IOWN GLOBAL FORUM™

INNOVATIVE OPTICAL AND WIRELESS NETWORK GLOBAL FORUM VISION 2030 AND TECHNICAL DIRECTIONS

Overview

Empowered by the evolution of photonic networking technologies and the emergence of Silicon Photonics technologies, the Innovative Optical Wireless Network Global Forum (IOWN GF) aims to develop by 2030 technologies that will lead to quantum leap improvements in communications capacity and latency, data efficiency, computing scalability, and environmental footprint minimization. A new communication and computing full stack architecture will be developed. Leveraging IOWN GF technologies, smart world applications will be created and augmented with beyond-human cognitive-communication capacity, beyond-human response speed, linear computing scalability, and superior energy efficiency. The accomplishment of this vision requires global collaboration and endeavor cross communication, computing, software platform, and applications.

Contents

1. Paradigm Shifts in a Connected World

The world today has experienced faster-than-ever technological and economic growth thanks to advancements in communication and computing technologies. Moving forward, another quantum leap in computing and communication capabilities is expected to empower the world toward a new era of growth. The mission of the IOWN GF is to develop fundamental technologies on communication, computing, and data management that will bring in a quantum leap in performance and energy efficiency improvement, and enable a much smarter world with advanced applications, including those with digital twin computing and the metaverse.

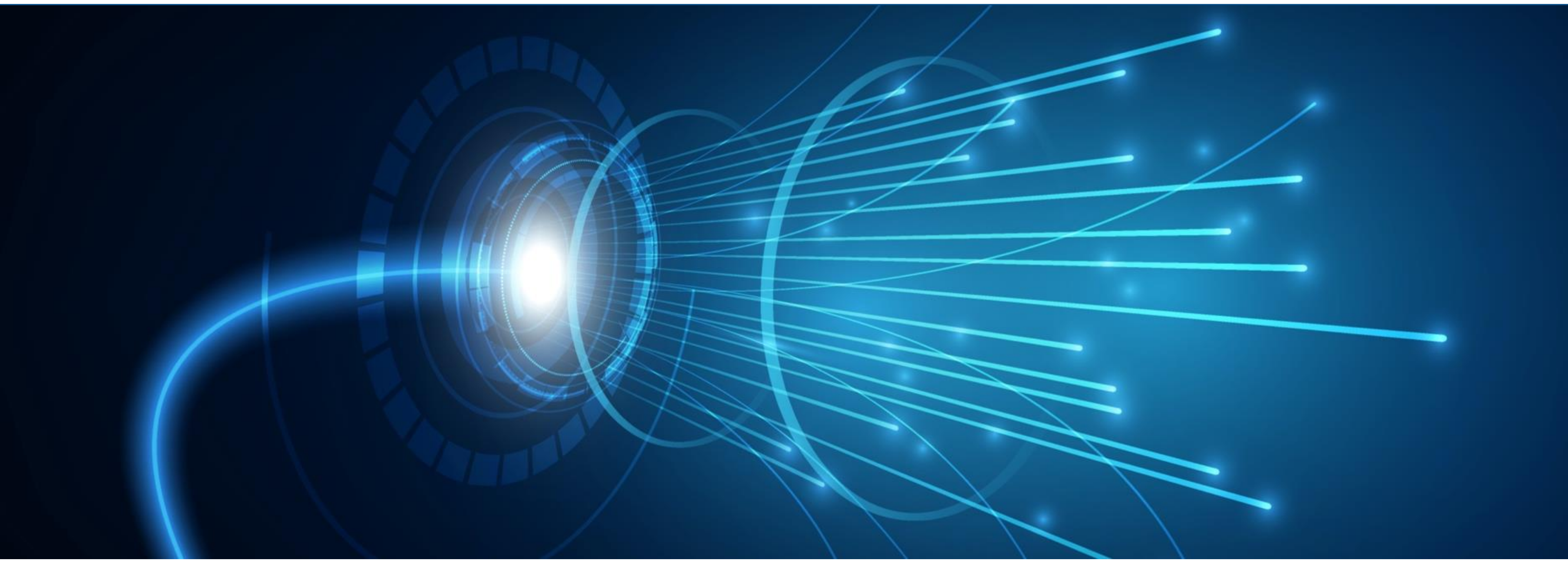
These new digital services will help address the United Nations Sustainable Development Goals (SDGs), for instance regarding health, education, industry, and energy. In addition, because sustainability, especially regarding climate change, is a challenge of our times, the IOWN GF will ensure the technology we develop will minimize the environmental impact of future digital services (in terms of energy, greenhouse gas emissions, materials, water) and will enable various sectors of society to minimize their own environmental impacts, resulting in a significant net benefit for society.

The IOWN GF released its initial Vision 2030 Whitepaper in April 2020, which helped steer the direction and set the work plan [1]. The first version of the vision whitepaper provided a glimpse of the advanced technologies that were foreseen for a smarter world in 2030 and beyond, and provided an overview of the performance level requirements, as well as a gap analysis regarding the performance that can be achieved with today's technologies. Similarly, the whitepaper highlighted the key technologies that the IOWN GF forum should focus on first, which included:

- Shift toward data-centric communication and computing infrastructure
- Full-stack communication acceleration
- An advanced computing scaling platform
- Energy efficiency, environmental footprint minimization, and sustainable growth

Since then, IOWN GF has made remarkable progress and released several reference documents that define use cases with their key requirements. Similarly, the world has undergone several changes, such as the increase of pressure against carbon emissions and the emergence of demand for remote services.

This new version of the Vision 2030 Whitepaper intends to update the forum's original vision with a clearer view of IOWN GF's technologies, reflecting the forum's achievements and the changes in the world.



2. IOWN GF Achievements

Since the inception of the IOWN GF, substantial progress has been achieved both in regard to laying out the key use case groups that are focus of this forum, as well as the base technological components to address these use cases' requirements. This section provides an overview of these achievements.

2.1. Use Cases

The IOWN GF released two use cases that validate the need to supplement today's overburdened communication and computing infrastructure with an all-photonics network and a data-centric infrastructure capable of supporting the explosive demand for global interconnectivity.

The completed use cases followed an extensive revision process and underscore the mission of the IOWN Global Forum, which is by 2030 to have developed advanced optical communication, computing, data, and energy-efficiency technologies that will enable a smarter, more sustainable world.

The findings of the Cyber-Physical System (CPS) Use Case and the Artificial Intelligence-Integrated Communications (AIC) Use Case provide a roadmap that will be used by the IOWN Global Forum and its members to develop technical recommendations for a long-term feasibility study. The outcome of this intensive program will uncover new approaches to work, entertainment, education, mobility, smart cities and electric grids, healthcare management, and new ways to improve social equity and data privacy.

Many of the use cases defined by the IOWN GF rely on the benefits coming from the latest digital twin technologies. In the scope, the Digital Twin Framework (DTF) TF was established by the IOWN GF to provide an analysis on the requirements and technology gaps for the use of digital twins in four targeted use cases: Area Management Security, Green Twin, Human Digital Twin, and Remote Robot Operations.

2.1.1. Cyber-Physical Systems Use Cases

Sustainability has become the touchstone for much of what the technology industry promises to deliver. The need is reflected in the United Nations' Sustainable Development Goals (SDGs) and the hastening adoption of corporate ESG (Environmental, Social, and Governance) measures that integrate investment strategies with social purpose and the environmental impacts of business.

In the near future, a quantum leap in communication and computing capabilities will propel the world into a new era of sustainable growth. The CPS use case details application-specific service requirements across multiple facets of society that depend on cyber-physical systems to meet those goals. These include smart buildings, smart grid management to enable carbon neutrality, remote factory operation, real-time disaster notifications, disease outbreak prediction and prevention, and event-driven security monitoring. Figure 1 depicts examples of CPS use cases.

Figure 1. Cyber-Physical Systems

2.1.2. AI-Integrated Communication Use Cases

The world has become smaller as technological advances have spurred new ways to connect with each other, new ways to work, new ways to enjoy entertainment, and new ways to approach old problems. The communication and computing infrastructure developed over the past 30 years has made these changes possible, but the world needs another quantum technology leap to deliver the infrastructure required to continue the pace of innovation.

Artificial Intelligence (AI) and Machine Learning (ML) are the key to this future. However, early efforts using current technology to create immersive experiences have met with mixed success. The AIC use case examines a spectrum of future states that will influence how we experience the world around us, from virtual concerts and interactive live sports, to cloud-based gaming and remote learning. The AIC use case also recommends new ways in which people will navigate the physical world, as well as AI-based, mind-to-mind communication that can overcome differences in language and culture to foster a better understanding of perceptions and emotions. Figure 2 depicts examples of AIC use cases.

