IEEE

International Network Generations Roadmap

- Whitepaper -

Optics

IEEE Future NETWORKS

An IEEE 5G and Beyond Technology Roadmap

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Last Updated: 9 June 2021

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 datq 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

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'S VISON

This working group has identified several key trends that form the vision for optical networks in the coming decade. Figure 2 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 (X-haul) networks for future wireless networks and fixed high speed access networks. X-haul 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 X-haul 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 Gb/s 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.

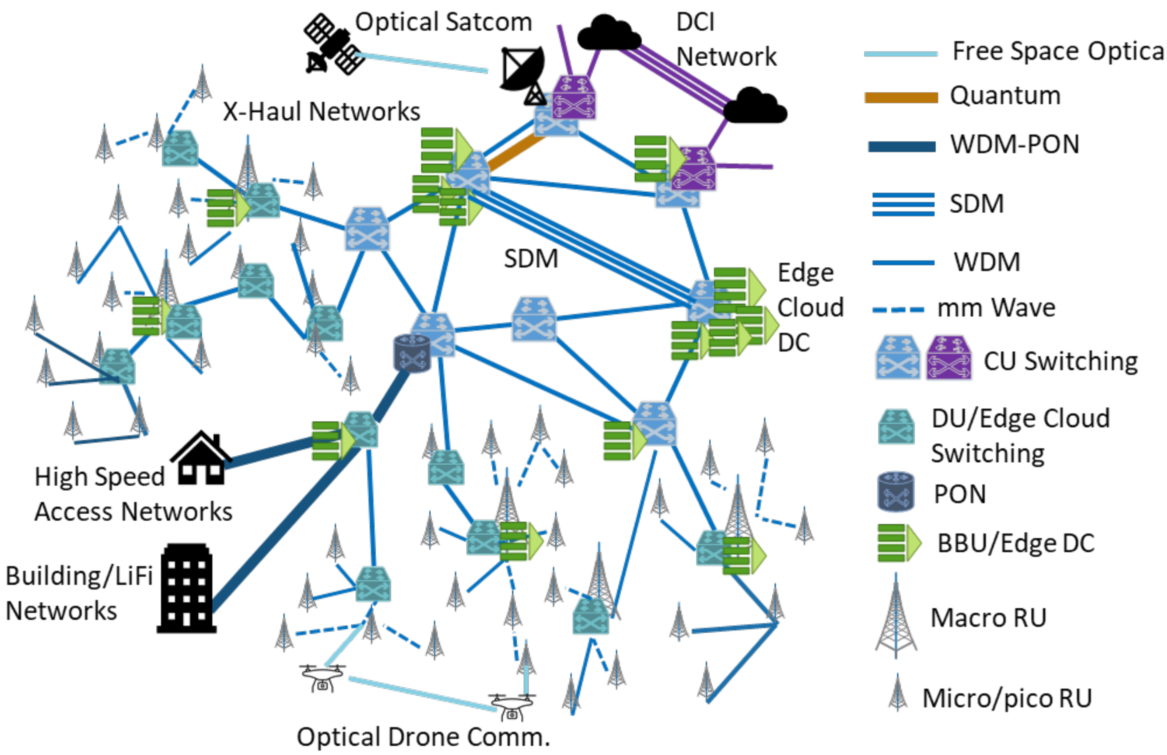


Figure 1. Vision of future optical communication networks.

2.1. Scope of Working Group Effort

The Future Networks Initiative's Optics Working Group (WG) will identify and build roadmaps for key optical technologies areas relevant to the INGR. The working group will seek to partner with existing roadmapping initiatives to avoid duplication and collaboratively identify new technology areas in need of roadmapping. Emphasis will be placed on new and emerging technologies and network evolution trends that are expected to shape future (optical) networks.

