been expanding its applications to mobile communication networks and business application as shown in the Figure 6 below. Thus, future PON have various challenges including high capacity, low latency, flexibility, and so on. First of all, the speed of the PON port is expected to evolve to 100 Gbps and beyond. The high-speed channel over 100

Gbps must be accommodated while maintaining the power budget of the legacy PON to implement future PONs over existing ODNs. However, a limited launched power in PON, poor receiver sensitivity of high-speed optical components, and chromatic dispersion of fiber are still obstacles to maintain a satisfactory power budget. The accommodation of mobile traffic with low-latency connection is demanding in future access networks. The higher carrier frequencies of 5G and beyond reduces the propagation distance of wireless links, and optical fiber will need to penetrate deeper toward the end users. Although multiple end-users in the optical power splitters-based point-to-multipoint (PtMP) PON could have easy optical connectivity anywhere in the network, high latency in upstream direction is a critical issue. Flexibility adding/replacing new functions and accommodating various types of applications in future PON are also needed. Scalability to serve more functions independent of physical infrastructure is also required. Since the conventional PON equipment has limited hardware and software flexibility, the accommodating various services and assignment of logically separated PON resources optimized for different types of service characteristics are difficult.

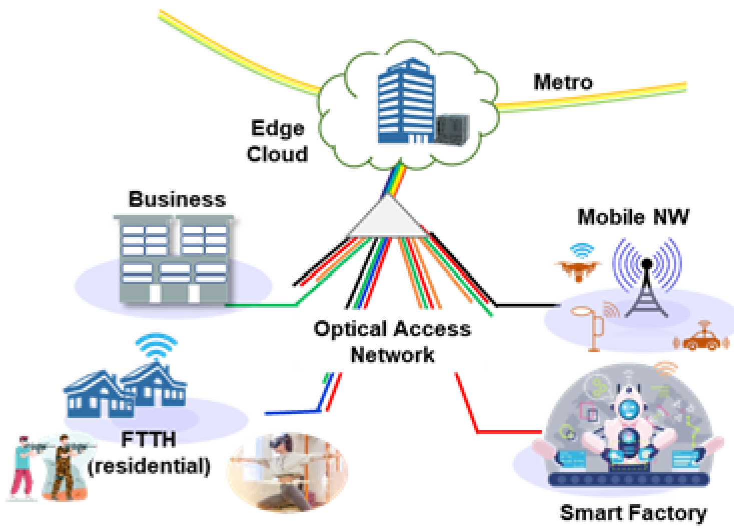


Figure 6. Future optical access network.

Table 5. Challenges Associated with High-Speed Optical Access Networks

Near-term Challenges: 2022-2025	*Description*
Low latency	Less than several hundred micro-second upstream latency to accommodate low-latency mobile traffic
Mid-term Challenges: 2026-2027	*Description*
Flexibility	-Flexibly adding and replacing new functions in the PON equipment -Accommodating various types of applications over PON and assigning logically separated PON resources optimized for different type of service characteristics
Long-term Challenges: 2028-2032	*Description*
High capacity	The speed of PON port over 100 Gbps while maintaining the power budget of the existing ODN

5.3.2. Potential Solutions

The capacity of current PON is not enough for the explosive data traffic and mobile applications. The latency with advanced bandwidth assignment is appropriated for backhaul and midhaul application, however, reduced latency is needed for fronthaul application. To support different types of applications within the same ODN and to accommodate more functions flexibly, virtualization and slicing of access network are needed.

Table 6. Potential Solutions in High-Speed Optical Access Networks

Near-term Challenges: 2022-2025	*Potential Solutions to Near-Term Challenges*
Low latency	Low-latency connection required for fronthaul application is possible by exchanging traffic scheduling information between optical and mobile equipment via CTI (cooperative transport interface) messages and co-operative dynamic bandwidth allocation (CO-DBA) in OLT.
Mid-term Challenges: 2026-2027	*Potential Solutions to Mid-term Challenges*
Flexibility	Flexible and sliced PON could be achieved by abstracting and virtualizing physical PON after disaggregating OLT into physical part and logical part.
Long-term Challenges: 2028-2032	*Potential Solutions to Long-term Challenges*
High capacity	The speed of the PON port 100 Gbps and beyond will be achieved by advanced modulation formats such as low-complexity coherent detection or direction modulation with digital signal processing.

5.3.2.1. Cooperative dynamic bandwidth allocation

Unlike the content-oriented conventional network focusing on the delivery of audio-visual and data traffic, the emerging future PON tactile internet demands steering/control-based communications providing real-time control and physical tactile experiences over the internet along with conventional data traffic. Virtual reality, augmented reality games, manufacturing facilities/control systems all require low latency as well as high bandwidth. The typical latency of TDM-PON with advanced DBA is appropriated for midhaul and backhaul in the mobile network. For the use of TDM-PON in the fronthaul, however, the latency should be further reduced. Mobile traffic utilizes slot-based scheduling, and each slot have various upstream and downstream traffic configuration. By exchanging this scheduling information between optical and mobile equipment via CTI (cooperative transport interface) messages, optical line terminals (OLTs) could have ultra-low latency connections with co-operative dynamic bandwidth allocation (CO-DBA).

5.3.2.2. Virtualization and slicing

The flexible and sliced PON could be achieved by abstracting and virtualizing physical PON after disaggregating OLT into physical part and logical part. By disaggregating and virtualization, PON can be divided into physical and logical resources. The physical resource includes upstream ports, PON cards, PON ports, and ONUs, while the logical resource contains hardware forwarding entries, bandwidth profile, type of DBA. These OLT resources can be allocated on demand and then exclusively used by the intended slices for the different applications. A flexible DBA with modular configuration could be used to provide optimized bandwidth as well as latency for different types of applications. The assignment of logically separated network resources optimized for different service characteristics and scalability to serve more functions independent of physical infrastructure are possible.

5.3.2.3. Advanced modulation format

There have been many researches to find appropriate modulation format for high-speed PON. One approach is coherent detection with a single carrier or orthogonal frequency division multiplexing (OFDM). Multi-level modulation such as DP-QPSK or dual polarization-quadrature amplitude modulation (DP-QAM) can be used for data modulation. Direct detection including NRZ-on/off keying

(OOK), duo-binary, differential quadrature phase shift keying (DQPSK) or multilevel-pulse amplitude modulation (PAM) combined with electrical digital processing technology (DSP) is also a solution for the high-speed PON. A direct detection has merits of simple configuration and nonlinearity tolerance particularly in NRZ format, whereas the chromatic dispersion compensation and relatively high baud rate are issues to be resolved. The coherent detection has many merits such as good receiver sensitivity, chromatic dispersion compensation and distortion mitigation. Complexity and real-time operation to practically use the coherent detection technology should be resolved [10].

5.4. Co-Packaged Optics and Data Center Networks

5.4.1. Challenges

Data centers (DCs) have developed very fast in recent years. In 2014, 10 Gbps was the main solution, but currently 100 Gbps is commonly used. Now 400ZR (400 Gbps optical transmission over a single wavelength for DWDM deployments was recently standardized. Until recently, people were still considering C band and coherent optics too expensive. Now in 400ZR, C-band and coherent are clearly identified as mainstream options for data communications.

Modern DC networks with their bandwidth requirements are necessarily based on photonic technology, because only optical communication can offer sufficient capacity. However, the current DC network architectures limit the use of optics to transmission between electronic switches and typically to each server within a rack. DC networks are generally classified as intra-DC or inter-DC networks.

Intra-DC networks are enterprise networks constructed in a variety of architectures. A common hierarchical DC network architecture consists of three levels, referred to as tiers, i.e., access (edge) tier, aggregation tier, and core tier, see Figure 7 [11]. They are currently based on electronic packet switches (EPSs). Optical links connecting EPSs use either individual fibers or fiber ribbons, which are costly, bulky, hard to manage and not scalable.

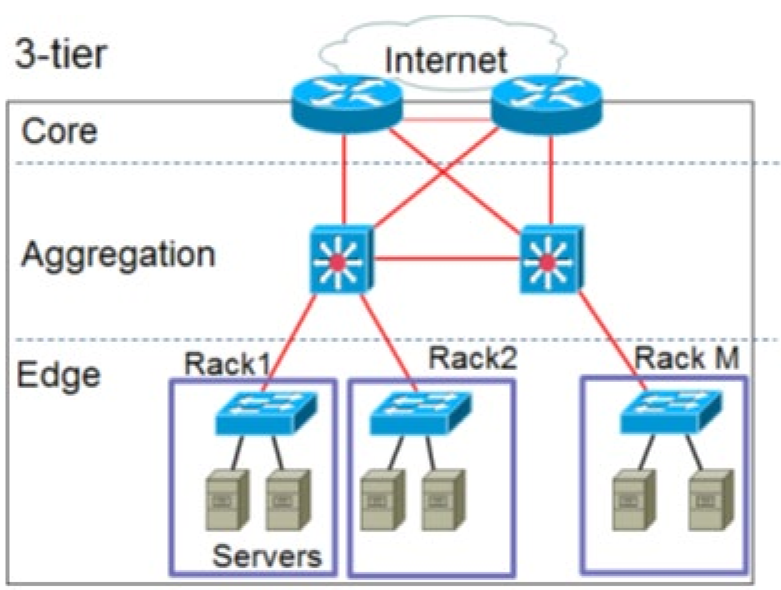


Figure 7. Hierarchical DC network architecture.

The access (edge) tier is often referred to as top of the rack (ToR) switch. In the current DC networks, the optics is mainly used for transmission, while switching is performed by EPSs. One of the major issues of such EPS-based DC network is the high-power consumption. Therefore, the next step in the evolution of the DC network architecture is reducing the number of EPSs by merging aggregation and core tiers and by replacing electronic switching with optical switching.

The increasing service demand leads to a need for upgrading DCs with more compute resources. Currently, an inefficient utilization of compute resources comes from the deployment of integrated servers, where the number of CPUs, memory and storage units are pre-defined. In a large DC, thousands of blade servers are interconnected in the network. A blade server contains a fixed amount of resources (i.e., CPU, memory, storage) integrated together on the server's bus. However, the virtualized services running on the servers are diverse and may require different amounts of the various resources.

5.4.1. Data Center Interconnect

The Data Center Interconnect (DCI) is a new class of optical systems that has grown out of enterprise networks. In general DCI systems are point-to-point, high-capacity optical line systems connecting to enterprise campuses or buildings. The scale of these systems can vary between intra-campus to metro area to long haul and even sub-sea systems. Being point-to-point systems, DCIs can be loaded to full wavelength capacity without wavelength blocking and can be deployed at full capacity from day one. DCIs can also involve multiple parallel fibers. While often using the same technologies as other systems operating at the same reach, the fact that DCIs are used at full capacity changes the economics and design of certain features, such as the transceivers and node architectures.