Figure 2. AI Integrated Communications

2.2. Technology Stack

2.2.1. All Photonics Network (APN)

In order to address the extreme bandwidth and latency requirements of IOWN use cases, the IOWN GF has defined a new network called Open All-Photonics Network (APN) and published its Release 1 architecture document in early 2022. The APN is a wavelength-switching-based, connection-oriented network that supports various physical deployment scenarios including those that deploy wavelength multiplexing/switching nodes in customer premises. This deployment flexibility comes from the APN's open and disaggregated architecture, which defines three functional components, which are the APN-T (Transceiver), APN-G (Gate), and APN-I (Interchange). By dynamically creating optical wavelength connections between communication endpoints, the APN achieves data transfer at very high speed and with very low latency, e.g., tens/hundreds of Gbps and less than one millisecond. In this way, APNs will effectively and efficiently support IOWN GF use cases.

2.2.2. Data-Centric Infrastructure (DCI)

Data-Centric Infrastructure (DCI), which was published together with APN in early 2022, complements the APN. DCI is a disaggregated computing infrastructure that composes resources from hardware pools into computers in an on-demand fashion. Computers created this way are called Logical Service Nodes (LSN). LSNs may comprise components such as heterogeneous processors, fast memory devices, and smart Network Interface Cards (NIC). By composing chains of such heterogeneous resources, DCI streamlines data transferring and processing at the speed of optical communication. In this way, DCI effectively and efficiently supports IOWN GF use cases.

2.2.3. IOWN Data Hub

To realize future digital experience services, it is necessary to develop a new platform that can process large amounts of data generated from various places and devices timely, efficiently, flexibly, and securely according to the specified purpose. To build such a platform, the IOWN Data Hub Task Force at the IOWN GF is studying and working on data processing and management mechanisms from various angles and has defined the so-called IOWN Data Hub architecture. This architecture consists of three tiers: a front-end tier for distributed real-time primary data processing, a data service tier for data consistency assurance and global data utilization, and a storage tier for data persistence. Because the IOWN Data Hub Architecture is built on the Open APN and DCI, the IOWN Data Hub tiers are interconnected with high speed and guaranteed performance that can be scaled elastically and independently according to the workload. In addition, the IOWN Data Hub realizes the fast and efficient consumption of geographically distributed data with various functions such as query, filtering, and analysis, through the flexible deployment of front-end tiers and the efficient federation among multiple data service instances. With such a platform, developers can develop a wide variety of applications with high productivity while ensuring fast and efficient processing of large amounts of geo-distributed data.

2.2.4. Complementary Works

IOWN for Mobile Networks

Wide adoption of 5G has increased mobile traffic several times over 4G. Many futuristic use cases such as Area Management, Remote surgery, Augmented Reality/Virtual Reality (AR/VR), Metaverse, and Industrial Automation require enormous end-to-end bandwidth capacity, high reliability and availability, extremely low latency, and low power consumption. The IOWN GF for mobile network Task Force (TF) has engaged various studies to provide proposals and solutions to optimize the transport network for cost-effective deployment and operation efficiency and to improve network performance supporting mobile networks evolving toward 5G advance and 6G. The TF has delivered (1) Proof of Concept (PoC) specification for Mobile Fronthaul over APN, (2) Use cases and associated performance requirements submitted for ITU-R's IMT 2030 Vision and Beyond report, (3) How to apply extended Cooperative Transport Interface (CTI) feature to APN and Midhaul and Backhaul, (4) Various mobile network deployment scenarios over Open APN and DCI architecture to meet time synchronization, latency, and bandwidth requirements, and (5) Technologies recommendations and solutions for different sizes of mobile network for deployment and operation efficiency and cost saving to support mobile network evolving toward 5G advance and 6G.

IOWN Security (IOWNsec)

Quantum computers are making remarkable progress toward practical use, and it has been pointed out that public key such as RSA (Rivest–Shamir–Adleman) and elliptic curve cryptography, which are currently used in almost all aspects of ICT (Information and Communications Technology) society, can be broken in realistic time frames by using quantum computers in the future. In order to secure data transferring, processing, and storing in IOWN-based architectures, appropriate security solutions are required against threats brought by such quantum computers. Although there are existing technologies with quantum-safe security such as post-quantum cryptography, quantum key distribution, centralized symmetric key distribution, all security measures have pros and cons, and it is difficult to satisfy the various security levels required by users with a single solution. In addition, there is a risk that a particular quantum-safe algorithm may suddenly be compromised.

Therefore, the IOWN security TF is considering a Multi-Factor Security (MFS) architecture. The MFS is defined as a technology that combines multiple security methods to achieve a security level that cannot be reached with a single method. As for E2E data protection, applying the concept of MFS, combining and selecting various methods of authentication, key-exchange, encryption/decryption etc. could address a wider range of threats, including sudden cryptographic compromise, and achieve a required security level by the user.

Fiber Sensing with APN

Fiber sensing is an enabling feature to complement the Open APN. It will greatly improve the value of the network infrastructure by adding sensing functionality to the communications function. Sensing will also help improve the operation efficiency of the network by providing detailed, real-time physical and environmental information on the large-scale network and offer new network management and maintenance functions.

Since its establishment in 2021, the IOWN GF Open APN Fiber Sensing (OAF) Task Force has studied the addition of Distributed Fiber Optic Sensing (DFOS) in the Open APN and proposed three sensing architecture alternatives to the Open APN. These architectures represent different levels of interconnection between the two systems. They also have different levels of technology maturity, those currently available through future state, offering from simple connection of two parallel systems to an eventual dual-use network. These architectures and various use cases have been published in Deliverable 1.0 in December 2021.

Since then, the OAF TF continues to analyze the technology gap, and has identified 5 major areas to work on, including the sensing interrogator, sensing fiber and cable, connection to Open APN, data channel, and system control. Specific topics were proposed to experimentally evaluate the performance and verify potential solutions. Various PoC tasks were planned and are being carried out, including the study of the crosstalk between sensing and communication signals, the solution to overcome the directional issue caused by isolators in optical amplifiers, and the utilization of fiber sensing for network provisioning and protection.

3. New Trends

Since the creation of the IOWN GF, the world has undergone multiple changes, which introduce new trends that are important to take into account for the forum's work. In this section some of the main new trends and developments to be considered are described.

3.1. Increasing Pressure on Carbon Emissions

The Glasgow Climate Pact was signed at the 26th United Nations Climate Change Conference (COP26) in November 2021. More than 70 countries have set a net-zero target. Over 1,200 companies have put in place science-based targets in line with net-zero [2]. In its 2020 report, Global Sustainable Investment Alliance (GSIA) announced that global sustainable investment reached USD 35.5 trillion in five major markets [3].

Table 1. Snapshot of global sustainable investing assets (USD billions) [3]

REGION	2016	2018	2020
Europe	12,040	14,075	12,017
United States	8,723	11,995	17,081
Canada	1,086	1,699	2,423
Australasia	516	734	906
Japan	474	2,180	2,874
Total (USD Billions)	22,839	30,683	35,301

Each industry has different conditions and requirements for net-zero emissions. For instance, the size and number of data centers have continuously increased. A hyper-scale data center is 400,000-square-feet with thousands of cabinets. While the effectiveness of power usage is improved, increasing of size and number of data centers requires more power. Nowadays, it is not easy to secure the electricity for a hyper-scale data center in comparison with securing its building site and putting up the building.

Now, modern companies should consider taking responsibility for net-zero emissions from both a social and economic perspective. As described in the Sustainable Development Goals (SDGs), it has become an overall market consensus that industry, innovation, and infrastructure are essential elements for our sustainability.

Minimizing the energy consumption of equipment when in use is a central requirement of any future ICT technology, both to minimize the associated environmental impact and to minimize the operation costs. IOWN-based equipment should therefore enable energy use monitoring of different functions, in order for the network operator to determine whether the system components are underutilized or overutilized, so that the network deployment can be better adjusted to optimize the energy consumption.

However, minimizing the environmental footprint of ICT goes beyond energy consumption. Indeed, a large part of the CO2 produced during an equipment lifecycle is generated during the manufacturing, transportation, and dismantling/end-of-life phases. In addition, the manufacturing process, including mining the necessary ore, consumes natural resources (e.g., water), and can be a source of pollution. The IOWN GF has the ambition to design technologies that enables their total environmental footprint to be minimized.

As a result, IOWN technologies need also to facilitate extending the usage time of equipment, e.g., by facilitating hardware modularity to ease repairability, and software modularity to facilitate upgrades. In addition, the IOWN technologies need to enable/facilitate hardware sharing/pooling between different functions, and/or between different operators when relevant, in order to maximize the efficiency of hardware deployment. Other needed actions are related to the implementation and manufacturing process which are not directly in the scope of the IOWN GF such as anticipating from their design phase the dismantling and recycling of the equipment/component; nevertheless, the IOWN technology choices should not prevent efficient implementations and manufacturing from the sustainability perspective.