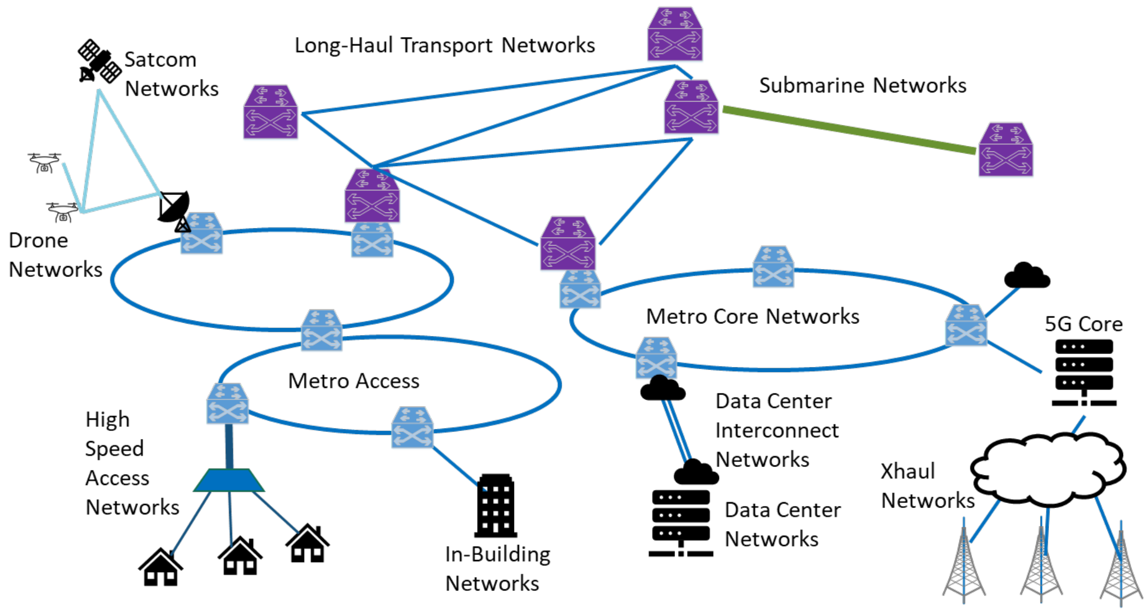


Figure 2. Different types of optical networks.

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. Aspects of these areas are considered within this whitepaper.

- Optical Xhaul (front/mid/backhaul) Networks.
- High Speed Access Networks
- Co-packaged Optics / Data Center Networks
- In-Building Optical Networks
- Optical Networks in Space
- Optical Fibers/SDM
- 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)
- 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)
- 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

3. TODAY'S LANDSCAPE

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.

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 Gb/s on-off keyed systems, to systems exploiting advanced modulation formats, e.g. 40 Gb/s differential phase shift keying to 100 Gb/s coherent (polarization multiplexed quadrature phase shift keying, PM-QPSK)) and 200 Gb/s 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, and 1000 Gb/s in different steps and formats, as discussed below. Access networks have evolved from 1 Gb/s and 2.5 Gb/s to 10 Gb/s, both for PON and point to point networks.