Shorter reach or Edge Direct Fiber DCI systems are used for applications such as private peering, CDN or WAN services. For co-location office/data center providers, these systems can include a path from the cage of one customer to another cage of different customer or Business units, in the same Internet Data Center provider with different metro ranges up to 30 km in order to avoid amplification.

5.4.2. Co-Packaged Optics

Co-packaging of optics and electronics is the next step where optics will replace copper wiring. While optics and electronics are technically "co-packaged" in transceivers today, the term refers to co-packaging chiplets of transceiver optics (detectors and modulators or lasers with an attached fiber) with a valuable ASIC switch chip inside a multi-chip module, shown in the Figure 8. This was the topic of an OIDA workshop on 30-31 March 2021 (details here).

Optical communication first appeared in commercial networks in long-haul and undersea links, where its substitution for copper wire was most compelling. Innovations in optical technology tilted the balance over the years to the point that optical fiber extends to homes and inside data centers to racks and boards. The next milestone would be to reach inside the board edge to a multi-chip module containing the switch chip and multiple transceiver chiplets. Commercial CPOs have recently been introduced and they are rapidly becoming the main evolution path for many processors and electronic switch chips. Also critical is that integrated photonics is necessary to reduce the size, power, parts count, and cost.

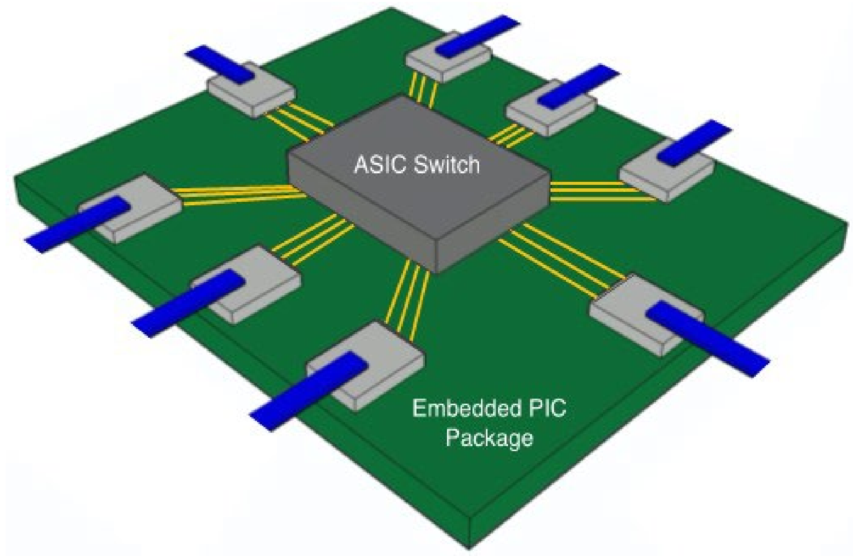


Figure 8. Illustration of integrated photonics transceiver chiplets co-packaged with an ASIC switch in a multi-chip module. Source: Peter O'Brien, Tyndall Institute and European PIXAPP pilot line (2021).

Table 7. Challenges Associated with Co-Packaged Optics and Data Center Networks

Near-term Challenges: 2022-2025	*Description*
Scaling DCI Networks	C band high capacity DWDM systems are near spectral efficiency limits in the fiber and the power density in telecom offices is pushing the thermal limits of rack power. Continued growth requires similar reductions in power, footprint, and cost.
Off-chip capacity	Processors (CPU and switch) are become limited by the available capacity of the off-chip interconnects. Sub 10 picojoule/bit efficiencies are needed.
More challenges	Add rows for each additional challenge
Mid-term Challenges2026-2027	*Description*
Data center power and interconnect capacity	Another factor of 10 growth in data centers will result in massive campuses using proportionally larger power. The energy scaling of all of the data center components from servers to switches is slowing down resulting in more greater increases in electricity use as capacity increases.
Long-term Challenges: 2028-2032	*Description*
Long term scaling	Power and footprint for data centers will continue to be critical challenges for data centers over the long term.

5.4.3. Potential Solutions

Several architectures utilizing optical switching technologies have been proposed for the aggregation and core tiers. A hybrid solution, where electronic packet switching is applied for small data volumes (referred to as mice connections) and optical circuit switching technology is applied for high volume data flows (referred to as elephant flows) was proposed in Helios [12].

Table 8. Potential Solutions for Co-Packaged Optics and Data Center Networks

Near-term Challenges: 2022-2025	*Potential Solutions to Near-Term Challenges*
Scaling DCI Networks	Greater capacity will be achieved through a combination of multi-fiber systems and multi-band systems, such a C+L+S. Both approaches require new strategies for scaling such as sharing amplifier pump power for more efficient amplification across the bands or fibers.

Off-Chip Capacity	Co-packaged optics using optical interposers to increase the shoreline bandwidth density of the chips.
Mid-term Challenges: 2026-2027	*Potential Solutions to Mid-term Challenges*
Data Center power and interconnect capacity	An evolution of disaggregation down to the chip level while making best use of renewable energy and efficient facility wide operation is expected to provide significant efficiency improvements, going beyond current technologies. Disaggregated data centers will rely on co-packaged optics to move data more efficiently off chip as well as data center optical switching for efficient operation across the data center. In addition, the growing capacity demand for connectivity between the disaggregated resources can potentially be addressed by SDM solutions (e.g., use of multicore fibers)
Long-term Challenges: 2028-2032	*Potential Solutions to Long-term Challenges*
Long term scaling	Potential directions for long term scale are to move to co-production strategies in which heat lost in data centers is repurposed for other manufacturing processes or building controls. This includes applications in edge cloud scenarios in which computing and networking equipment is integrated into the urban infrastructure. Optical switching and adaptation with changing load requirements will be needed.

5.4.3.1. Optical Switching

In order to further reduce energy consumption and cabling complexity aggregation and core tiers can be merged by all-optical switching architectures, see Figure 9. The optical switching can be based on either optical circuit switching [13] or optical packet switching [14]. In both cases the optical switching architectures require active optical switching devices, e.g., wavelength selective switches (WSSs) and optical space switching matrices. Additionally, in optical packet switching the buffering is performed in the electronic domain.

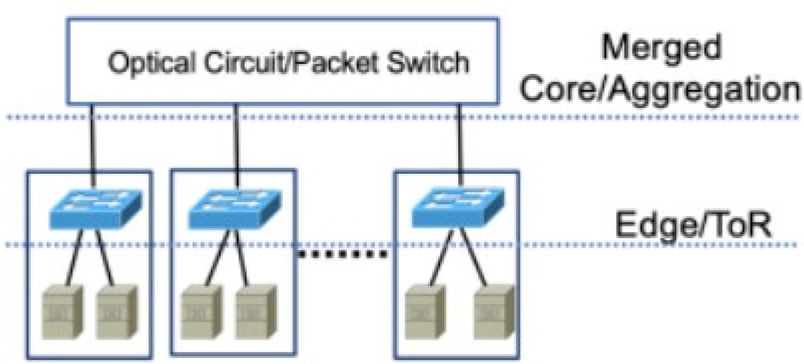


Figure 9. DC network architecture with merged core/aggregation tier based on optical switching.

However, it has been shown that applying optical switching technologies in the core/aggregation tier (Figure 9) can reduce energy consumption per bit by at most a factor of 2, compared to DC networks based entirely on EPSs [15]. This limitation is caused by the large number of EPS devices in the edge, i.e., at ToR. Therefore, to further reduce the energy consumption, passive optical interconnects (POIs) at ToR have been proposed. It has been shown that these architectures are able to reduce energy consumption per bit by a factor of 10.

5.4.3.2. Data Center Disaggregation

The mismatch between the diversity of resources required and the fixed amount of resources integrated in the physical blade servers may lead to so called resource stranding, which is one of the major reasons that limit resource utilization in DCs. Resource stranding means that the running applications in a server have used up one type of resource while the other types of resources are still idle and cannot be used. Therefore, it may be beneficial to disaggregate different resources in DCs and utilize them according to the demand. However, it comes with tough requirements on the capacity and latency of network interconnecting different types of compute resources, which can only be satisfied by photonic technology [16].

5.4.3.3. Data Center Interconnect

DCI is a rapidly growing optical system market that is becoming a technology leader in terms of high-capacity optics over distance. DCI relies heavily on photonic integration in order to deliver this capacity while meeting the cost and thermal density requirements of the data centers and co-location sites that they connect. DCI will increasingly make use of parallel fiber solutions and potential spatial division multiplexing within the fiber (see below). DCI systems used by co-location DC operators and telecom providers can be expected to use multi-tenant solutions in order to fill the links. Disaggregated optical systems might be used for this purpose. In particular, partially disaggregated systems separate the transceivers from the line system, allowing for easier upgrade of the transceivers and multi-tenant, bring your own optics, approaches. As edge services proliferate and demand for data starts reaching beyond capacity availability, one would expect edge network DCI to offer dynamic connectivity by time and volume with anticipated spot pricing models to encourage and discourage usage patterns to spread across time. Also, one expects adaptation of different bands and use of coreless or multicore fiber with different programmable characteristics to match the requirements for low latency and higher throughput.

5.4.3.4. Space Division Multiplexing

In order to address the increasing capacity demand and to reduce fiber complexity in DC networks space division multiplexing (SDM), in particular multi-core fibers (MCF), can be applied. Combining SDM with WDM can further improve utilization of connectivity resources. Further details on SDM are included in Section 5.8.

5.4.3.5. Co-Packaged Optics

Some data center architectures will require co-packaging with 50 Tbps switches by 2023. All architectures that migrate to 100 Tbps switches, due to appear as soon as 2025, will require co-packaged solutions. Specialty processors for artificial intelligence applications were identified as one of the leading platforms needing the highest density and highest speed for co-packaged optics.

Table 9 summarizes two applications: the traditional architectures of today and next-generation architectures that disaggregate resources, such as memory. The targets call for an order of magnitude improvement in power to Pico Joules(pJ) per bit or less, “shoreline densities” of 100s-1000s Gbps per mm of board edge, and a cost of much less than USD 1/Gbps. (All specifications refer to the overall link from “microcode to microcode” or “buffer to buffer.”)