3.2. Demand for Remote Services

Remote network service has established its position as a must-have tool across business industries, educational institutes, and consumer domain. While the recent driving factor for increased remote service adoption was COVID-19 lockdowns, its inherent value, which led to saving time and energy to travel between locations, is raising expectations to expand use cases beyond remote conversation-meeting tool.

With an increased capability to capture real-world spatial information, reconstruct and augment in a digital-virtual-world, and presenting this data back to the real-world, it is expected that many of the constraints of being separated by distance can be eliminated with the combination of having an ultra-high bandwidth and ultra-low latency network. Interactive and personalized Six Degrees of Freedom (6DoF) contents with synchronized control will provide an immersive experience addressing diverse service scenarios spanning from remote live music/sport entertainment to remote diagnostics/operations requiring high professional skills to be offered from the remote.

Enabling such a remote service is critical in meeting the challenges posed in the sustainable development goals. Remote service will lead to provide equal opportunity to be cared for wellbeing with affordable and environmentally friendly manner.

3.3. Data Spaces with Data Sovereignty

Data Spaces are the next step in the evolution of data integration architectures, allowing for data over different data sources and providers to co-exist regardless of how integrated they are. They are expected to become the major topic and instrument for the future data economy due to the rising need to bring together data coming from very different domains, industries, and jurisdictions. A confirmation of the increasing interest in Data Spaces (and related data sovereignty and sharing necessities) can be found in the many multi-industry data sharing initiatives such as DSBA, Gaia-X, IDSA, and DATA-EX. More examples include an integrated, collaborative, open data ecosystem for the automotive industry founded in 2021 (Catena-X), and a pre-competitive, cross-industrial, and cross-functional ecosystem driving industrial decarbonization started in 2022 (Estainium).

Data Spaces collect data from different data sources coming from very different domains. Therefore, it is key to provide the highest standards in terms of interoperability of data (e.g., with AI-driven ontology matching and/or merging), and especially in giving the rights to data providers to decide the scope of data disclosure and data usage at their discretion, which realizes trusted data sharing across the global value chain. This is often referred to as Data Sovereignty and aims at addressing the concerns coming from companies on the impossibility to share their data with other companies, because there is a risk that important data and business secrets could be exposed. All the bodies and initiatives listed in the previous paragraph recognize Data Sovereignty to be a key challenge in the context of Data Spaces are therefore have started to focus on it. However, there is still a lot of work that must be done in this direction. For example, a technology that enables data providers to control the right to decide the scope of data disclosure and data usage even after sharing their data, is not yet established.

To address the requirements in terms of Data Sovereignty and interoperability, Data Spaces require a dynamically adaptable and highly distributed infrastructure in terms of connectivity, storage, computation, and security. Concepts like the “Data Centre Interconnect Core” described in section 4.1.2, based on the All-Photonic Network (APN) and the Data-Centric Infrastructure (DCI), and Data Hub are developed by the IOWN GF to satisfy such requirements and allow to build, operate, and use data spaces up to the granularity of potential future endpoints and suddenness of analytical needs.

Finally, being able to take advantage of the heterogeneous data amounts coming from Data Spaces, means also being able to build and manage large scale and high-fidelity Digital Twins, to monitor, simulate and analyze such data. And it can be considered as a strong enabler for collaboration between multiple twins belonging to different administrative domains and environments, because of the above-mentioned interoperability and data security requirements.

4. Infrastructure Evolution with IOWN

To address the new demands and challenges described in the previous section, the system needs to be able to handle a 10x or even 100x increase in data traffic. In addition communication and computing latency needs to be reduced by 10x to meet the extreme requirements of advanced use cases. The power consumption also needs to be reduced by 10x to 100x for economic and environmental sustainability. Finally, the computing system needs to be able to handle extreme, complex, and diverse workloads and data models that could require fundamental changes in computing platforms across edge and center clouds.

Some advances are being made, as the rapid evolution of optical communication technologies such as coherent optics has been doubling the capacity, i.e., bandwidth, of fiber every 1-2 years. Besides capacity, the advancement of semiconductor manufacturing and silicon photonics technologies has made long-distance optical transceivers so small that computers or switches can be connected directly to optical networks. Furthermore, the emerging photonics-electronics convergence technology, e.g., co-packaged optics, will enable closer integration between optical networks and computing systems. In this section, we describe how the IOWN GF will address the above challenges with these technologies.

4.1. Technical Points

4.1.1. Overview

Today's Infrastructure

Figure 3 depicts today's infrastructure. Summarized below are some unresolved issues with today's infrastructures:

- While many telecommunication carriers have already deployed optical access infrastructures for fiber broadband services, they are tailored for best-effort service and cannot support, at a large scale, the strict requirements of emerging use cases such as mobile fronthaul and industrial cyber-physical systems. Likewise, mobile network operators have to build their own fiber infrastructures for mobile fronthaul. This is one of the blocking points for 5G and 6G market growth, because 5G/6G utilizes millimeter radio whose very small coverage requires antenna deployment on a demand-driven basis.

- Between carriers' local Data Centers (DCs) and cloud data centers are tiers of packet networks. As a result, when devices on customer premises communicate with servers in the cloud data centers, the packet transfer delay and jitter often end up being tens of milliseconds.
- Edge computing is considered to be a solution for the delay and jitter issue stated above. However, distributing computing infrastructures to many edge points will spoil the benefit of cloud computing, i.e., being able to create a large resource pool for cost optimum operation. Besides, many enterprise customers are reluctant to rely on a single network carrier's DC.
- Cloud data centers keep getting larger and larger. Many of today's hyper-scale data centers require a power supply of more than 100 megawatts; for local communities that are trying to reduce their carbon footprint, this huge amount of power is too much to supply to a single location solely from green energy sources.