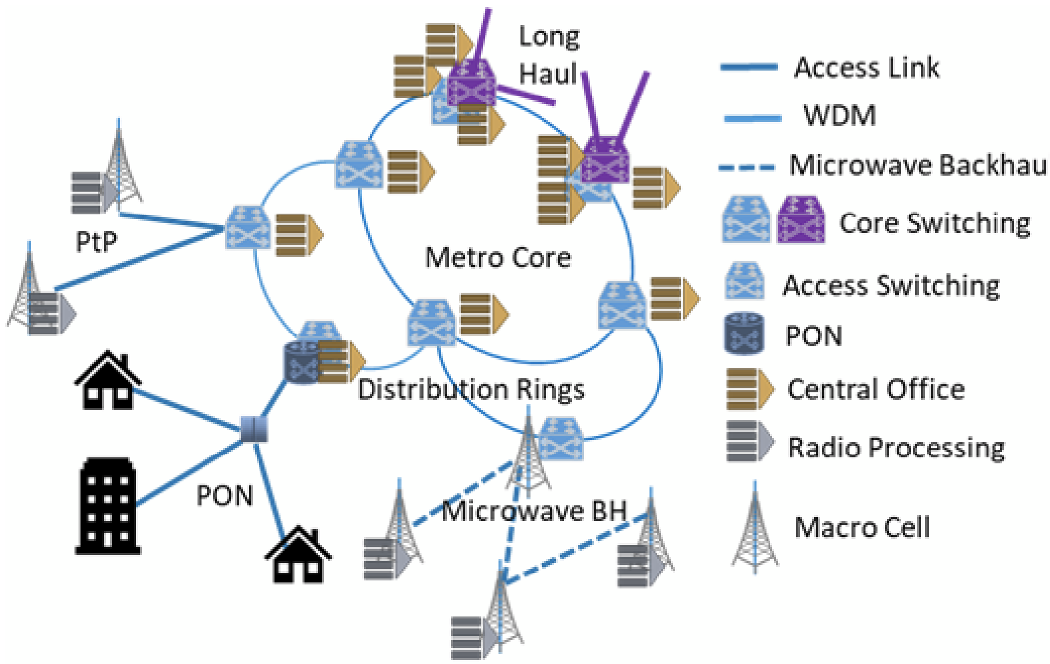


Figure 3. Today's optical networking landscape.

4. Optical Xhaul networks

4.1. 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 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].

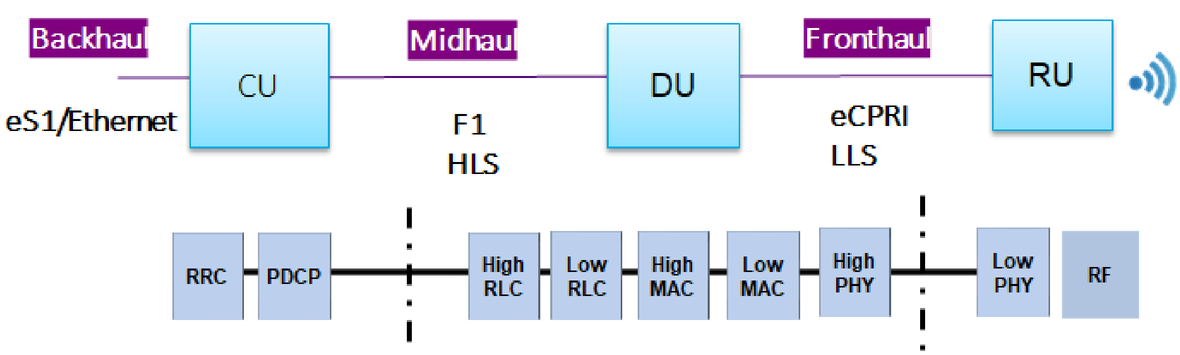


Figure 4. Xhaul Network; processing functions shown in grey boxes below the corresponding node types at which they are executed; dot-dashed lines indicate split locations.

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.

4.2. Future State

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]
- or 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.

4.3. 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.

5. High Speed Optical Access Networks

5.1. Current State

Optical access is a segment of network providing broadband services to mobile, residential, business users within typically a distance of 20 km. The optical link between edge cloud/central office and end users is often called the last mile by service provider, or the first mile by end user's perspective. With the replacement of traditional copper wires with optical fibers since the 2000s, 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 to accommodate 5G and beyond. Optical access networks can be roughly categorized into two parts according to link configurations: point-to-point (PtP) networks with WDM or dark fiber and point-to-multipoint (PtMP) networks with time division multiple (TDM) access. While PtP TDM-based PON are widely deployed worldwide for broadband access to residential users, PtP WDM based optical access such as WDM-PON are being applied to mobile fronthaul over PtMP optical distributed networks (ODN).