Table 9. Summary of target specifications for co-packaged optics and electronics in two data center applications

Function	Copackaged optics For traditional DC networking	Copackaged optics For disaggregated resources (e.g., memory)
Optical link reach	10s to 2,000 m	10s to 100 m
Latency	Hundreds of ns + prop delay	ns + propagation delay
Energy (pJ/bit)	<10	<1
Bandwidth/shoreline (Gbps/mm)	100s	100s
Reliability (FITs)	Better than pluggable	?
Cost (per Gbps)	<$1	<<$1

Source: OIDA Workshop on Developments in Co-Packaging Technologies for Data Centers (30-31 March 2021).

A key question is how to get the power per bit down from 10's pJ/bit today to the single digit pJ/bit with the cost targets needed, and the workshop differed about how to make it happen. An informal poll of workshop attendees suggested that about 25% believed the laser would have to be in the package, another quarter thought it would have to be outside the package, and half thought that both solutions would prevail, depending on the application. Intel is in the latter group; it is pursuing both solutions for its customers. Likewise, with substantial innovation continuing in areas like fiber attach, participants were mixed about standards. About one quarter thought standards would be necessary, one third thought proprietary solutions would come first, and the rest thought both would coexist for the time being.

5.5. Machine Learning in Optical Networks

5.5.1. Challenges

Nowadays, as computing power has been increasing, the ability to build the artificial intelligence (AI) systems that can observe dynamic environments, handle complex tasks, and make intelligent decisions has become more and more attractive. Machine learning (ML) is an important enabling technology for AI systems, and has been successfully adopted in a number of applications, most notably speech and image recognition. Many networking problems may also benefit from ML, and there has been an explosion of papers in the literature recently on applying ML-based approaches to solve a variety of problems related to optical networks. Specifically, people have tried to apply ML-based approaches to quality-of-transmission (QoT) estimation and prediction, network design and planning, resource management and service provisioning, network control and management, failure detection and location, etc. These efforts have promoted the idea of network automation, *i.e.*, transforming future optical networks from based on software-defined networking (SDN) to knowledge-defined networking (KDN). As shown in Figure 10 below, the centralized SDN controller collects network status data and feeds it to the knowledge plane that is based on ML. The knowledge plane first leverages ML-based approaches to extract the knowledge for network automation with predictive analytics, and then uses the knowledge to make intelligent decisions for addressing complex tasks regarding network operation. Therefore, the optical network can be managed timelier with less human intervention.

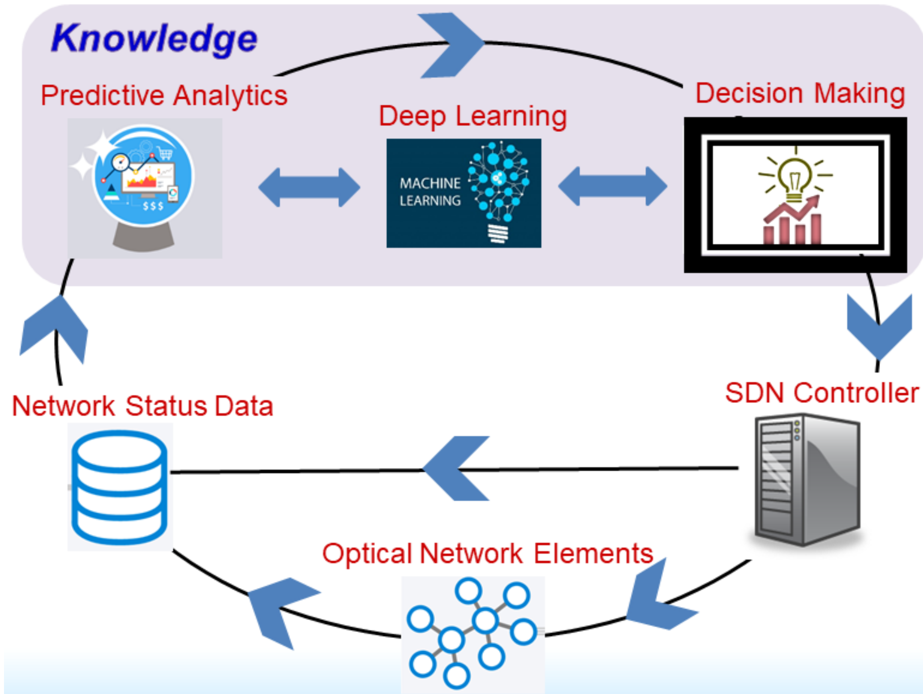


Figure 10. Network automation in a KDN-based optical network.

Despite the initial success, there are still several challenges to facilitate network automation in production/real-world optical networks:

(a) ML-based approaches cannot be effective without being trained and verified with significant amounts of network status data, either labeled or unlabeled. However, the availability of realistic data obtained from production/real-world optical networks is a major challenge. First of all, due to the considerations on privacy and business interests, network operators might not be able to share such data with the research community. Second, even if the data can be provided by network operators, the configurations of the optical networkers where it was collected might still be a black hole to researchers. Third, for the research on next generation optical network architectures and technologies, network status data can only be obtained through simulations or lab experiments.

(b) As an ML model is essentially designed and trained for a specific dataset, different ML-based approaches designed for a same task cannot be compared properly without an open and standard dataset. However, it is still a significant challenge to compose open and standard datasets that are related to optical networks and can be shared among the research community.

(c) Optical networks can have very large-scales and numerous network elements, which will make their network states fairly complex (i.e., each state can only be represented with highly dimensional status data). Therefore, how to design, train and maintain scalable ML models that can work with large optical networks and complex and dynamic network environments will be another major challenge.

(d) One concern about introducing ML-based approaches to reduce human intervention in planning, provisioning, and maintaining optical networks is that how saft and robust the ML-based approaches are. For example, it is known that ML-based approaches can be easily misled by the attacks based on adversarial samples. Hence, the security and reliability of ML-based approaches for optical networks will be a challenge.

(e) There is no clear consensus or understanding yet on which ML model is the best suitable for a specific problem related to optical networks. Moreover, the application of ML to many problems related to optical networks (e.g., survivability, and disaster management) has either not been explored at all or only received very little attention.

(f) The generalization of ML-based approaches is also a major challenge. This is because the current work on an ML-based approach for a specific optical network problem is usually only suitable for a given network topology and/or a specific network configuration. When we need to apply it to a different network topology and/or a different network configuration, we need to retrain it or even redesign the neural networks in it. This greatly restricts the application of ML-based approaches in optical networks. However, how an ML model that was designed and trained for one optical network can be transferred to another one with a different topology and/or different network configuration, is still an open issue.

Table 10. Challenges for Machine Learning in Optical Networks

Near-term Challenges: 2022-2027	*Description*
Datasets	Very few public datasets are available, and the collection of data is often limited by either customer privacy requirements or business constraints. Great efforts are needed to compose open and standard datasets that can be shared among the research community.
Problem spaces	Only a few specific problems related to optical networks have been studied thus far and clear problem definitions are often lacking. Application of ML is needed to more optical network problems.
Scalability	Optical networks often have large-scales and numerous network elements, and thus the ML models for them would be trained and verified with fairly large and complex datasets. How to design, train and maintain scalable ML models that can work with such optical networks is a major challenge
Security and Reliability	Introducing ML-based approaches to reduce human intervention in planning, provisioning, and maintaining optical networks can raise concerns related to safety and robustness.
Application of ML models	There is no clear consensus or understanding yet on what ML models are the best suitable for specific problems related to optical networks.
Generalization of ML models	Need a wider range of test cases and scenarios to build confidence in methods and benchmark results. Need to make sure that an ML model that was designed and trained for one optical network can be easily transferred to be applied on another one.
Long-term Challenge: 2027-2032	*Description*
Long-term scalability	Scalability of ML techniques is expected to be a long-term challenge as ML finds application in a broader range of areas and addresses more challenging problems.
Digital Twins	The use of digital twins both for optical networks and integrated with other networks has not been studied in detail and presents challenges in terms of computational complexity and speed.
Practical-ness	ML-based approaches should be verified in production optical networks, and comprehensive and standard test cases should be generated by the industry.

5.5.2. Potential Solutions

A range of solutions are currently under investigation and the field is rapidly developing. Three key areas that need particular focus have been identified below and near-term and long-term solutions are described in Table 11 below.

(a) Researchers and practitioners must agree on the types and formats of data to be used for ML.

(b) More work is needed on evaluating the effectiveness of various ML methods to other optical networking problems, and best practices on what tools are the best suited for specific problems need to be developed.

(c) There has been some work, but the power and limits of transfer learning need to be investigated more thoroughly.

Table 11. Potential Solutions for Machine Learning in Optical Networks

Near-term Challenges: 2022-2027	*Potential Solutions to Near-Term Challenges*
Standards and best practices	Several of the challenges identified will be largely addressed through the introduction of best practices and standards related to the use of ML in optical networks. More R&D is needed on methods in order to support this.
Reference datasets and testbeds	The use of testbeds, particularly involving field deployed hardware, to collect data can solve the need for datasets and also provide use case scenarios for benchmarking. Such testbeds can be costly and would require much instrumentation and thus would need either industry consortia or government funding.
Transfer learning	More investigation of transfer learning methods for optical networks could address use in a wider range of topologies and scenarios, as well as improving the scalability for large datasets.
Long-term Challenges: 2027-2032	*Potential Solutions to Long-term Challenges*
Long Term Scalability	*Improved computational methods and use of physical models, taking advantage of features of the physical systems involved can improve scalability.*
Digital Twins	Research into digital twins for optical technologies, standardization of digital twin approaches and new methods to accelerate associated computation will improve the viability of digital twin in optical network applications.

5.6. In-Building Optical Networks

5.6.1. Challenges

Today's home networks serve use cases in 5G in industrial/office/residential scenarios. Applications are used by humans and run on fixed and mobile devices with variable computing power. Best-effort traffic is considered enough, and first real-time applications such as video conferencing are seeing massive use due to Covid-19. The architectures are centralized with distributed fixed and wireless clients. Uplink to fixed access networks is a bundle of single- and multimode fibers for industry and office buildings on campuses, ending in a central office. On each floor, there is a 10G uplink to the private data center which is split by a factor of 10-100x among fixed and wireless access points sharing the uplink capacity. Residential homes have a single fiber/DSL/cable which are aggregated in a passive optical network node and fed through a single fiber to the central office (CO). Typical fixed port performance in homes is 1G Ethernet. Wi-Fi 5/6 access points are massively deployed serving an area capacity of around 1 Mbit/m².

Future home networks (2030) are expected to serve traditional and new use cases in 6G in similar scenarios. Applications will serve humans increasingly supported by large numbers of sensors, actuators and autonomous machines. Traffic changes from download-dominated best-effort Internet to upload-dominated ultra-low latency, reliable, high capacity connecting imaging devices (cameras, radars, lidars) to the private cloud in the campus network offering increasing computing power, thus forming the future Internet of Things (IoT). There will be a trend that wireless replaces cables on the last 1-5 meters. These would cause interference if radio alone was used penetrating through walls and experiencing numerous reflections in each room.