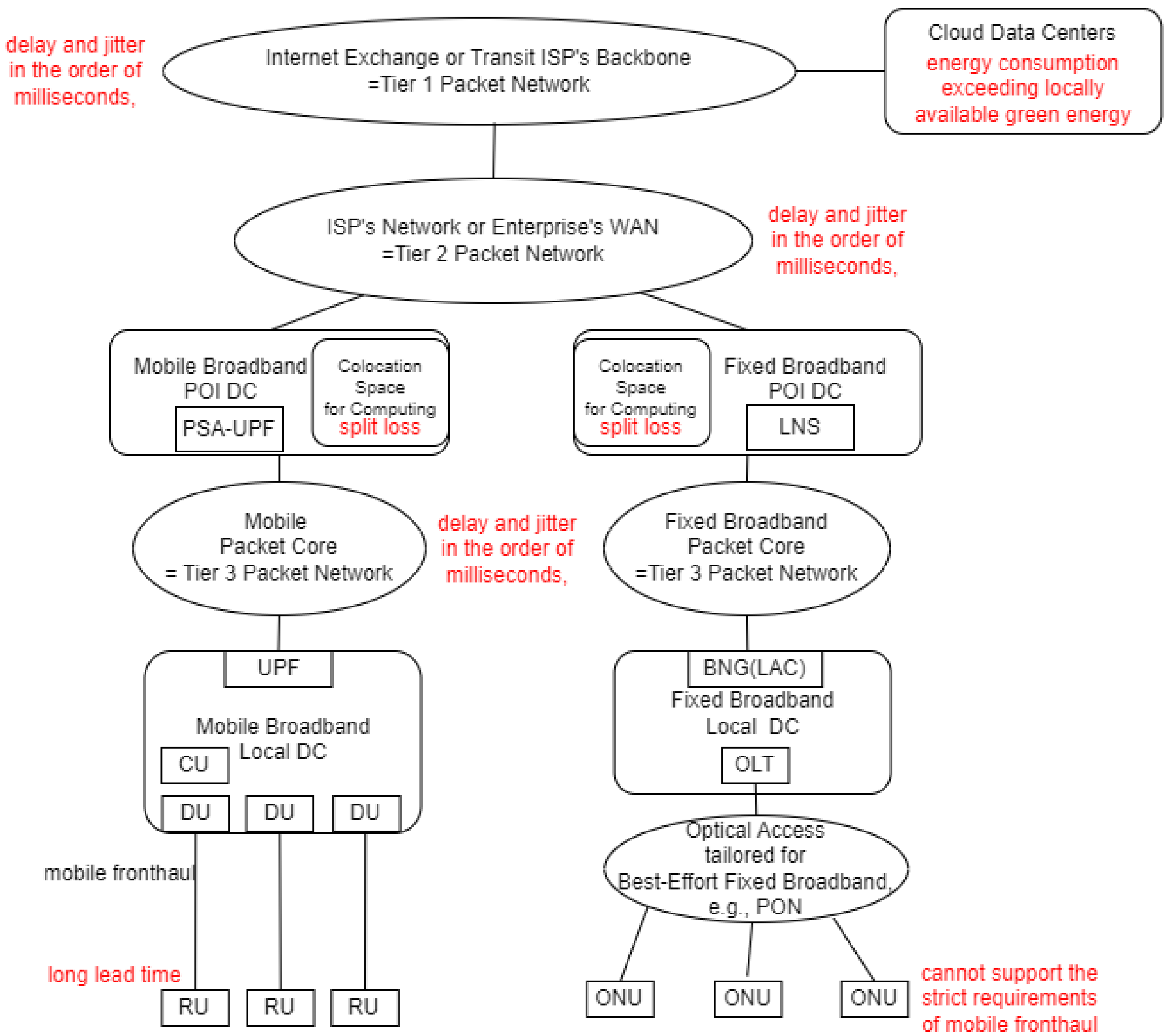


Figure 3. Today's Infrastructure

Evolved Infrastructure

Figure 4 proposes an evolved infrastructure. By complementing today's packet-based infrastructures with the Interconnect Core, the evolved infrastructure achieves quantum leaps in capacity, latency, and energy efficiency. In addition, the new access infrastructure, Converged Optical Access, will be a common optical access infrastructure shared by multiple grades of services and multiple sizes of users. We summarize the technical advantages of the proposed architecture in the remainder of this subsection.

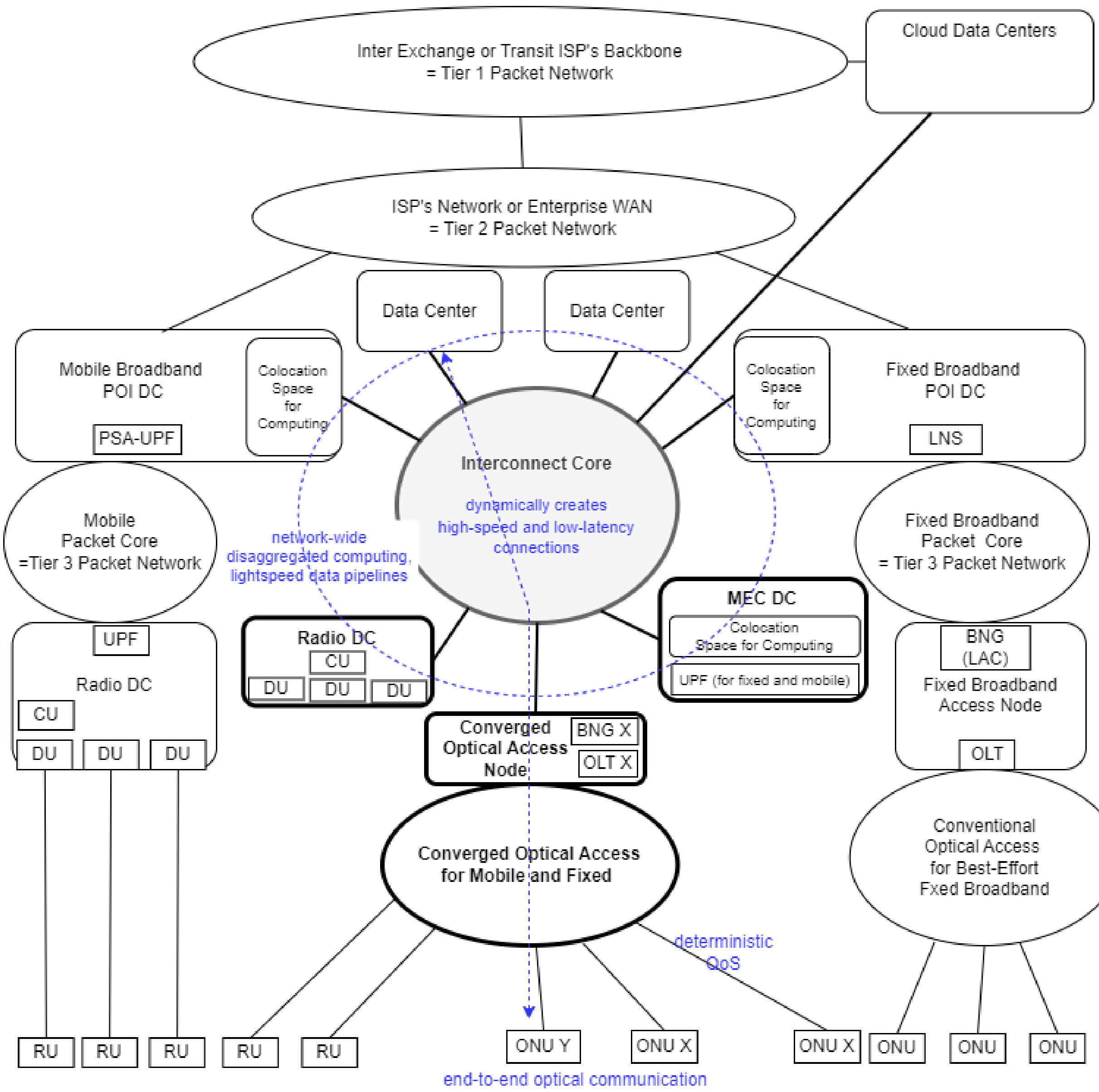


Figure 4. Evolved Infrastructure

4.1.2. Inter-connect Core for High-Speed and Low-Latency Data Transport

The Interconnect Core is defined as a network that dynamically creates high-speed, low-latency connections between any points connected to the network. Speaking in the packet communication layer model, while today's packet-based core infrastructures function at layer 3, the Interconnect Core provides optical transport links that function at layer 1. More intuitively, the Interconnect Core is “the Internet of Data Centers.”

Today, customers use dark fibers for high-speed transport links, such as those provided by data center providers. On the other hand, the IOWN GF considers Open APN as a viable architecture for the Interconnect Core. As shown in Figure 5, the APN-based Interconnect Core is a network of APN-G and APN-I, which are capable of DWDM-based multiplexing and switching. What differentiates the Open APN-based Interconnect Core from today's dark fiber-based L1 solutions are capacity, agility, and dynamicity, as explained below.

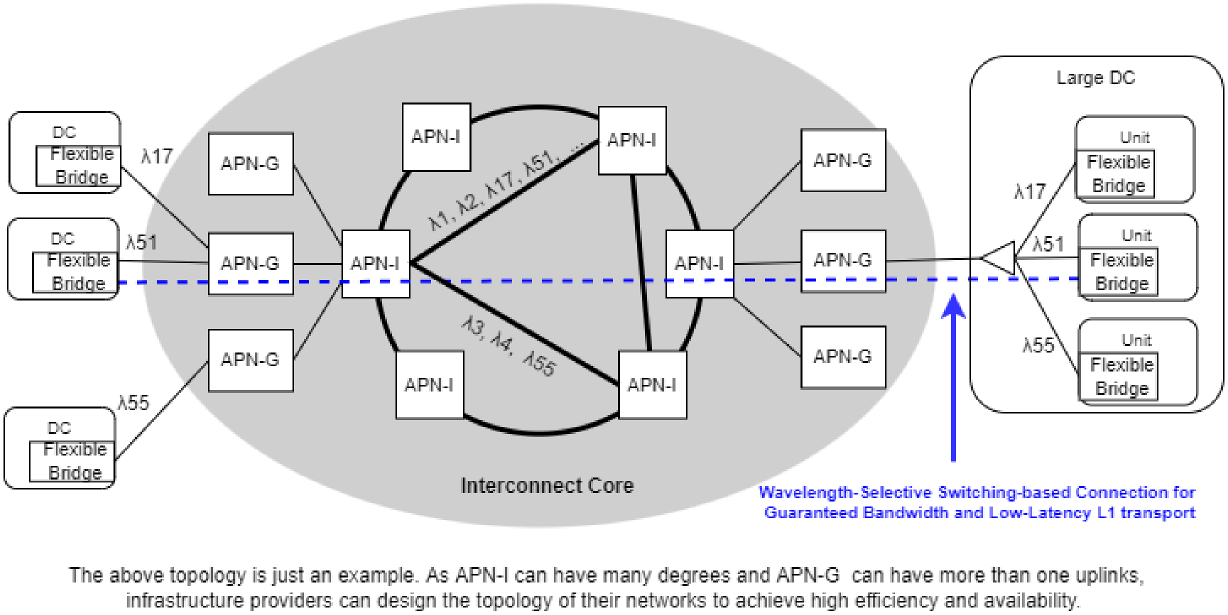


Figure 5. Interconnect Core with Open APN

Capacity: The adoption of DWDM will significantly increase the number of transport links creatable under a given number of fibers. Future ultra-wideband optical transmission technologies will further enhance this advantage.

