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Optics



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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.

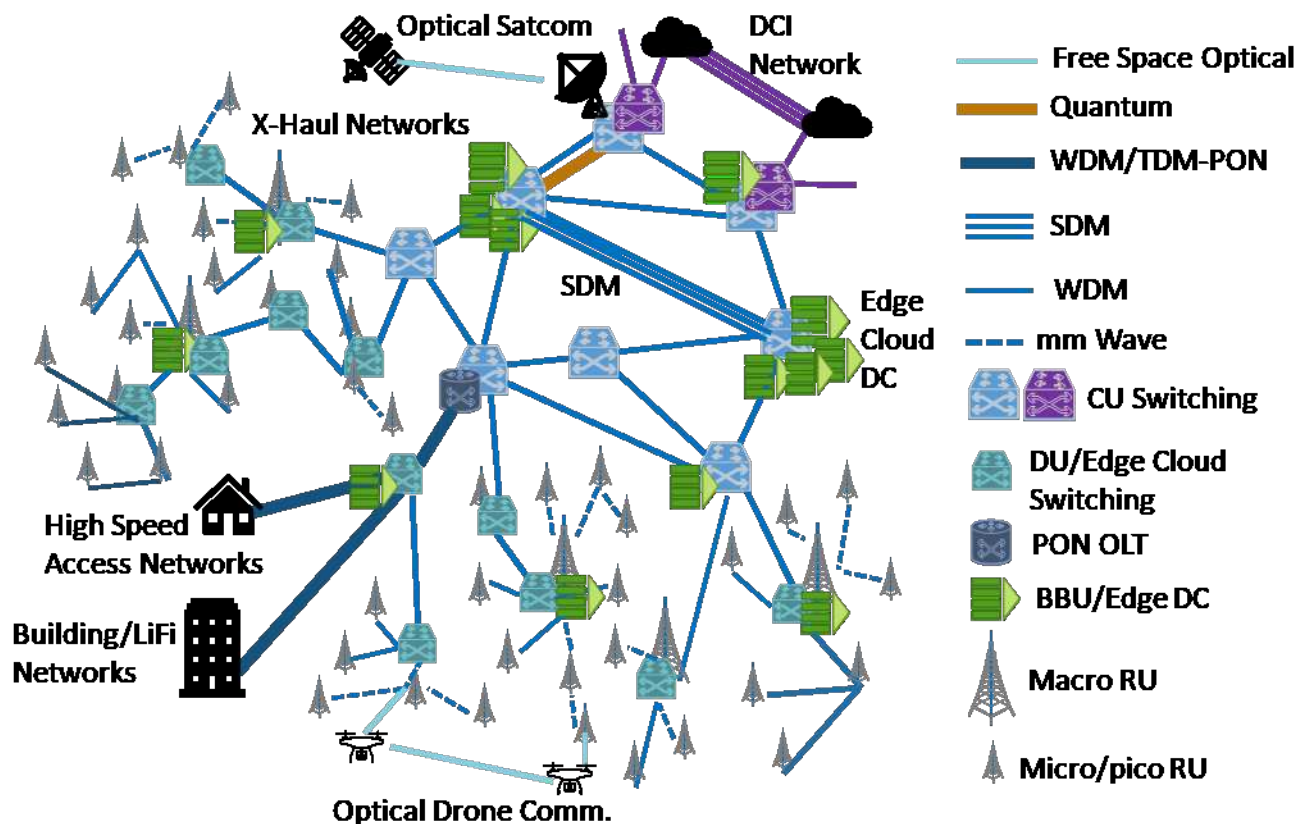


Figure 1. Vision of future optical communication networks.

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.