Future architectures will continue to be centralized with a massively increased number of distributed fixed and wireless clients. Industry and office campuses will connect through multiple MCF as uplinks to the fixed access network ending in a central office which will be augmented with remote data center resources (Central Office Rearchitected as a Datacenter, CORD). In the building, there will be a private cloud connected by 1Tbit/s Ethernet to each floor, then split by a factor of 100-1.000x to connect the larger number of fixed and wireless clients. Port capacity will vary between 1-10G. Residential homes will be connected by fiber-to-the-home (FTTH) and equivalent technologies, i.e., G.fast and wireless-to-the-home (WTTH) using 60 GHz and potentially also short range (10-100 m) optical wireless (LiFi) links. PONs for FTTH will upgrade by use of MCF going parallel from the passive split point to the CORD. Wireless area capacity will reach 100 Mbit/s/m^2.

Evolved Wi-Fi 7 will be deployed with a higher density of access points but may become inefficient to serve cable-like quality of service (QoS) for future IoT. There are new ideas for Wi-Fi 7 and beyond to coordinate interference from other Wi-Fi networks in neighbor homes. While these occur randomly today, they could be coordinated from the CORD by considering Wi-Fi access points as remote antennas and the uplink to the CORD via the fixed access network as the fronthaul [17]. This requires the definition of a functional split also in the MAC and PHY layer in Wi-Fi 7 and beyond, showing what protocol functionality is being centralized and what distributed. Together with using the new 6 GHz spectrum for Wi-Fi, which no longer ISM and thus uncontended from other wireless technologies and intentionally left free by the IEEE from coexistence issues with legacy Wi-Fi, the listen-before-talk method may be replaced by deterministic channel access to meet strict QoS requirements for future IoT.

Additional spectrum with more reliable QoS will be increasingly used, creating the case for 10G 60GHz and LiFi links (802.11ay/G.vlc). Both media do not penetrate through walls, cover just a single room and create little or zero interference. Propagation is with line-of-sight only. These emerging technologies are alternative answers to manage the rising interference for large numbers of future IoT devices [18]. The ultra-dense short-range fixed infrastructure to connect the many access points is a big techno-economic challenge for small-cell wireless networks in general. Proposed solutions for new or renewed buildings are Power-over-Ethernet and a new, low-cost fiber-to-the-room (FTTR) PON technology. In existing buildings, powerlines in the lighting infrastructure can be reused as a fronthaul, i.e., luminaires are co-located with wireless access points (e.g., LiFi).

A visionary view of the future in-building network technologies is shown in Figure 11.

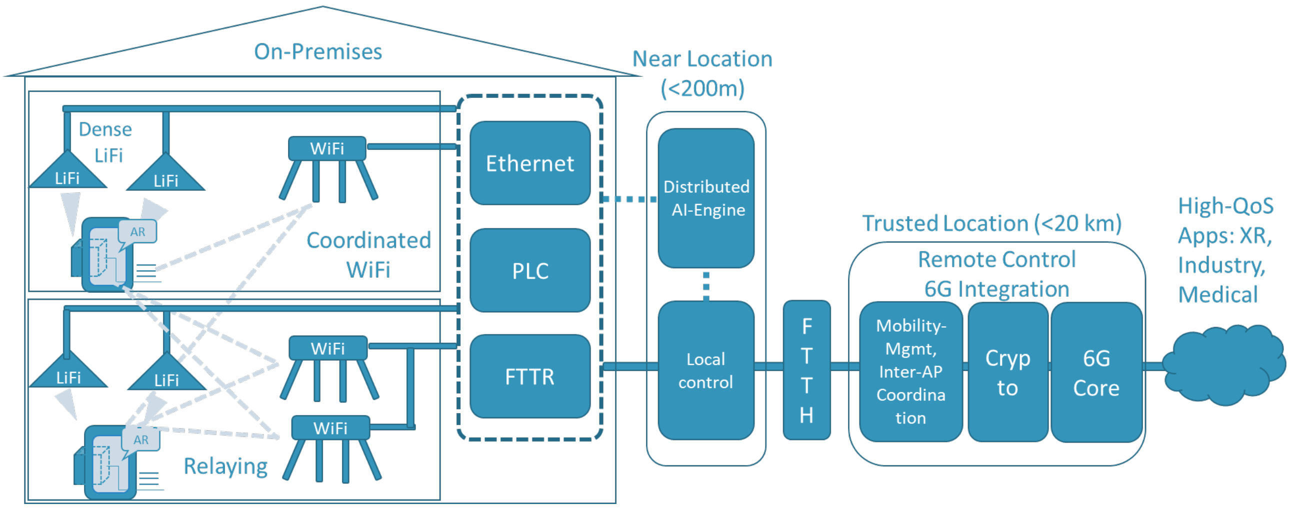


Figure 11. Envisioned in-building network architecture for 6G era.

It is expected that the intelligence to control the home network will be in- and outside the building, e.g., in a private cloud in the campus network (such as distributes AI and some local control e.g., for the LiFi subsystem) as well as in a trusted location owned by the network operator (i.e., the CORD) where mobility and interference are managed, security terminated and an interface to 6G provided.

The key idea is to consider the future in-building network, which consists of heterogeneous set of fixed and wireless technologies, altogether as a non-3GPP indoor radio access network (RAN) which can be integrated with the 6G core, same as native 6G RAN technologies. The advantages are i) significantly lower cost, compared to 6G-only indoor deployment, ii) simple in-building technologies deploy- and maintainable by IT technicians, while more complex network functions will be provided by the telecom operator, iii) similar QoS and security levels like native 6G RAN.

With a range of technologies as the candidate for providing indoor wireless delivery such as optical wireless channels, terahertz frequencies, and millimeter wave frequencies, it will be a key challenge to see how such technologies can coexist within buildings and around buildings and how they will become part of the integrated 6G/Wi-Fi networking environment.

Table 12. Challenges Associated with In-Building Optical Networks

Near-term Challenges: 2022-2025	*Description*
Challenge 1: High performance Wi-Fi via a centralized Wi-Fi architecture	Wi-Fi is an essential network segment and their capacity offer highspeed access with high performance is important. Architecting Wi-Fi as a centralized network with a cloud-RAN, which consists of distributed radio units (RUs) being remote-controlled by a central unit (CU), will lead to improved bandwidth, improved interference mitigation, and enhanced security.
Challenge 2: High bandwidth wireless delivery using 60 GHz and LiFi technologies	Different indoor settings demand a diverse connectivity requirement with the possibility of radio frequency free transmission in certain rf denied environments such as medical hospital environments. Indoor wireless delivery needs alternative methods such as the use of 60 GHz and LiFi as alternative wireless transmission technologies.
Challenge 3: Ultrabroadband delivery indoor using fixed or wireline technologies	Buildings will demand even greater bandwidth for connectivity inside and with the outside world. Despite presence of many current technologies, Fiber has emerged as the only sustainable medium to deliver indoor fixed connectivity. This requires new and customized optical access technologies need to be developed to meet the cost and the performance expectations of in-building networks.
Mid-term Challenge: 2026-2027	

Challenge 4: Improved security of indoor networks and 6G integration	With the seamless integration of inbuilding network with mobile and access networks, security of indoor networks become a major challenge. Security of these networks needs to be at a similar level of 5G and 6G and we will require new approaches to enhance security especially given the diversity of wireless connection technologies that may be used across inbuilding networks.
Long-term Challenges: 2028-2032	
Challenge 5: New channels for delivering very highspeed connectivity indoor	*Development of LiFi and other optical wireless communication alternatives, considerations of terahertz frequency bands for indoor wireless delivery, Integration with 6G and beyond*

5.6.2. Potential Solutions

Roadblocks/challenges/requirements towards this future home network include the development of new technologies such as SDM PON, low-cost Tbit Ethernet, meshed and daisy chain topologies to connect a 10x larger number of fixed/wireless access points and the availability of 60 GHz and LiFi technologies, which are expected to reach the mass market [19].

Table 13. Potential Solutions for In-Building Optical Networks

Near-term Challenges: 2022-2025	*Potential Solutions to Near-Term Challenges*
Challenge 1: High performance Wi-Fi	Develop Wi-Fi into a cloud-RAN, which consists of distributed radio units (RUs) being remote-controlled by a central unit (CU). Define suitable functional splits for Wi-Fi and enable network-assisted synchronization. Develop subscription basic physical and MAC layer technologies
Challenge 2: Technologies for High bandwidth wireless delivery	Develop 60GHz and LiFi as alternative wireless technologies Integration of such technologies with IoT to facilitate machine to machine communication needs in buildings and their surroundings Integration of these technologies within Wi-Fi, fixed, and mobile networking to support seamless network connectivity
Challenge 3: Ultrabroadband delivery indoors using fixed or wireline technologies	Fiber becomes the only sustainable medium. Provide powerful indoor distribution network technology (FTTR) and connect buildings to the operator network with enhanced optical access technologies (e.g., SDM-PON for FTTH). Support also legacy technologies (PoE, PLC) which will coexist but be replaced by fiber in the end.
Mid-term Challenges: 2026-2027	*Potential Solutions to Mid-term Challenges*
Challenge 4: Improved security of indoor networks and 6G integration	Add a security solution comparable to 6G to also Wi-Fi, integrate the heterogeneous in-building network as trusted non-3GPP indoor-RAN with the 6G core network.
Long-term Challenges: 2028-2032	*Potential Solutions to Long-term Challenges*
Challenge 5: New channels for delivering very highspeed connectivity indoor	*Development of LiFi and other optical wireless communication alternatives, considerations of terahertz frequency bands for indoor wireless delivery, Integration with 6G and beyond*

5.7. Optical Wireless Technologies for Space Communications Using Satellites or High-Flying Platforms

5.7.1. Challenges

Long-distance, high data rate communication in space, be it satellite-to-satellite, satellite-to-Earth, or even to or from our Moon or Mars, is expected to become increasingly important to support science data transfer, telemetry, remote monitoring, and Internet connectivity. An example of why this is essential now is the plan by NASA to place a permanent human base on the Moon before the end of this decade. There is currently a strong trend in space communication to make a transition from the currently widely used radio frequency (RF)-based links to links based on laser or optical beams. There are clearly many challenges associated with this. However, in addition to the benefit of an unregulated spectrum, smaller size, weight, and power consumption, the key motivations for this transition are the larger bandwidth and the significantly smaller beam diffraction resulting in much smaller link loss and thus higher capacity. This is true even when considering the very large difference between the RF apertures, which are as large as up to 70 m in diameter in the current Earth-based deep space network receiver antennas, and the much smaller laser-beam apertures (typically 10-30 cm diameter). Therefore, the capacity (transmitted information bits per second) and reach of the optical links are expected to significantly surpass those using radio waves. The capacity in an ideal optical communication link scenario is determined by, in addition to the link loss, the available transmitted optical power and the receiver sensitivity (defined as the needed minimum optical power to recover the data without error, sometimes being expressed in photons per information bit, PPB). The transmitted power is limited by engineering constraints (e.g., practical power consumption limits), while the receiver sensitivity is fundamentally limited by unavoidable vacuum noise.