Agility: The adoption of DWDM will allow us to place WDM-based splitters on customer premises or hosting sites, e.g., data centers, and let customers or hosting providers add branch lines so that they can deploy new systems without having to wait for circuit delivery.

Dynamicity: The adoption of DWDM will enable us to dynamically create and release connections in accordance with the lifecycles of application processes. For example, customers will be able to connect their enterprise data centers with cloud data centers only for the duration of data analysis.

4.1.3. Converged Optical Access for Mobile and Fixed – Multi service

The converged optical access infrastructure allows the co-existence of multiple access systems to accommodate multiple grades of services and multiple sizes of users. As shown in Figure 6, the converged optical access infrastructure has a fiber cross-connect (See a note shown below) to flexibly associate access fibers with multiple access systems. This yields the following technical advantages:

Note: The fiber cross-connect is a node that has optical fiber ports and flexibly joints the connected fibers. Although several products are already available in the market, the scale, i.e., the number of ports, may not be enough to handle a large number of access fibers. So, while we develop technologies to increase the scale of fiber cross-connect, we should cope with the scale limitation by aggregating small-size users into one access fiber. Future versions of IOWN GF Open APN Functional Architecture may define the functions and open interfaces of the IOWN GF Fiber Cross-Connect, although the current version does not define them.

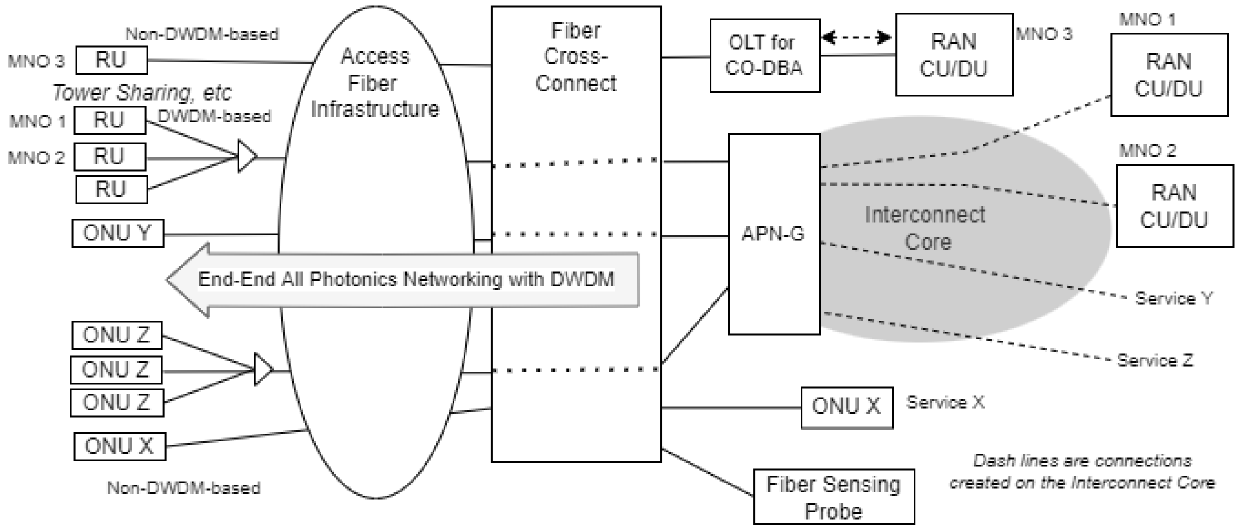


Figure 6. Converged Optical Access Infrastructure

Co-existence of Multiple Grades of Services and Multiple Sizes of Users: While the Internet access services can tolerate packet delay and jitter on the order of milliseconds, data center interconnection and mobile fronthaul require a very low delay and jitter, i.e., less than a millisecond. In addition, while a residential consumer would not occupy the entire fiber bandwidth, some business users and service providers may want to fully utilize the entire fiber bandwidth. The fiber cross-connect allows the access infrastructure provider to assign fibers to multiple access systems while maintaining a common pool of fibers. Different access systems may use different multiplexing technologies, such as Time-Division Multiplexing (TDM), Wavelength-Division Multiplexing (WDM), both Coarse-WDM/Dense-WDM (CWDM/DWDM), Time-WDM (TWDM), and packet-based multiplexing, each of which may be static or dynamic. In this way, the converged optical access can accommodate multiple grades of services and multiple sizes of users.

Optical Branching by Customers or Hosting Providers: Most users or hosting providers want to add branch lines by themselves so that they can connect new systems or tenants to an access fiber quickly. For example, enabling a mobile radio tower operator to add a branch line for a new tenant mobile operator will reduce the lead time in mobile antenna deployment. Otherwise, the lead time for fiber deployment would slow down the user's business activities. Today, we use packet routers/switches for self-service branching. However, routers/switches to multiplex tens/hundreds of Gbps lines would be very costly and energy consuming. An access system based on WDM will realize self-service branching that is less costly and energy consuming.

Optical Path-Through to Core (APN Spanning Across the Access and the Core): Adopting DWDM for an access system will enable us to create wavelength-switched connections across the access and the core. In other words, we can create an All Photonics Network (APN) that spans across the access and the core. Not only does this effectively implement low-latency computing applications but this also enables mobile network operators to reduce the number of radio DCs, i.e., Distributed Unit/Centralized Unit (DU/CU) sites, concentrating radio signals from multiple access areas into one DC. As a result, the mobile network operators will have one DU/CU resource pool for multiple access areas and benefit a lot. For example, the mobile connectivity demand is high in commercial areas and low in residential areas during the daytime, and it turns to the reverse in the evening; taking advantage of this alternating cycle and establishing a single CU/DU resource pool that is shared by antennas located in both types of areas, the total amount of required CU/DU hardware can be reduced.

Coordinated Resource Management Between Optical and Radio: As stated above, the converged optical access with DWDM will be a vital mobile fronthaul solution that realizes express antenna deployment with fiber branching and concentrates radio signals from multiple access areas into one radio DC through wavelength-switched connections. Furthermore, mobile network operators will be able to raise the infrastructure's efficiency by dynamically controlling optical resources in accordance with radio resource management. For example, leveraging the common DU/CU resource pool for multiple access areas, mobile network operators can dynamically switch active antennas between office areas and residential areas. For such use cases, the DWDM-based access and core infrastructures may expose the connection control API so that the mobile operators can redirect wavelength-switched connections accordingly. In addition, for areas with low population densities, we can implement an access system that lets multiple antennas share one access fiber or a wavelength and dynamically assigns bandwidth in accordance with the radio resource assignment by the radio systems. This is called Cooperative Dynamic Bandwidth Assignment (CO-DBA) and will further raise the infrastructure's efficiency.

Fiber Sensing: Connecting an access fiber to a fiber sensing probe with the fiber cross-connect will make the network infrastructure an area-wide sensor for environmental monitoring and infrastructure monitoring. This additional benefit will further reduce the hurdle for fiber investment.

4.1.4. Network-wide Disaggregated Computing

Many applications are expected to greatly benefit from high-speed and low-latency connections from the Interconnect Core. For example, in the case of a regional client-server applications, while RTT between the client and the server in today's infrastructures is typically tens of milliseconds, it would be no more than 1-2 milliseconds if the client and the server were connected to the Interconnect Core. This would lead to about 5-10 times difference in the number of request-reply transactions achievable in a given period of time. However, today's computing infrastructures are not ready to benefit from this difference because the data should undergo packet handling by the host CPU, which would be overwhelmed with the increased packet rate. This is where the IOWN Global Forum's Data-Centric Infrastructure (DCI) comes into play. As explained in section 3, DCI composes chains of computing resources, such as NICs, processors, and storage, to streamline data transferring and processing at the speed of optical communication. Connecting DCIs in different DCs with the Interconnect Core will realize network-wide disaggregated computing, in other words, computing with chains of computing resources across data centers. Network-wide disaggregated computing will yield the following technical advantages:

Resource Pooling and Sharing across Data Centers: We can achieve efficient remote procedure calls for accelerator-requiring computing tasks with a pair of Infrastructure Processing Unit (IPU)/Data Processing Unit (DPU) cards performing fast inter-DC data transfer as shown in Figure 7 and Figure 8. This will allow us to form a pool of accelerator resources for multiple edge data centers. Similarly, we can achieve storage resource sharing/pooling by disaggregating database/storage systems, as shown in Figure 7 and Figure 8. This advantage will help us significantly reduce the CAPEX/OPEX per edge DC in edge computing.