Unlike long-distance transmission networks, which mainly focus on maximizing the transmission capacity per fiber, optical access networks aim at minimizing the price per subscriber. Thus, there is a dogma that optical amplifiers and dispersion compensation are not allowed in the access link for cost-effective implementations. 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. The first generation of Ethernet PON (EPON (e.g., 1G EPON) provided bidirectional 1 Gb/s link. It was a natural extension of the Ethernet systems, and the PtMP connectivity was supported by the multipoint control protocol. Whereas the gigabit PON (GPON) supported an asymmetric bitrate of 2.48 Gb/s downstream and 1.24 Gb/s upstream. It was also a PtMP network and employed data encapsulation methods. High speed access standards such as XGS-PON and 10G-EPON support symmetric downstream and upstream transmission at 10 Gb/s and 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 Gb/s, corresponding to up to 10 Gb/s 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. Around 2020, the development of new PON standards started for beyond 10 Gb/s per wavelength. The 50G-EPON by IEEE supports one or two wavelengths of 25 Gb/s, and aggregated capacity reaches 50 Gb/s by channel bonding. Unlike the NG-PON2, the 50G-EPON does not require tunable optics at the optical network unit to support the two 25-Gbps wavelengths. The 25GS-PON MSA group has published a specification for 25 Gb/s 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 Gb/s per single wavelength with NRZ modulation and digital signal processing. The WDM-PON standard with 25 Gb/s per wavelength, mainly for the mobile fronthaul application, is also under study in ITU-T. Unlike the 10 Gb/s 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.

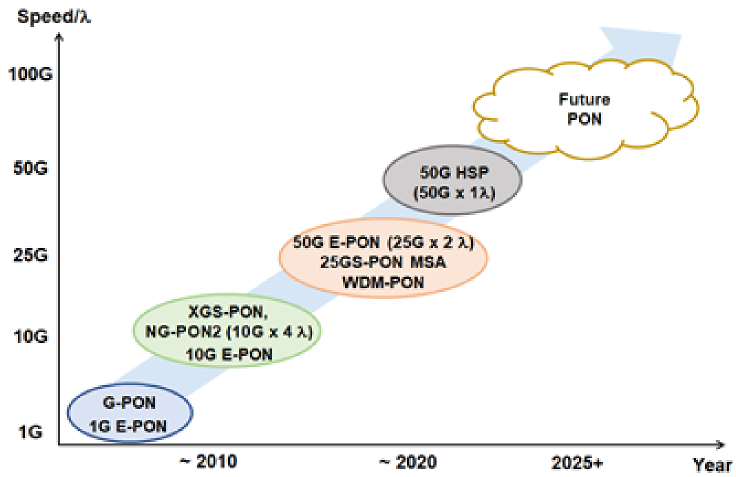


Figure 5. PON technologies evolution and standard trends.

5.2. Future State

High capacity and low-latency mobile traffic are expected to be the major performance demands for 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. Thus, optical connectivity to end users becomes a very important issue. In the PtMP PON, multiple end-users in the optical power splitters based optical distribution network (ODN) will need easy optical connectivity anywhere in the network. Optical connectivity for mobile, business, and conventional residential services could be possible in a single ODN through TDM or WDM technologies, as shown in the Fig 6 below.

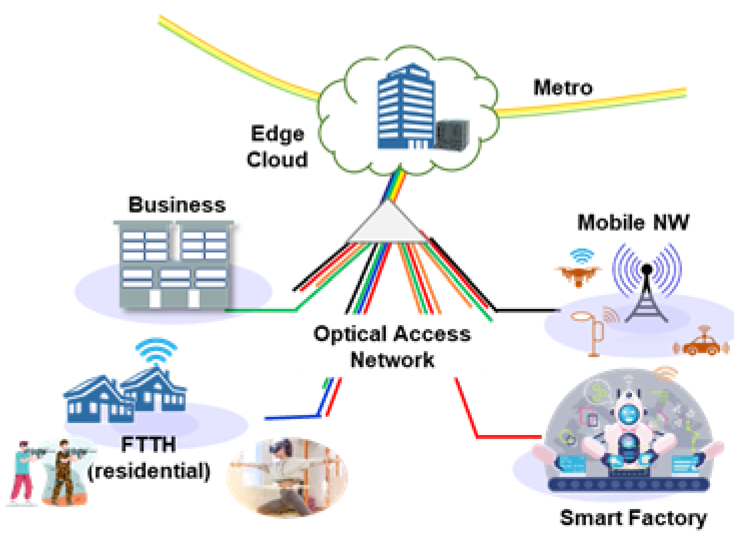


Figure 6. Future optical access network.