Free-space optical communication (FSOC) or optical wireless communication (OWC) in space and/or at high-elevation atmosphere has two main use cases. Satellites or high-elevation airborne platforms, such as balloons or unmanned aerial vehicles (UAVs), could utilize OWC to transfer data among each other to at high speeds and form a backhaul network for end-to-end transfers among terrestrial or low-elevation locations. First use case is to provision high-speed Internet access to rural terrestrial areas where it is infeasible or too costly for wireline or 5G deployments to reach. Second use case is to provision high-speed Internet access to airborne platforms such as commercial aircrafts or drones.

OWC has been utilized among geosynchronous (GEO) and Medium Earth Orbit (MEO) satellites for data transfer. These Optical Inter-Satellite Links (OISLs) provide a backhaul for end-to-end transmissions among terrestrial or low-elevation locations. OISLs use lasers and photodetectors as OWC components. Even though there is no existing standard, near infrared wavelengths around 1,550 nm are considered [20] while infrared light wavelengths have also been reported [4] for situations where atmospheric effects may hinder the link. Recent efforts on standardizing OISLs point to using near infrared light bands in the 1,528 – 1,577 nm range with a center frequency of 193.1 THz [5]. On-Off Keying (OOK) modulation is typically used for these links and a 100 GHz or more optical bandwidth is accessed. For satellite-to-Earth transfers, legacy Ku, Ka, and E bands are utilized, sometimes with phased arrays with beam steering capability.

The type of satellite being used significantly impacts the scope of wireless applications. GEO and MEO satellites provide 270 ms and 35-85 ms latency for earth-satellite-earth transfers. These latencies rule out most real-time Internet applications such as video/audio conferencing or gaming as they require smaller latencies. On the positive side, it is possible to cover the entire Earth with 3 GEO or 10 MEO satellites and they can orbit at speeds similar to Earth’s rotational speed which makes them more convenient for pointing to/from specific locations on Earth. With Low Earth Orbit (LEO) satellites, it is possible to attain 1-7 ms round-trip latency but their orbital speed must be 27,000 km/h to escape Earth’s gravitational force which makes it hard to organize the coverage of the Earth’s surface. At least 50 LEO satellites are necessary to attain a minimal coverage of the Earth, while using switching among the satellites.

Existing Internet download rates with GEO satellite-based commercial solutions can reach up to 100 Mbps with several hundreds of milliseconds of latency due to the long distance the signal has to travel to the GEO orbit and back to the Earth. Though it is possible to attain much larger download rates (e.g., 1,000 Gbps) with customization of the satellite link, providing such high download rates at scale has not proliferated. In GEO or MEO based solutions, the signal typically travels to the satellite and back to a station on Earth, after which it uses terrestrial transmissions (fiber or point-to-point wireless) to reach its destination on Earth. With the LEO satellites, however, OISLs become more critical as the signal may need to travel across multiple LEO satellites to reach a ground station on Earth.

Table 14. Challenges Associated with Optical Wireless Technologies for Space Communications Using Satellites or High-Flying Platforms

Near-term Challenges: 2022-2025	*Description*
Challenge 1: Pointing and Acquisition for Mobile Directional Links	In order to establish optical wireless or highly directional wireless links for very long-distance communications in space, highly sensitive pointing and acquisition methods are necessary. Existing solutions work for several kms, but solutions are needed for very long ranges at thousands of kms.
Challenge 2: Highly Directional Optical Wireless Transmitters	Directional wireless beams (be it RF or optical) diverge as they propagate. This is called the divergence angle or half-power beamwidth. At very long ranges (1000+ kms), it is needed to bring the divergence angle to very low numbers such as a few milliradians so that the transmitted energy does not dissipate much and arrive at the receiver with a high intensity. Existing high-end lasers can operate with 1-3 milliradian divergence angles but they can be costly and bulky. Solutions are needed to keep the divergence angle small while minimizing the form factor of the transmitter system.
Challenge 3: Low SWaP Transceiver Systems	Transceiver systems with low size, weight, and power (SWaP) are needed as the existing RF-based transceiver systems can be quite bulky and only a few kgs is available for accommodating transceivers on a space platform such as a satellite.
Mid-term Challenges: 2026-2027	*Description*
Challenge 4: Optical Receivers Operable at Photon-Starved Environments and Multi-Aperture Receivers	At extremely long ranges exceeding 1,000 km, the number of photons arriving at the receiver will be few. Solutions are needed to tune receiver sensitivity for such photon-starved settings. Further, the receivers should be able to operate under a varying background noise as the background light arriving at a receiver will be changing in space. Multi-aperture receivers are also desirable to capture a large fraction of the beam.
Challenge 5: Economically Viable Satellite Deployment at Sufficient Mass	Provisioning sufficient coverage (e.g., to Earth) may require many satellites to be deployed. For instance, thousands of LEO satellites are needed to provide good coverage to Earth. Solutions are needed to keep the costs of such massive deployments under control and attain a viable and sustainable satellite-based access network.
Long-term Challenges: 2028-2032	*Description*
Challenge 6: Optoelectronic Components for Harsh Environments	Due to the vastness of space, exposure to harsh conditions rarely happens for satellites or other space platforms. However, as the deployment at space is increasing, hardware must become radiation-hard and capable of resisting extreme temperatures or cold. Optoelectronic and/or directional radio components that are robust against harsh environments will be needed to establish reliable communication links in space.
Challenge 7: Characterization of Atmospheric Conditions of Different Types	Earth's atmosphere is relatively well understood and atmospheric turbulence models are well established. However, as other planets or moons are being explored, channel conditions in these new types of atmospheres will have to be characterized so that new physical layer methods can be developed.

5.7.2. Potential Solutions

There is already a transition for RF carriers to light wave carriers in space communication links with a key motivation to increase the link capacity. This trend is expected to continue with a rapid expansion in the coming decades. An example of an impressive trial was the 622 Mb/s Moon-to-Earth (400.000 km) link at a 1,550 nm wavelength by NASA's Lunar Laser Communication Demonstration in 2014 [6] [7]. Quantum key encryption in a satellite-to-Earth optical communication was also demonstrated in a fully secure communication link in 2017 using the Chinese satellite Micius [8].

LEO deployments are a major platform for future NextG connectivity provisioning. With OISLs, an inter-satellite mesh network is being pursued for providing backhaul networking to terrestrial NextG connectivity with hundreds of megabits-per-second rates and a few millisecond latencies. With the recent advent of phased arrays, it is possible to provide continuous signal to a specific location on Earth as the LEO satellites are orbiting around the Earth. If thousands of LEO satellites are deployed, along with a well-organized inter-satellite mesh, it will be possible to provide continuous Internet access to any place on Earth. Commercial OISLs using OOK format and direct detection at 1,550 nm have already started to be deployed e.g., in the Starlink constellation by SpaceX to provide Internet services to rural areas. Plans are to launch several 1000s more satellites and to provide customers with downlink speed of at least 100 Mb/s. Only a few satellites currently have optical links, but this is expected to be the case for most future launches. Coherent systems appear a reasonable future step if higher capacity is needed.

OISLs will be a critical component of the mesh networking of LEO satellites. The communication range needed for such OISLs is 2,500-4,500 km, assuming thousands of LEO satellite deployments in a constellation. Attaining gigabit-per-second speeds at such long distances while operating with the limited power budget and form factor of the satellites involves significant research and development to be undertaken. Pointing-and-acquisition-and-tuning of OISLs will be challenging at extremely high orbital speeds. Further, there will be thousands of such OISLs in operation and failures will be common in this mesh network composed of OISLs. Hence, recovering from failures will have to be managed very carefully and backup paths as well as dynamic routing will be necessary. Lastly, the economic viability of the LEO satellite-based service is in question. LEO-based Internet access will likely become a viable option for rural areas and commercial aircrafts (if dishes can be integrated with planes), as there is other major technology to solve the high-speed Internet access problem for these two use cases. However, as a mainstream Internet access technology, the LEO satellite-based service will have to compete with fiber-based wireline solutions.

For a truly widespread transition to optical links in space communications, several challenges need to be successfully addressed, some of which are discussed briefly below.

Some aspects, rather obvious and generic, such as energy consumption limitations, weight (both of which favors optical systems over RF systems), and component tolerance to harsh radiation as well as to the very large temperature variations in space. In addition, because of the high directionality of laser beams, misalignment tolerance is small and can result in large pointing losses. Also, it is important to consider additive background noise from the sky, especially in cases of very large link loss. Since the challenges are quite different depending on the actual link, it is useful to make distinctions between links operating in atmospheric conditions (e.g., up/downlinks to Earth) or not, as well as between links of moderate reach (up to say 1000 km) or very long links (millions of km) which may operate in a "photon-starved" regime in the receiver.

For satellite-to-Earth links there is the special challenge due to the disturbances caused by the atmosphere such as absorption (due to weather conditions), scattering, and scintillation causing fluctuations in the received signal due to variation in refractive index which distorts the received signal. This currently may favor the use of RF links. However, the issue with bad weather could be significantly mitigated by using several ground stations across a continent allowing much lower outage by directing the beam to a place with nice weather, e.g., eight stations across Europe are predicted to provide 99,7% link availability [9]. Optical links with OOK, differential-BPSK or differential-QPSK modulation formats along with direct detection receivers are realistic short-term solutions. Coherent receivers can facilitate higher capacity by using higher level modulation format as well as DSP-based mitigation of various impairments, but the challenge of dealing with the spatial phase distortion in the received signal remains significant. However, progress is being made and techniques for spatial-division-multiplexed systems in optical fibers are promising candidates to handle this problem using digital signal processing (DSP).

OISLs are being explored also for GEO satellites communicating with LEO satellites. This will improve the connectivity with Earth by collecting data from a LEO satellite for subsequent transfer to Earth. For example, the European Space Agency (ESA) and Airbus demonstrated a link with a data rate of 1.8 Gbps using coherent detection and a BPSK modulation format at 1,064 nm [10]. NASA plans include 100 Gbps GEO-GEO links operating at 1,550 nm and using a similar solution also for the next manned mission to the Moon in 2023. It is expected to rely on commercial off-the-shelf technology from fiber telecommunications including silicon-photonics-based coherent receivers and DSP.