Computing with Design for Failure: We want to deploy edge systems in many locations to achieve low latency. However, it would be costly if each edge system had to achieve high availability, scalability, and data persistence. With network-wide disaggregated computing, we can build systems in a two-tier architecture that comprises the frontend tier and the core tier, as shown in Figure 7, and assume that a subsystem at the frontend tier may fail or run out of resources under the peak demand. The subsystem at the core tier can achieve high availability/scalability and assure data persistence by maintaining multi-DC redundancy with high-speed and low-latency connections over the Interconnect Core.

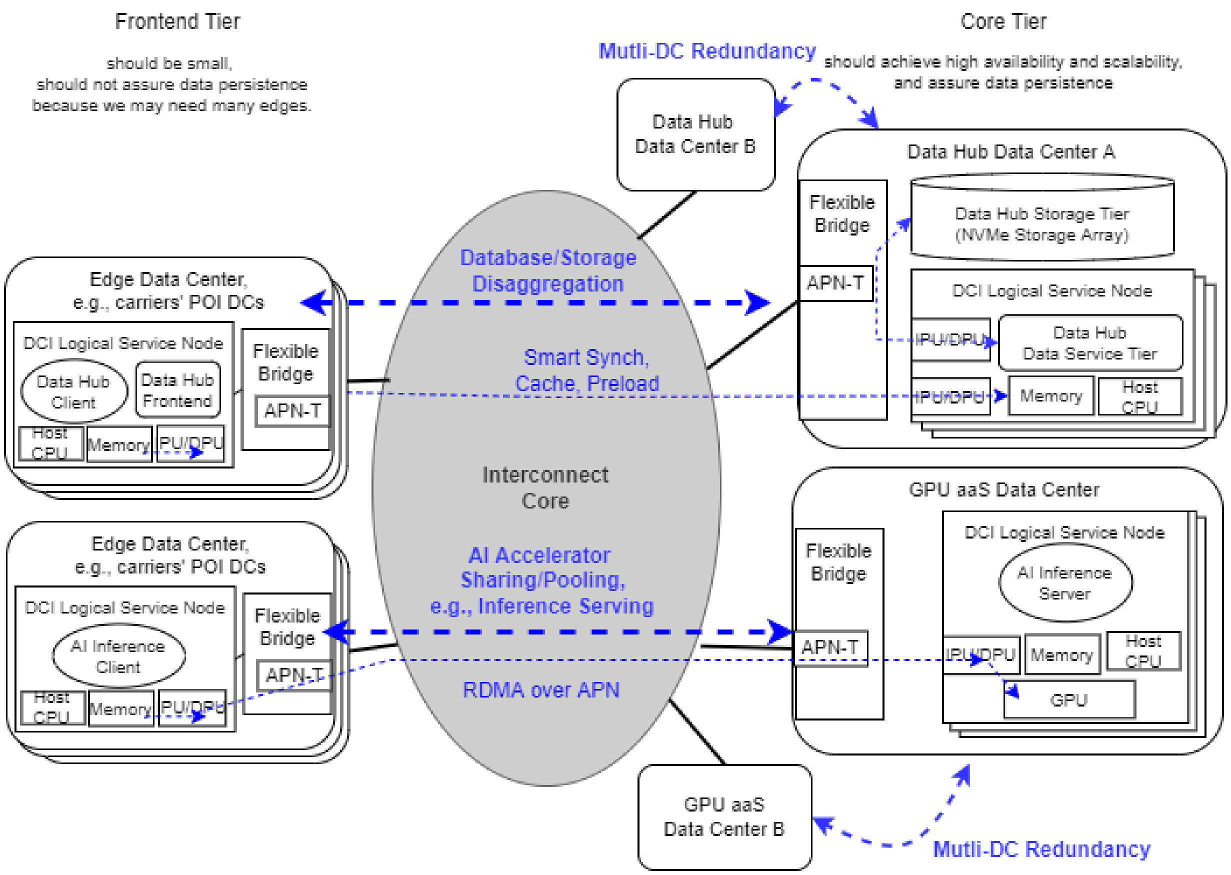


Figure 7. Network-wide Disaggregated Computing with DCI

Separation of Data and Applications: We can achieve fast remote storage access by having the remote storage server and client exchange data over the high-speed and low-latency connections on the Interconnect Core as shown in Figure 8. In other words, we can separate points of data storage from points of computing or applications. This advantage will help enterprises maintain their confidential data in their DCs while taking advantage of service providers' modern computing platforms.

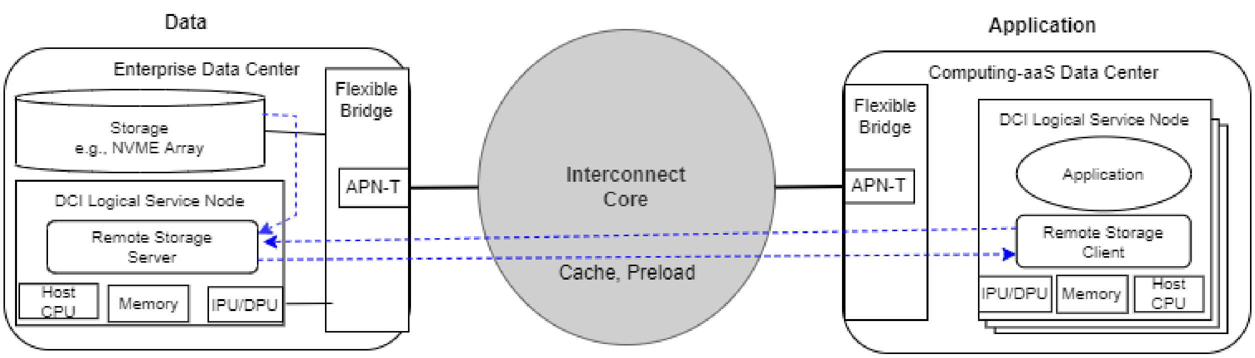


Figure 8. Separation of Data and Application

4.1.5. Lightspeed Data Pipelines with Disaggregated Data/Stream Hub

A data pipeline, which is defined as the flow of data among microservices for an application, is the key element of high-performance applications built with a microservices architecture. While today's communication infrastructures are focusing on packet forwarding, future communication infrastructures should also provide other functions that are necessary for customers to build data pipelines. Examples of such functions are message broker, database, and storage. The IOWN Data Hub, explained in section 3, will achieve this infrastructure evolution. By deploying the IOWN Data Hub tiers over the Interconnect Core, customers can build highly efficient data pipelines (see Figure 9). Similarly, we can also build data pipelines for high-resolution and low latency streaming applications by deploying stream relay nodes over the Interconnect Core. Such data pipelines will yield the following technical advantages.