Future optical access networks 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 Gb/s and beyond. The high-speed channel over 100 Gb/s 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. Recently, there have been substantial efforts to find practical solutions for high-speed PON. One approach is applying coherent detection to achieve improved receiver sensitivity for modulation formats such as dual polarization quadrature phase shift keying (DP-QPSK) and orthogonal frequency division modulation (OFDM). Although the coherent detection is beneficial in terms of power budget and high-speed operation, there are still issues to be resolved such as complexity and real-time operation to practically use the coherent detection technology [10]. A direct detection approach such as NRZ with on-off keying (OOK) or multilevel pulse amplitude (PAM) combined with digital signal processing (DSP) is also a good candidate to achieve 100 Gb/s and beyond because of its simple configuration. Secondly, low latency data transmission in optical access networks is also important. 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. Ultra-low latency transport technologies are being standardized in ORAN/ITU-T. By exchanging 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). Other technologies in future PONs might include optical access slicing and flexibility through virtualization and optical disaggregation. The assignment of logically separated network resources optimized for different service characteristics would be useful to accommodate time-critical and non-time-critical applications in a high-speed PON. Since the purpose oriented current OLT has limited flexibility, assigning optimized resources for various services and replacing new functions are difficult. The flexibility and slicing of optical access networks could be achieved by abstracting and virtualizing physical PONs combined after disaggregating the OLT into a physical part and a logical part. A flexible DBA with modular configuration is also critical to provide optimized bandwidth as well as latency for different types of applications.

6. Co-packaged Optics and Data Center Networks

6.1. Current State

Data centers (DCs) have developed very fast in recent years. In 2014, 10Gbps was the main solution, but currently 100Gbps 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.

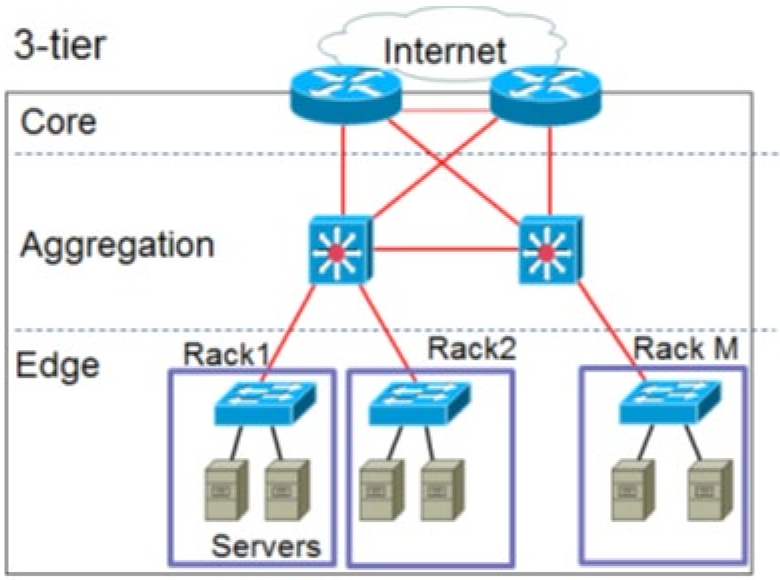


Figure 7. Hierarchical DC network architecture.

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.

6.1.1. 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.

6.1.2. 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.