Mars-to-Earth links are currently only using RF links at a data rate of several kb/s which is causing a very problematic "science-return bottleneck" already today. Optical links are therefore certainly being considered seriously and would, in principle, have the capability to increase the link capacity by several orders of magnitude (to several Mb/s). However, the link loss will be huge (100s of dBs) with large variations and very few photons will remain to capture at the receiver. Thus, receiver sensitivity is essential in this "photon-starved" regime. Spectral efficiency can also be a very important aspect. However, in contrast to WDM systems used in fiber communication links, deep-space optical links are going to operate with a single optical carrier. In fact, as the received power will be very small (as will also the signal-to-noise ratio, SNR), it can be shown by inspecting the Shannon capacity limit that there is no significant advantage, in terms of overall data rate, to use WDM instead of a single carrier (assuming that the total available optical power is the same). Therefore, when considering spectral efficiency in this case, it is related to the electrical receiver bandwidth rather than the optical bandwidth. Pulse-position modulation (PPM), in which the position of a pulse among several possible temporal slots represents the information, and direct-detection photon-counting receivers is being considered as this format, in principle, can provide an arbitrarily good sensitivity at the expense of increasingly poor spectral efficiency. The best detectors (incorporating superconducting single-photon detectors for superior sensitivity) need to operate at temperatures of 2-4 K so in practice these are only useful for receivers on ground. In practice, this means that the analogue receiver bandwidth can limit the sensitivity as well as the capacity in a sensitivity vs. bit-rate trade-off. Therefore, with the PPM approach excellent sensitivity can only be achieved at relatively low bit rates, as this requires a very large number of temporal slots corresponding to a very large analogue bandwidth. Another approach being considered is adopting coherent receivers widely used in fiber communication, allowing formats (e.g., QPSK) with much higher spectral efficiency while also providing excellent (but not arbitrarily low) sensitivity (1 PPB has been demonstrated in a lab environment). If the signal is to be sent directly to Earth (as today) the atmospheric concerns remain. Therefore, it might be reasonable to consider an intermediate repeater hub e.g., on the Moon. It is of course important to capture an as large as possible fraction of the very large beam at the point of the receiver. Multi-aperture approaches are therefore being investigated. These include mainly analogue optical interferometric (in theory lossless) combiners and post-detection DSP based combining of the signal components.

In summary, significant efforts are currently invested into a transition to space communications using lasers. This involves not only national space agencies such as NASA, ESA, and JAXA, but also many commercial players such as SpaceX, Google, and Blue Origin. Much of the technology needs to be further refined and optimized for use in space including high power optical booster amplifiers, integrated chips, non-mechanical beam steering, adaptive optics, etc. It should also be noted that the technology developed is likely to find applications in secure communication as well as in Lidar systems e.g., for Earth monitoring.

Table 15. Potential Solutions for Optical Wireless Technologies for Space Communications Using Satellites or High-Flying Platforms

Near-term Challenges: 2022-2025	*Potential Solutions to Near-Term Challenges*
Challenge 1: Pointing and Acquisition for Mobile Directional Links	Design GPS-free methods for pointing and acquisition of directional wireless links. Utilize RF-based synchronization among mobile platforms to localize and discover neighboring mobile platforms. Design methods that do not require mechanical steering of transceivers and only use electronic steering.
Challenge 2: Highly Directional Optical Wireless Transmitters	Design and develop optical beamforming techniques. Develop adaptive optics methods to dynamically tune optical wireless beams' divergence angles.
Challenge 3: Low SWaP Transceiver Systems	Design optical wireless transceivers for replacing RF-based transceiver systems. Minimize the use of mechanical steering for optical wireless transceiver development.
Mid-term Challenges: 2026-2027	*Potential Solutions to Mid-term Challenges*
Challenge 4: Optical Receivers Operable at Photon-Starved Environments	Explore the use of more sensitive photodetectors such as single-photon avalanche diodes (SPADs). Employ an array of photodetectors and apply diversity combining to increase the probability of symbol detection. Use more amplification after the optical signal is received. Design machine learning methods to process the received (weak) optical signal and increase the capability to predict the symbol that was sent.
Challenge 5: Economically Viable Satellite Deployment at Sufficient Mass	Develop OISL technologies to reduce the need for more LEO satellites. Design inter-satellite mesh network protocols.
Long-term Challenges: 2028-2032	*Potential Solutions to Long-term Challenges*
Challenge 6: Optoelectronic Components for Harsh Environments	Design radiation-hard circuits, semiconductor devices, lasers, and photodetectors. Design techniques for sealing electronics against extremely high temperatures.
Challenge 7: Characterization of Atmospheric Conditions of Different Types	Run channel sounding experiments in atmospheric chambers imitating atmospheres of other planets or moons. Deploy optical wireless and RF communication links on other planets or moons.

5.8. Optical Fibers and Spatial Division Multiplexed Networks

5.8.1. Challenges

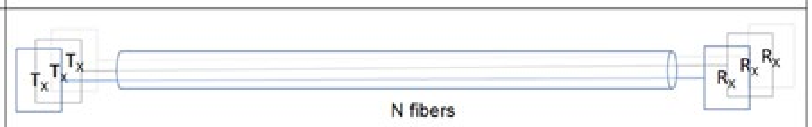
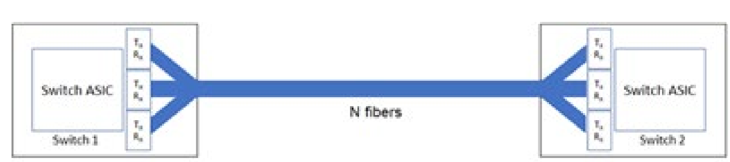
The optical fiber roadmap has been strongly influenced by the requirements of optical networks since low loss silica fiber was first demonstrated in 1970 [11] and adopted in the early 80s. Two types of fiber innovation have been seen over forty years of commercial use – an increase in fiber capacity by optimizing its properties for the highest and most economical transmission and improved fiber attributes to enable easy and quick deployment. The first use of optical fiber in long-haul applications utilized 1310 nm light sources and the first fiber standards, e.g., ITU-T Recommendation G.652, were targeting O-band transmission. By the late 80s and 90s, transmission equipment began using the wavelength region where optical fiber has the lowest attenuation i.e., 1550 nm (C-band) and the roadmap of optical fiber was defined by the optimization of chromatic dispersion (CD) in the C-band – first for a single wavelength and then for WDM systems. This drove the development of ITU-T Recommendations G.653 (dispersion shifted fibers), G.655 and G.656 (non-zero dispersion shifted fibers). In the 2000s and 2010s, the need to increase optical fiber capacity led to the expansion of transmission bands to L-band and S-band, and G.655 and G.656 standards were updated for a wider range of wavelengths. In addition, the deployment of broadband access networks based on optical fiber which began in the early 2000s led to creation of the whole new class of bend insensitive fibers described by ITU-T Recommendation G.657. Ironically, in long-haul networks, adoption of coherent transmission which compensates for CD through digital signal processing resulted in declining interest in CD optimization. Instead, roadmaps for the optical fibers used in the long-haul (especially submarine) transmission emphasized low attenuation and lower nonlinearity by increasing the fiber effective area.

Today, the most important development in optical fiber is dictated by the requirements of highly parallel systems where a large number of optical fibers, or more generally optical cores or optical modes, must be deployed in a constrained space. This is referred to as SDM and may take different forms ranging from deploying many small diameter single-core optical fibers to MCF and few-mode fibers (FMF). MCF and FMF are more disruptive implementations of SDM and require fanout devices, mode multiplexers and demultiplexers. In addition, FMFs with strong mode mixing require MIMO signal processing in order to separate different optical modes. The importance of the SDM trend is acknowledged by the fact that ITU-T is currently working on a technical report [12] that could become the first globally recognized and consented perspective of SDM technologies including characterization of key parameters. This document is informative guidance and serves as a first steppingstone to potential standardization.

5.8.2. Potential Future Directions

SDM is expected to be first adopted in three applications driven by their unique challenges (see Table 2x). In long haul and submarine links the driver for using SDM is based on reaching the capacity limit of optical fiber, the so-called Shannon limit, that stipulates that increased spectral efficiency requires higher signal to noise ratios and therefore higher optical channel power, which is limited by optical fiber nonlinearities especially in the very long systems like transoceanic submarine cables. Moreover, increasing channel power is challenging in submarine links since electric power is fed from the landing points and is limited by the available voltage and size of the cable conductor. SDM in submarine systems has been realized by using more single-core fibers in the cable and operating them in a linear or slightly nonlinear regime, thus requiring less power per fiber from the amplifiers [13]. This has resulted in the challenge to place more fibers in the existing cable to avoid very costly cable redesign and extensive requalification. SDM today in the long-haul systems manifests as using more optical fibers but the next generation SDM systems may use smaller diameter single-core fibers and even MCF [14].

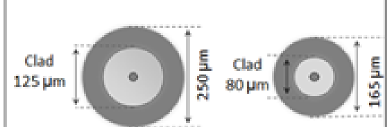
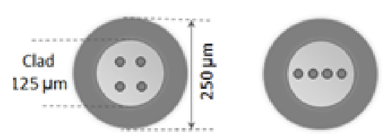
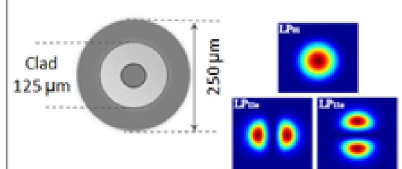
Table 16. The key applications that will benefit from the development of SDM.

Application (use case)	Reference Link Configuration
Long-haul submarine and terrestrial links	
Data Center Interconnects (DCIs)	
Intra Data Center Links	

The next use case where SDM can find adoption is data center interconnects (DCIs) where distances are rather short (≤10-20 km), and transmission systems are unamplified and operate in a linear regime (second row in Table 1). The challenge is in the number of fibers that must be deployed (today fiber counts in DCI cables approaches 3456 and 6912) and the size of the ducts (2 inch for one cable or large diameters e.g., 4 inch for multiple cables). This challenge is driven by the capacity requirements for DCIs connecting large data centers and transceiver economics: it is less expensive to use gray duplex transceivers that consume 2 fibers per transceiver than dense WDM transceivers (e.g., 400G ZR) that may transmit up to 64 channels in the C-band over one fiber pair. In addition, the cost of civil works in developed countries is high and drives the preference for deploying as many fiber cores as can be fed into the existing ducts.