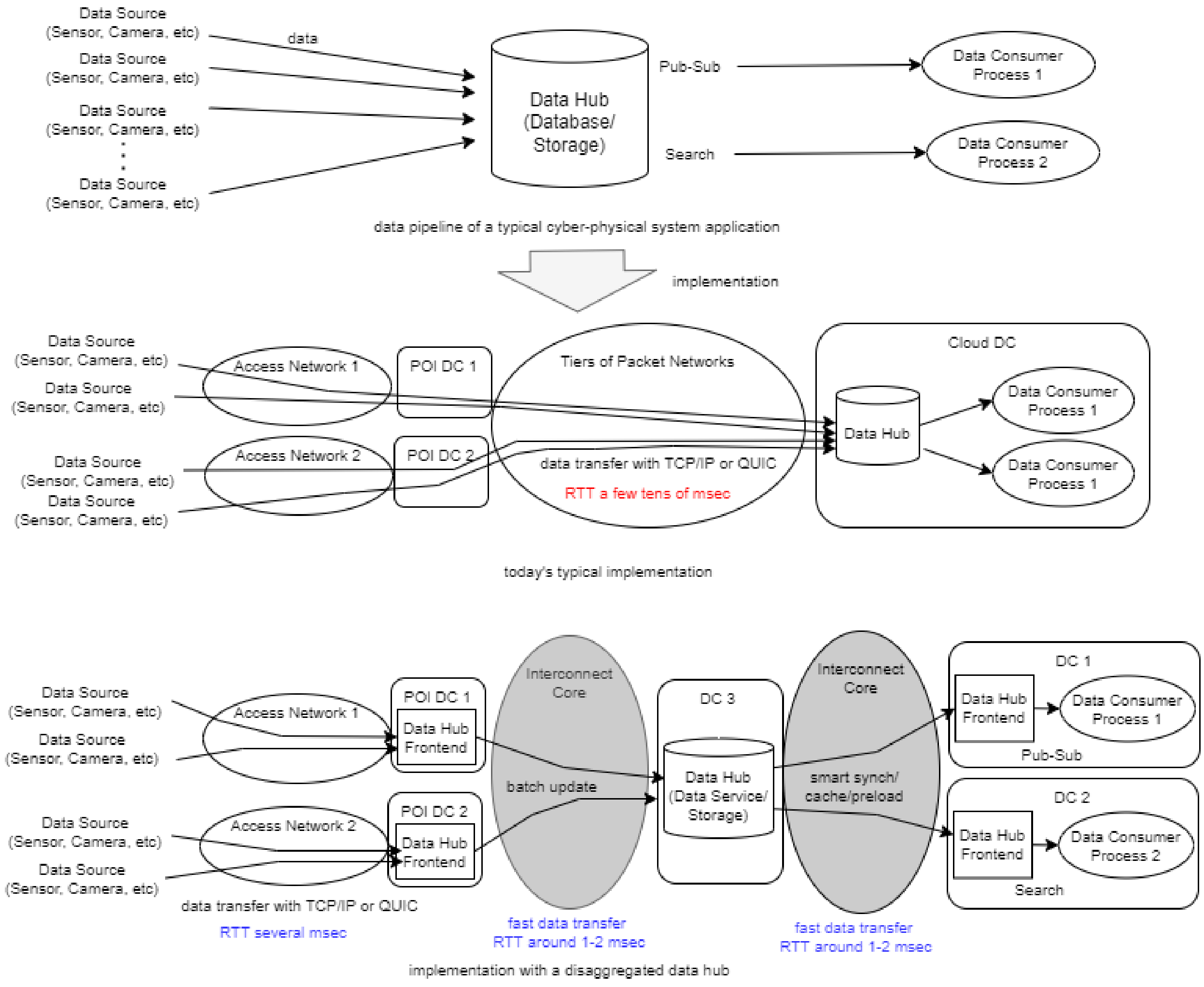


Figure 9. Lightspeed Data Pipeline with Disaggregated Data Hub

High-Capacity and Low-Latency Data Pipelines Across Data Centers: In today's infrastructure, the data transfer across data centers experiences packet and jitter around a few tens of milliseconds, which lowers application performance significantly. This makes many application developers concentrate microservices into one DC, resulting in many issues, such as inefficient cyber-physical data transfers and slow data sharing among applications. By contrast, in the evolved infrastructure, application developers can distribute microservices to multiple DCs with far fewer performance concerns because the inter-DC transfer benefits from high-capacity, low-latency connections over the Interconnect Core.

Efficient Massive Data Collection: Some CPS use cases, such as distributed energy resource management, must handle data updates from a myriad of data sources distributed in a wide area. In some use cases, the aggregated data updates may exceed one million per second. Figure 9 illustrates how the IOWN Data Hub addresses such requirements. Deploying the frontend tier to a point closer to data sources such as a carrier's Point of Interconnection (POI) DC will shorten the packet Round Trip Time (RTT) in the update data transfer and increases the number of updates achievable in a given period of time. Furthermore, by letting the frontend tier perform batch updates, we can significantly reduce the workload of the data service and storage tiers. In this way, we can achieve efficient massive data collection.

Event-Driven and Topic-Oriented Data Delivery: As stated above, the Interconnect Core will allow us to distribute microservices to multiple DCs and help us achieve the separation of data and data consumers, i.e., allowing data consumer processes to be located in DCs other than that of the database/storage. However, the performance degradation with the DC separation won't be completely zero. If we copied all the data to the DCs of data consumers, that would not be efficient. As a solution, as shown in Figure 9, the IOWN Data Hub achieves event-driven or topic-oriented data delivery, which reduces the amount of copied data by letting data consumers identify topics or events. Alternatively, we may let data consumers get data with search queries and make the front-end tier preload data based on past queries. In this way, we can efficiently achieve the separation of data and data consumers.

Data-Oriented Access Policy Enforcement: CPS applications for society-wide optimization depend on multi-source data analysis across data stored at different DCs. The separation of data and data consumers stated above will help us implement multi-source data analysis. However, such applications often involve multiple data owners, and they may hesitate to share their raw data. Adding a data disclosure policy enforcement function to the data service tier will solve this issue, as shown in Figure 10. Implementing a policy enforcement function at the data layer as opposed to the packet communication layer will enable more accurate policy enforcement.

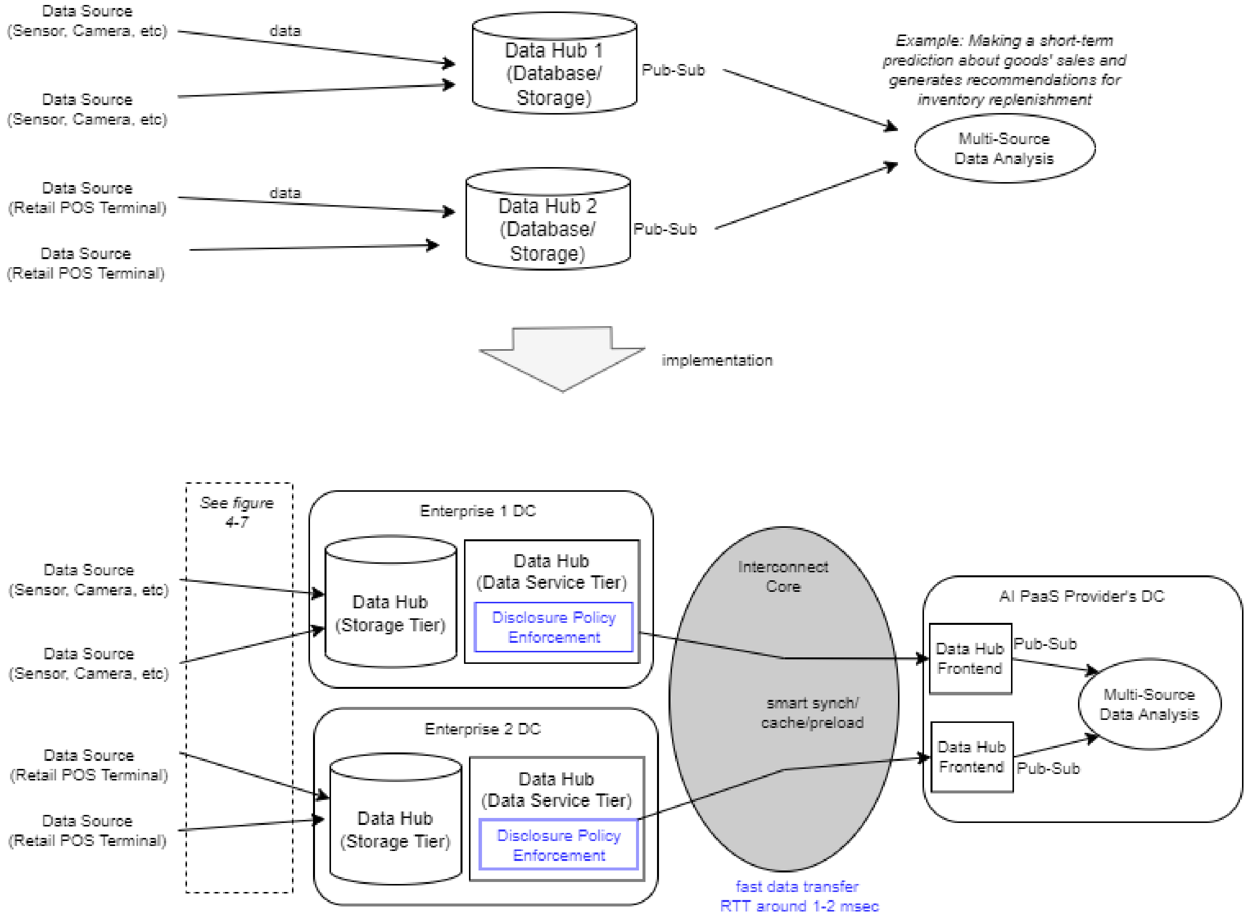


Figure 10. Lightspeed Data Pipeline for Multi-Party Data Analysis

Low-Latency Interactive Application: As streaming is bandwidth-consuming, it is an application area that has long been benefiting from a data pipeline-aware design. Figure 11 shows an example of a data pipeline of a streaming application and its implementations. A typical streaming application is built around a stream hub, which gathers streams from multiple clients and then distributes the aggregated streams back to them. A stream hub can be implemented with distributed stream relay nodes, including stream gathering nodes and stream distribution nodes. Even today, we can achieve massive-scale streaming by deploying stream relay nodes using platforms by cloud or Content Delivery Network (CDN) providers. However, as the stream relay nodes send data over packet networks, reducing the data rate of high-resolution video with a high compression ratio is inevitable and this results in significant latency. By contrast, with the evolved infrastructure, the stream relay nodes will be able to send data over high-speed connections on the Interconnect Core, and hence the low-latency mode can be chosen for video encoding. As for the access network, the converged optical access will provide the bandwidth necessary to support low-latency video encoding. In this way, the evolved infrastructure will achieve very low-latency streaming.