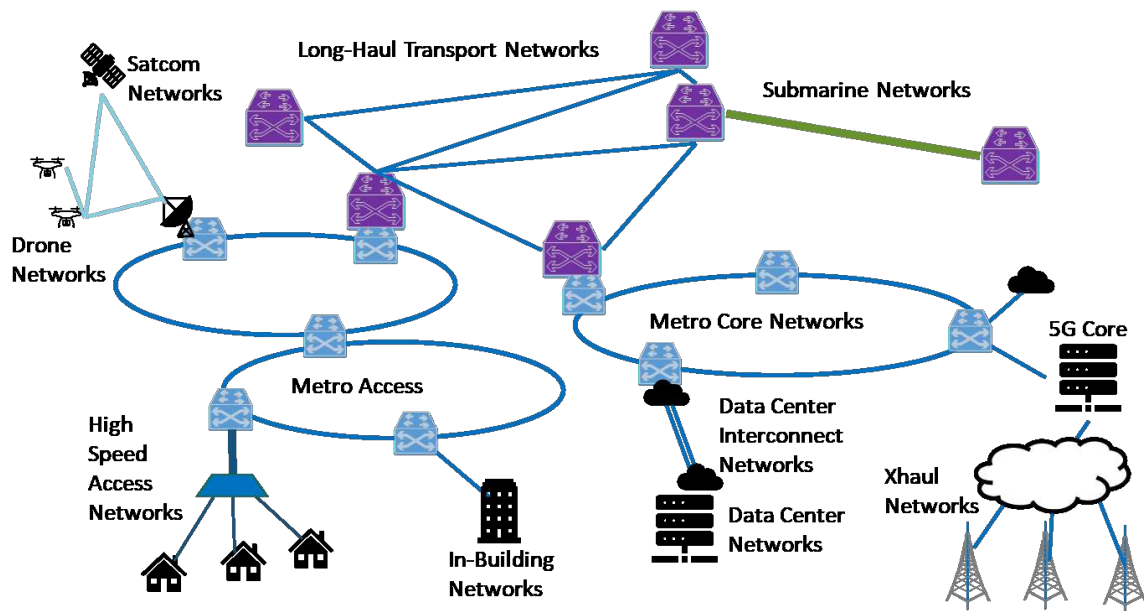


Figure 2. Different types of optical networks.

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 from 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.

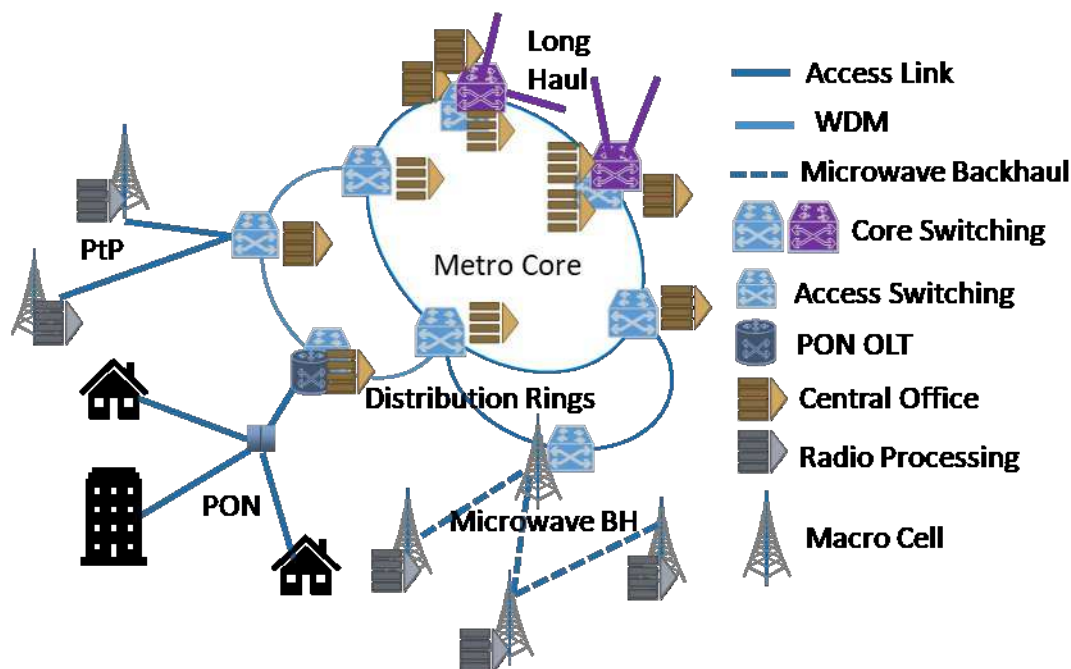


Figure 3. Today's optical networking landscape.

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

<i>Needs</i>	<i>Description</i>
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].

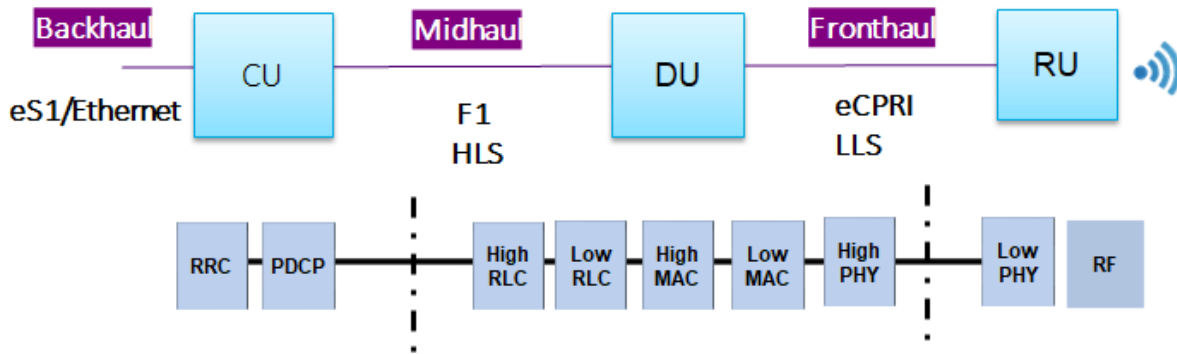


Figure 4. Xhaul Network; processing functions shown in grey boxes below the corresponding node types at which they are executed; dot-dashed lines indicate split locations.

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