The last use case for SDM is in intra-data center links where the expected adoption of co-packaged optics [21] will lead to the challenge of connecting more than 1024 fibers to silicon photonics chiplets (i.e., highly integrated transceivers) for an expected 51.2 Tb/s switch ASIC and even more for the later generations of ASICs. Achieving these connections with discrete fibers may prove challenging due to the high linear density of the optical cores at the edges of silicon photonics chiplets. The advantage of using smaller diameter fibers or MCFs would be increasing the density of cores. Moreover, MCF may create an additional advantage of doing one alignment for all cores in the MCF simultaneously.

Table 17. Different implementations of SDM: using single core fibers with smaller cladding and coating diameters, multi-core fibers and few-mode fibers.

SDM with Single Core Fibers	SDM with Multi-Core Fibers	SDM with Few-Mode Fibers
		
• Reduced coating and cladding diameter fibers e.g. 80 µm cladding	• Multiple cores in the cladding e.g. 4 cores in 125 µm cladding • Two variants – coupled and uncoupled cores	• Single core supporting multiple modes e.g. 6 mode FMF (each mode is double degenerate)
• Pros: Increased fibre density, does not need SDM components, compatible with current transceivers • Cons: need adapter Connection to standard 125 mm fiber, microbending sensitive, less coating material protection	• Pros: Increased fiber core density, • Cons: Not compatible with 125 µm cladding diameter fibre, Requires specialized connectors and splicers, needs SDM components (fan in/out),may require cable design with less microbending	• Pros: Large number of SDM channels, compatible with 125 µm cladding fibers, manufacturing costs lower than MCF, easier splicing • Cons: Complex mode mux/demux, FMFs with mode mixing require complex MIMO

The use cases listed above will likely use different implementations of SDM that are listed with their pros and cons in Table 2. The least disruptive is the use of single core fibers with smaller diameter coating or smaller coating and cladding. Today the majority of optical fibers have 125 mm cladding. The vast ecosystem of installation tools like cleavers and splicers was developed for this cladding size. High core density in the cable can be achieved by reducing the coating diameter from 250 mm to 200 mm (and possibly even smaller until the limit for necessary fiber protection is reached) without reducing fiber cladding diameter. The next step would be reduction of the cladding diameter and there are already examples of using smaller cladding fibers e.g., 80 mm in photonics modules. The miniaturization of a single core fiber will continue, likely targeting both cladding and coating diameters and it is unclear today what smallest single core fiber size can be achieved. Smaller diameter fibers will not require special devices like fanouts or mode multiplexers and will be compatible with incumbent transceivers and represent the least disruptive implementation of SDM.

The second implementation of SDM is MCF. It provides higher core density than smaller diameter fibers can achieve but it is the most disruptive implementation for SDM from a fiber design point of view. Today, many efforts are focused on MCF with cladding diameter of 125 mm to make it more compatible with incumbent single-core fiber designs. However, MCF will need specialized splicers and fanout devices that interface MCFs with traditional single-core fibers. It is expected that MCF designs will be optimized for different use cases (see middle column in Table 2) e.g., for DCIs links 2x2 MCF design may be used (or even higher core number) and for CPO applications cores may be aligned along the line e.g., in 1x4 or 2x4 designs.

The last implementation of SDM using FMFs is less disruptive from an optical fiber design and fabrication point of view but will require complex mode division multiplexers and demultiplexers. FMFs could be divided into two categories – with mode mixing, where modes can easily mix because their propagation constants are similar [15] and without mode mixing where mode propagation constants are sufficiently different, and their mixing is suppressed [16]. The former category will require MIMO receivers to separate individual modes. This MIMO processing is not new and is used in the single mode coherent systems where orthogonal polarizations are modulated independently and must be separated at the receiver, since they are degenerate and their propagation constants are equal, hence 2x2 MIMO is needed. However, the computational complexity of MIMO grows rapidly with the number of modes and its implementation becomes complex and power hungry. The latter category of FMFs relies on weak mixing of spatial modes and may not require MIMO at all [7], but the mode mixing must be kept sufficiently low. It remains to be seen if FMF will be adopted as one of the implementations of the SDM and which FMF type will prevail.

In conclusion, SDM represents the key trend in the evolution of optical fiber that would enable highly parallel and compact optical interconnects. The combination of fundamental physics and practical considerations like the economics of transceivers and availability and the cost of deploying ducts will drive the adoption of SDM. The winning implementation of SDM will likely depend on the use case and its adoption will be critically dependent on the availability of all parts of the ecosystem like fanouts, mode multiplexers and splicers. SDM will be an exciting area of the optical communications roadmap in this decade.

5.9. Quantum Communications

5.9.1. Challenges

Quantum key distribution optical systems are commercially available using low light level techniques. Recently these have been demonstrated to interoperate with classical fiber optic systems using an SDN based control plane [18]. Enterprises and data center operators are using quantum communication systems as part of a larger quantum strategy that often includes quantum random number generation and quantum vault technologies. Long distance QKD systems make use of satellite communications and systems of ‘trusted’ nodes to relay information.

Research programs are focused on developing methods to distribute qubit entanglement between quantum computers to enable distributed quantum computing and ultimately a quantum Internet. Linear optical amplification methods do not work in quantum systems. Therefore, much work is underway to develop a quantum repeater, which would allow for qubits in quantum memories at intermediate nodes to become entangled through a stepwise process of sequentially entangling neighboring pairs [19]. Recent experiments have achieved transmission beyond the repeaterless bound [20]. In addition to distributing entanglement, quantum networks will need to provide distillation and error correction methods in order to create reliable quantum communication at high fidelity.

Table 18. Challenges for Quantum Communications

Near-term Challenges: 2022-2025	*Description*
QKD Integration	Progress is needed on cost effective methods to integrate QKD and similar commercial quantum capabilities into the current network infrastructure across all relevant layers.
QKD Management & Control	Network control and management methods for QKD systems need to be developed and standardized for widespread adoption.
Mid-term Challenges: 2026-2027	*Description*
Entanglement Repeater	Basic repeater operation for extending entanglement distribution beyond nearest neighbors at a finite secure key rate. Useful for long distance key distribution and as a milestone towards entanglement distribution networks.
Classical Control of Quantum Networks	High performance classical network to manage quantum networks including coordination of photon heralding, quantum memory and repeater operations, and impairment and time synchronization management.
Long-term Challenges: 2028-2032	*Description*
Robust entanglement distribution	Basic building block for entanglement distribution networks, allowing for scalable high-fidelity teleportation between distant quantum memories. Includes quantum error correction coding or other purification and distillation techniques.

5.9.2. Potential Solutions

Considerable investment in quantum technology solutions are underway in both the public and private sectors. In terms of QKD technologies, the European Flagship and EuroQCI initiatives are a model for accelerating development in these areas. A European Union wide staging network is expected to start construction in 2022, with emphasis on the integration with classical networks and the management and control challenges related to quantum networks.

Table 19. Potential Solutions for Quantum Communications

Near-term Challenges: 2022-2025	*Potential Solutions to Near-Term Challenges*
QKD Integration	In-band methods (1550nm) require extraction of the quantum signal before or around any inline amplifiers and may be sensitive to the power of the neighboring classical channels or their Raman scattering. Out of band is also possible (1310nm) at a higher loss.
QKD Management and Control	Software Definited Networking (SDN) methods are the most promising approach to integrate QKD systems into classical communication systems, enabling a cross-layer approach to manage the QKD physical layer while also delivering the secure keys to the application layer.
Mid-term Challenges: 2026-2027	*Potential Solutions to Mid-term Challenges*
Entanglement Repeater	Cryogenic solutions include color centers in diamond (NV, SiV) and ion trap-based memories. Photonic cluster states might be feasible for room temperature operation, but pose more challenging implementation requirements.
Classical Control of Quantum Networks	Two basic approaches are considered: 1) distributed control of entanglement between neighbors and path formation based on successful results or 2) step by step entanglement path formation along set paths. Layering methods might be used to simplify operations if possible. New solutions are needed for this challenge.
Long-term Challenges: 2028-2032	*Potential Solutions to Long-term Challenges*
Robust Entanglement Distribution	Graph state coding and other quantum error correction methods are under investigation. More progress is needed.

6. STANDARDIZATION LANDSCAPE AND VISION

As discussed throughout the different technology roadmaps, there are a wide range of standards in use today in optical networks. Many high-performance technologies such as high speed transceivers and advanced architectures such as open line systems, have been developed through alliances and fora, often through multi-source agreements. New areas such as LEO satellite networks and optical switching in data centers might benefit from the creation of standards. IEEE is developing a report on spatial division multiplexing, which will be a first example of a standard in that area.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Summary of Conclusions

Optical networks are undergoing important technological changes across a range of different domains and application areas, including finding use in new areas such as space networks and quantum networks. The need for higher speeds is expected to remain particularly strong in access networks and data center interconnect systems. Overall capacity increases will also be achieved through greater use of parallel fiber systems, which will eventually move to multi-core fibers and other space division multiplexing solutions in some applications. Optics is being used in new ways within data centers with the emergence of co-packaged optics—combining optical interfaces into the electronic processor or switch chips. Optical switching has the potential to improve energy efficiency in data centers, particularly if it can be deployed at the top-of-rack. LiFi access networks will find greater use in in-building networks, particularly to provide higher capacity, while reducing the RF interference due to an increasing number of IoT devices. Xhaul approaches to radio access networks will evolve to higher speeds and greater use of DWDM, while adapting to tight latency constraints. Across this wide range of application areas, optical networks and technologies are seen to play an increasingly important role with greater performance demands and greater functionality.

7.2. Working Group Recommendations

Eight different optical network technology areas have been addressed in these roadmaps. Within each area, key challenges were identified and solutions expected in near, mid, or long-term time frames were described. In general, these solutions still require considerable research and development in order to find use in applications. The working group findings and recommendations are detailed within each section or referenced to other roadmapping or standardization activities and findings.

7.2.1. Future Work

The field of optical communication networks continues to evolve and these roadmaps will need to evolve with it. The fiber and spatial division multiplexed networks roadmap identified the key issues around their potential future use, but roadmap tables have not been developed. The development of the quantum networks roadmap can be considered a preliminary effort to be developed in more detail as the technology matures. The machine learning for optical networks roadmap is exploratory in nature and will be refined in future editions. In particular, machine learning can be used in many different aspects of optical networks and which areas will gain traction is still uncertain. Furthermore, many of the roadmaps will benefit from further development and descriptions of the challenges and solutions in future editions.