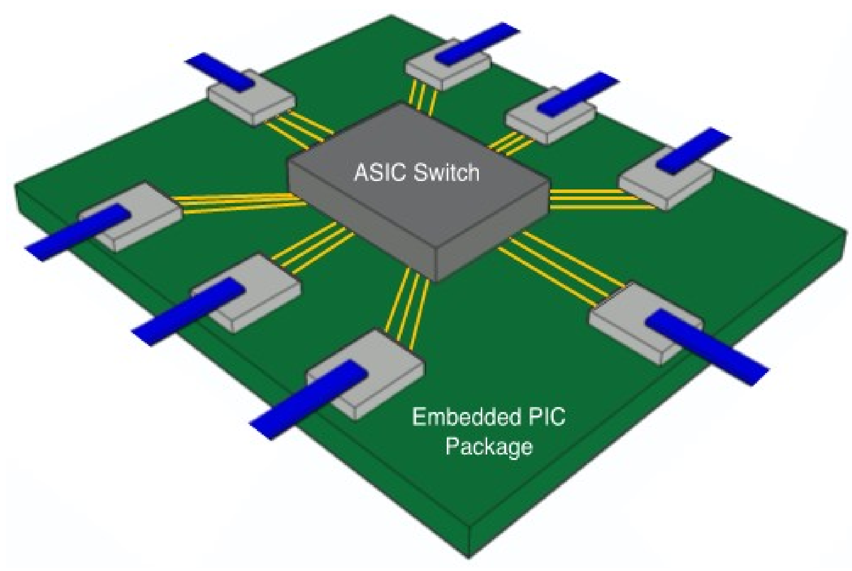


Figure 8. Illustration of integrated photonics transceiver chiplets co-packaged with an ASIC switch in a multi-chip module. Source: Peter O'Brien, Tyndall Institute and European PIXAPP pilot line (2021).

6.2. Future State

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].

6.2.1. 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.

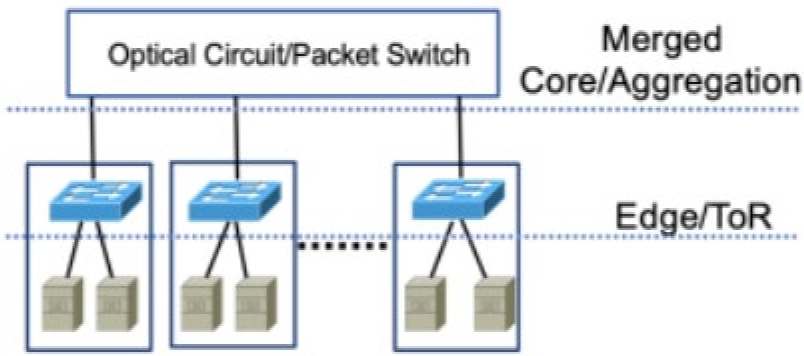


Figure 9. DC network architecture with merged core/aggregation tier based on optical switching [15].

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 [16]. 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.

6.2.2. 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 [17].

6.2.3. 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.

6.2.4. 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 9 below.

6.2.5. 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.

The workshop converged around several performance targets to make co-packaging possible, summarized in the table for 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 1. 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.

7. In-Building Optical Networks

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 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/m^2.

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 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 and equivalent technologies, i.e., G. Fast and wireless-to-the-home using 60 GHz and LiFi. PON will upgrade by use of MCF going parallel from the passive split point to the CORD. Wireless area capacity will reach 100 Mbit/s/m². 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. New spectrum with more reliable QoS will be increasingly used, creating the case for 10G 60 GHz and LiFi links (802.11ay/802.11bb). Both media do not penetrate through walls. LiFi propagates with line-of-sight only and is possibly the best answer to rising interference problems due to future IoT [18].

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].

8. Space Networks

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.

8.1. Current State

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, visible light wavelengths around 1,550 nm are considered [20] while infrared light wavelengths have also been reported [21] for situations where atmospheric effects may hinder the link. Recent efforts on standardizing OISLs point to using visible light bands in the 1,528 – 1,577 nm range with a center frequency of 193.1 THz [22]. 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.

8.2. Future State

There is already a transition for RF carriers to lightwave 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 [23] [24]. 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 [25].

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 [26]. 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 Gb/s using coherent detection and a BPSK modulation format at 1,064 nm [27]. NASA plans include 100 Gb/s 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.

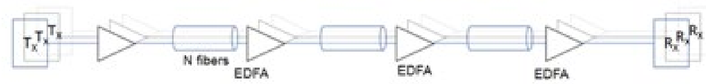
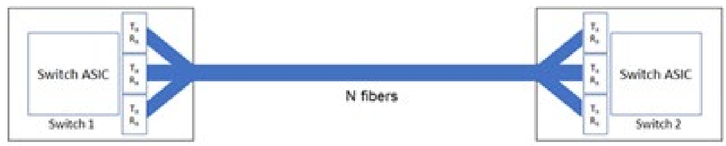
9. Optical Fibers and Spatial Division Multiplexed Networks

The optical fiber roadmap has been strongly influenced by the requirements of optical networks since low loss silica fiber was first demonstrated in 1970 [28] 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 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 [29] 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.

SDM is expected to be first adopted in three applications driven by their unique challenges (see Table 1). 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 [30]. 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 [31].

Table 2. The key applications that will benefit from the development of SDM.

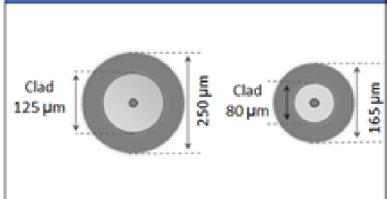
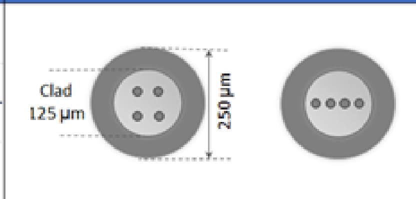
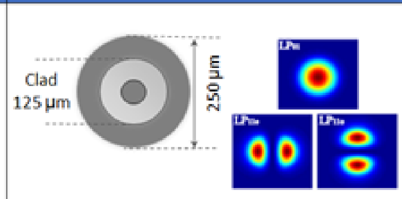
Application (use case)	Reference Link Configuration
Long-haul submarine and terrestrial links	
Data Center Interconnects (DCIs)	
Intra Data Center Links	

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 [32] 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.

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.

Table 3. 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 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 [33] and without mode mixing where mode propagation constants are sufficiently different, and their mixing is suppressed [34]. 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.

10. Quantum Communications

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 [35] 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 [36]. Recent experiments have achieved transmission beyond the repeaterless bound [37]. 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.

11. 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.

12. CONTRIBUTORS

Dan Kilper (Co-Chair)	CONNECT, Trinity College, Ireland
Thas A Nirmalathas (Co-Chair)	The University of Melbourne, Australia
Tom Hausken	OSA
Reza Vaez-Ghaemi	Viavi Solutions
HwanSeok Chung	ETRI, S Korea
Prakash Ramchandran	Cloud24x7
Volker Jungnickel	HHI Germany
Murat Yuksel	University of Central Florida, USA
Surgey Ten	Corning, USA
Rudra Dutta	North Carolina State University, USA
Paolo Monti	Chalmers University of Technology, Sweden
Lena Wosinska	Chalmers University of Technology, Sweden
Suresh Subramaniam	George Washington University, USA
Ahsutosh Dutta	Applied Physics Laboratory, John Hopkins University, USA
KRS Murthy	i3 World, USA
Peter Andrekson	Chalmers University of Technology
Brad Kloza	IEEE Future Networks Initiative
Matthew Borst	IEEE Future Networks Initiative

Other Working Group Members
Haydar Çukurtepe (TED University, Turkey)
Rentao Gu (Beijing University of Post and Telecommunications, China)
Zuqing Zhu (University of Science and Technology of China)

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14. 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 Spceific Integrated Circuit
BBU	Baseband Unit
BPSK	Binary Phase Shift Keying
CD	Chromatic Dispersion
CO	Central Office
CO-DBA	Cooperative Dynamic Bandwidth Allocation
CommSoc	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 Eploration 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

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