8. Contributor Bios

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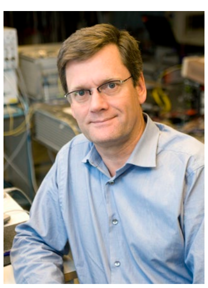
Lena Wosinska received her PhD degree in Photonics and Docent degree in Optical Networks from KTH Royal Institute of Technology, Sweden where she established a world leading research group working on optical networks. At KTH she was a Professor of Telecommunication until October 2018. Currently she is a Research Professor with the Chalmers University of Technology, Sweden, where she moved together with her team. Her research broadly concerns optical communications and networks, with a focus on fiber access and 5G/6G transport networks, energy and cost efficiency, optical data center networks, photonics in switching, network control, reliability, security, and survivability. She has been involved in many expert assignments and was working in several EU projects, as well as leading national and international research projects.



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9. References

[1] *H. Haas, et. al. "Introduction to indoor networking concepts and challenges in LiFi" J. Opt. Commun. Netw. 12, 2, pp. A190-A203 (2020).*

[2] *A. S. Hamza, J. S. Deogun, D. R. Alexander "Classification Framework for Free Space Optical Communication Links and Systems" IEEE Commun. Surveys & Tutor. 21, 2 pp. 1346-1382 (2019).*

[3] *Aaron Freeman, David Robie, "Multi mission capable optical inter satellite link," Proc. SPIE 11678, Free-Space Laser Communications XXXIII, 116780A (5 March 2021); https://doi.org/10.1117/12.2586138.*

[4] *General Atomics Partners with Space Development Agency to Demonstrate Optical Intersatellite Link, June 2020. https://www.ga.com/general-atomics-partners-with-space-development-agency-to-demonstrate-optical-intersatellite-link.*

[5] *Space Development Agency Optical Intersatellite Link (OISL) Standard, Space Development Agency, June 2020. https://www.sda.mil/wp-content/uploads/2020/08/9100-0001-01-OISL-Standard.pdf.*

[6] *Don M. Boroson, Bryan S. Robinson, Daniel V. Murphy, Dennis A. Burianek, Farzana Khatri, Joseph M. Kovalik, Zoran Sodnik, Donald M. Cornwell, "Overview and results of the Lunar Laser Communication Demonstration,",* Proc. SPIE 8971, Free-Space Laser Communication and Atmospheric Propagation XXVI, 89710S (6 March 2014); https://doi.org/10.1117/12.2045508.

[7] *Daniel V. Murphy, Jan E. Kansky, Matthew E. Grein, Robert T. Schulein, Matthew M. Willis, Robert E. Lafon, "LLCD operations using the Lunar Lasercom Ground Terminal," Proc. SPIE 8971, Free-Space Laser Communication and Atmospheric Propagation XXVI,,* 89710V (6 March 2014); https://doi.org/10.1117/12.2045509.

[8] *Liao, SK., Cai, WQ., Liu, WY. et al. Satellite-to-ground quantum key distribution. Nature 549, 43–47 (2017). https://doi.org/10.1038/nature23655.*

[9] *http://www.esa.int/Enabling_Support/Operations/ESA_Ground_Stations/Estrack_ground_stations.*

[10] *https://public.ccsds.org/Pubs/141x11o1e2.pdf.*

[11] *F. P. Kapron, D. B. Keck, R. D. Maurer, "Radiation losses in glass optical waveguides", Trunk Telecom. Guided Waves, IEE, p. 148, 1970.*

[12] *ITU-T work item TR.SDM (https://www.itu.int/ITU-T/workprog/wp_item.aspx?isn=16559).*

[13] *Maxim A. Bolshtyansky, Oleg V. Sinkin et. al. "Single-Mode Fiber SDM Submarine Systems" Journ. of. Light. Tech. Vol 38, p 1296-1304, 2020.*

[14] *K. Igarashi et al., "1.03-Exabit/s·km Super-Nyquist-WDM transmission over 7326-km seven-core fiber", ECOC, vol. PD3-E-3, 2013.*

[15] *R. Ryf, S. Randel, A. H. Gnauck, C. Bolle, A. Sierra, S. Mumtaz, M. Esmaeelpour, E. C. Burrows, R.-J. Essiambre, P. J. Winzer, D. W. Peckham, A. H. McCurdy, and R. Lingle,,* "Mode-division multiplexing over 96 km of few-mode fiber using coherent 6×6 MIMO processing," J. Lightwave Technol. 30(4), 521–531 (2012).

[16] *Ezra Ip et. al. "SDM transmission of real-time 10GbE traffic using commercial SFP + transceivers over 0.5km elliptical-core few-mode fiber" Optics Express. Vol. 23, No. 13, p. 17120 (2015).*

[17] J. M. Cioffi, "Cellular Subscriber Lines (CSL) A Wireless Wireline Physically Converged Architecture," *IEEE Transactions on Communications,* vol. 68, no. 12, pp. 7289-7310, 2020.

[18] R. S. T. E. H.-S. R. Wang, "End-to-End Quantum Secured Inter-Domain 5G Service Orchestration Over Dynamically Switched Flex-Grid Optical Networks Enabled by a q-ROADM," *J. Lightwave Technol.,* vol. 38, no. 1, pp. 139-149, 2020.

[19] R. V. Meter, "Quantum networking and internetworking," *IEEE Network,* vol. 26, no. 4, pp. 59-64, 2012.

[20] R. R. B. M. e. a. M.K. Bhaskar, "Experimental demonstration of memory-enhanced quantum communication," *Nature ,* vol. 580, pp. 60-64, 2020.

[21] *Co-Packaged Optics Collaboration http://www.copackagedoptics.com/.*

10. ACRONYMS/ABBREVIATIONS

Acronym	Meaning
10G-EPON	10 Gbps Ethernet Passive Optical Network
4G	4th Generation Mobile Networking Standard
5G	5th Generation Mobile Networking Standard
5GC	5G Core
6G	6th Generation Mobile Networking Standard
AIM	Automated Intelligent Management
ASIC	Application Specific Integrated Circuit
BBU	Baseband Unit
BPSK	Binary Phase Shift Keying
CD	Chromatic Dispersion
CO	Central Office
CO-DBA	Cooperative Dynamic Bandwidth Allocation
ComSoc	Communications Society
CORD	Central Office Rearchitected as a Datacenter
CPO	Co-Packaged Optics
CPRI	Common Packet Radio Interface
CPU	Central Processing Unit
CRAN	Centralized Radio Access Network
CTI	Cooperative Transport Interface
CU	Central Unit
CU	Central Unit
CWDM	Coarse Wavelength Division Multiplexing]
DBA	Dynamic Bandwidth Allocation
DC	Data Center
DCI	Data Center Interconnect
DSL	Digital Subscriber Line
DSP	Digital Signal Processing
DU	Distribution Unit
DWDM	Dense Wavelength Division Multiplexing
eCPRI	Enhanced Common Packet Radio Interface
EPC	Evolved Packet Core
EPON	Ethernet Passive Optical Networks
ePRTC	Enhances Primary Reference Timing Clock
EPS	Electronic Packet Switch
ESA	European Space Agency
ETSI	European Telecommunications Standards Institute
FIT	Failure in Time
FMF	Few Mode Fiber
FNI	Future Networks Initiative

FSAN	Full-Service Access Network
FSOC	Free Space Optical Communication
FTTH	Fiber-to-the-Home
Gbps	Gigabit per second
GEO	Geosynchronous Earth Orbit
GHz	Giga Hertz
GPON	Gigabit Passive Optical Network
HLS	Higher Layer Split
I/O	Input/Output
ICT	Information and Communications Technology
IEEE	Institution of Electrical and Electronic Engineering
INGR	International Network Generations Roadmap
IoT	Internet of Things
IPSR	Integrated Photonics Systems Roadmap
IQ	In-Phase and Quadrature
ITU-T	International Telecommunications Union - Telecommunications
JAXA	Japanese Aerospace Exploration Agency
LEO	Low Earth Orbit
LiFi	Light Fidelity, wireless communications
LLS	Lowe-Layer Split
LR	Long Range
LTE	Long Term Evolution
MAC	Medium Access Control
MCF	Multi Core Fibers
MEO	Medium Earth Orbit
MIMO	Multiple Input Multiple Output
MNO	Mobile Network Operator
MPO	Multi-fiber Push On
MSA	Multi-Source Agreements
MVNO	Mobile Virtual Network Operator
MWDM	Medium density Wavelength Division Multiplexing
NASA	National Aeronautics and Space Administration
NG-PON	Next Generation Passive Optical Network
NRZ	Non-return-to-zero
OCP	Open Compute Project
ODN	Optical Distribution Networks
ODTN	Optical Disaggregated Transport Network
OFDM	Orthogonal Frequency Division Multiplexing
OIDA	Optical Industry Development Associates
OIF	Optical Internetworking Forum
OISL	Optical Inter-Satellite Links
OLT	Optical Line Terminal
OOK	On-Off Keying

ORAN	Open Radio Access Network
O-RAN	Open Radio Access Network
OSA	Optical Society of America
OTA	Over-the-Air
OWC	Optical Wireless Communications
PAM	Pulse Amplitude Modulation
PHY	Physical Layer
pJ	pico-Joule
PM	Phase Modulation
PM-QPSK	Polarisation Multiplexed - Quadrature Phase Shift Keying
POI	Passive Optical Interconnect
PON	Passive Optical Networks
PPM	Pulse Position Modulation
PS	Photonics Society
PtMP	Point-to-Multipoint
PtP	Point-to-Point
QAM	Quadrature Amplitude Modulation
QKD	Quantum Key Distribution
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
QSFP	Quad Small Formfactor Pluggable
RAN	Radio Access Network
RF	Radio Frequency
RLC	Radio Link Control
ROADM	Reconfigurable Optical Add-Drop Multiplexers
RU	Radio Unit
SDM	Spatial Division Multiplexing
SDN	Software Defined Networking
SFP	Small Formfactor Pluggable
SNR	Signal to Noise Ratio
SR	Short Range
TAE	Timing Alignment Error
TBC	Telecom Boundary Clock
TC	Transmission Convergence
TDM	Time Division Multiplexing
TDM-PON	Time Division Multiplexed Passive Optical Network
TIP	Telecom Infra Project
TK	Technological Knowledge
ToR	Top-of-the-track
UAV	Unmanned Aerial Vehicle
USD	US Dollar
WDM	Wavelength Division Multiplexing
WDM-PON	Wavelength Division Multiplexed Passive Optical Network

WG	Working Group
WSS	Wavelength Selective Switch
XGS-PON	X Gbps Symmetric Passive Optical Network
Xhaul	fronthaul, midhaul and backhaul

IEEE ANTITRUST STATEMENT

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