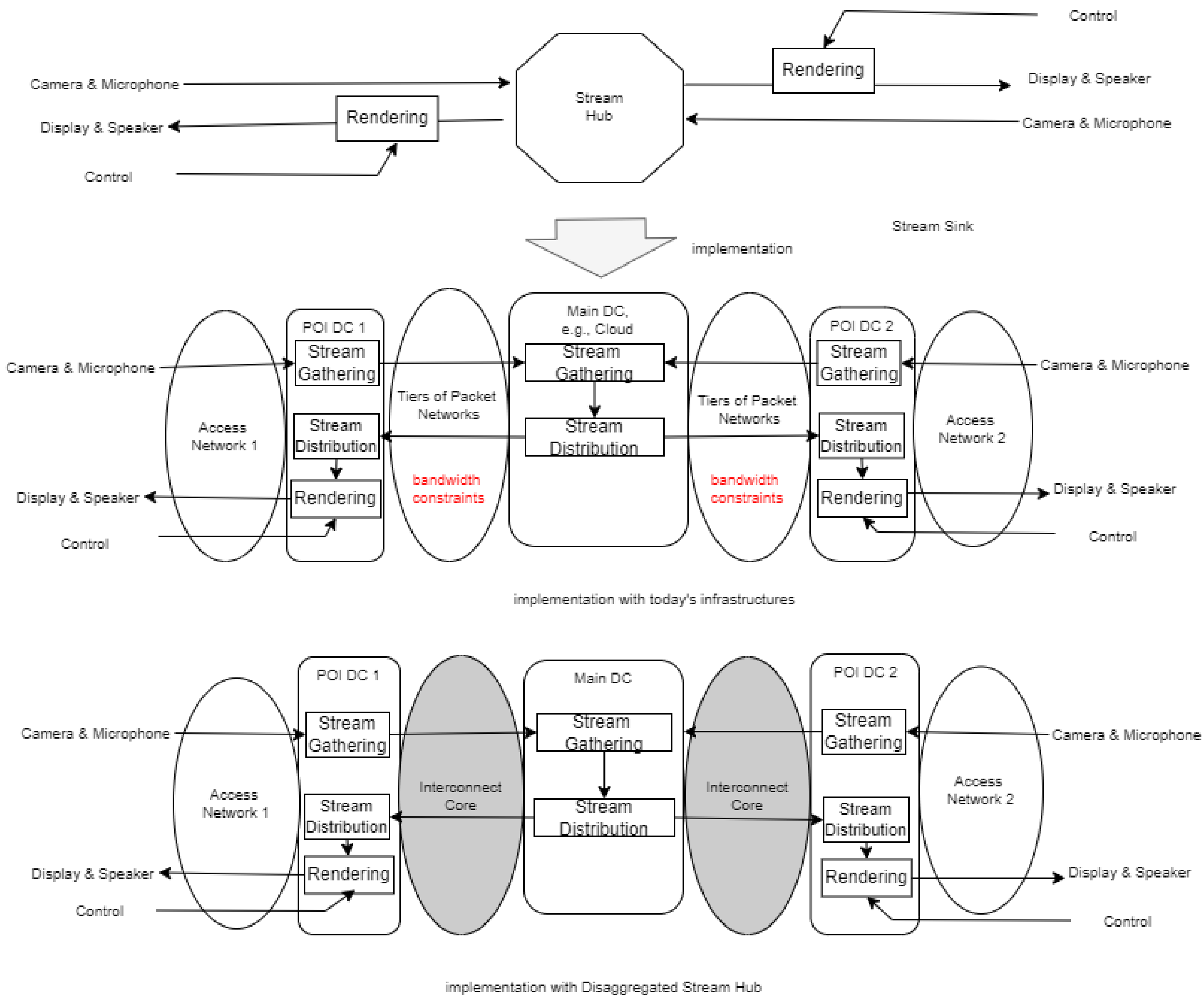


Figure 11. Lightspeed Data Pipeline for Interactive Streaming Applications

4.1.6. Energy-Efficient Data Transport with Reduced Protocol Overhead

IP and optical transport technologies will continue to form the bedrock of future networks with the anticipated year-on-year increase in overall traffic (increases up to 1,000 times), the transport networks will have to cope with a huge upsurge in capacity. Additionally, an intriguing side-effect of the rising trend towards disaggregation and microservices architectures is an even larger upsurge in the amount of traffic between the compute entities that needs to be carried over by the intra-/inter-data center data planes. The energy consumption per bit at the transport networks, therefore, becomes a significant consideration.

Just as application and software architectures evolve, so should the used transport protocols. Some of the legacy protocols have been running in deployments different than what they were originally designed for e.g., TCP/UDP over IP for wide area networks, may be used to connect applications over optical point to point links inside a DC, etc. The stacking of the different protocols on top of one other might lead to packet bloating. The networking protocols need to be analyzed and bench-marked for energy efficiency for new scenarios and deployment models. Adaptation of protocols with minimization of the networking layers as a set target should be considered as part of transport network design to optimize energy consumed due to the protocol overhead.

To complement user plane adaptation, there must be control plane evolution for dynamic determination of the best protocol and parameter configurations for energy efficiency. The control plane design should ensure a flexible selection of user plane protocols based on operating conditions, e.g., switch to ethernet from IP for application layer data that is transported between compute nodes in a datacenter's Local Area Network (LAN), or to Remote Direct Memory Access (RDMA) over APN for memory transfers between compute and memory nodes in adjacent data centers.

In terms of sustainability, optical transport evolution has a key role to play as an optical transport solution that is much more energy efficient as compared to high-speed electronics-based systems we have today. It takes far more energy to transport bits at the electrical layer than at the optical layer. The interface transitions between electrical and optical layers consumes energy. Therefore, network designs should strive to minimize the number of such electro-optical interchanges transport path and maximize transmission at the optical layer.

Silicon photonics is a revolutionary technology that enables the major improvements in performance, density, and economics and provides the high-speed backbone that make next-generation optical communications networks a reality. Thus, it becomes a key technology in building energy efficient systems, particularly in the domain of data center photonics and switching.

Likewise, AI is increasingly becoming a part of network implementations to improve efficiency, simplify operations, and enhance the end-user service experience. It enables generating inferences from a large amount of complexly intertwined data. This can be used to identify patterns and derive optimal configurations to satisfy desired Key Performance Indicators (KPIs) based on information from multiple network functions, e.g., network load and related factors, such as user behavior. An example is the application of AI to the case of Radio Densification to determine the optimal set of small cells to be turned off and power boosted based on prediction of user mobility to minimize energy consumed in the overall network. AI offers a powerful tool for not only improving energy efficiency but also as a key enabler for evolving functionalities in the future network, such as ensuring security by predicting and isolating anomalous behavior, simplify orchestration of disjointed multi-domain networks, etc.

Additionally, the impact of AI systems on the environment, which relates to the amount of energy required to train and run the AI systems, is also an important aspect to be considered. Design and architecture for collection and transport of data, generation and transport of models need to consider the cost of compute and the consequent cost of energy.

4.1.7. Network Digital Twins (Digital Twins for IOWN networks)

Emergence of Digital Twins: Digital Twin is a concept that historically emerged several decades ago, essentially in industries such as aeronautics or aerospace, associated to Computer-Assisted Design and Manufacturing (CAD/CAM) and Production Lifecycle Management (PLM) technologies. Its more recent development is greatly associated with the advent of new technologies such as the Internet of Things (IoT), artificial intelligence, edge computing, or augmented reality/virtual reality, making it possible to generalize the concept in a greater number of industries and more and more complex and interrelated cyber-physical systems and "system of systems" (i.e., systems developed independently, whose interconnection was not foreseen at the time of their development).

While there is no unanimously recognized definition to date, the vast majority of definitions converge on a few essential characteristics:

- **Digital/physical coupling:** a digital twin is a digital representation, i.e., a set of digital data sets and models constituting structured information that describes an entity or a process of the real/physical world asset (e.g., an object, a product, a machine, a complex system such as a building, a factory, a city, etc.). The existence of a digital twin is intrinsically linked to the existence of a physical twin.
- **Digital/physical synchronization:** there is a link by which the physical and digital twins are synchronized and feed each other. The physical entity will typically regularly feed its digital twin with its state, information, or location. The digital twin will in turn use this link to control the physical entity (e.g., stop a machine that is no longer in its nominal operating mode, or the bandwidth on a link). The frequency of synchronization is given/specified but variable between digital twins and specific to each use case considered.

- **Arbitrary fidelity:** the precision of the digital description also varies from one digital twin to another, and again depends on the use case considered. It is generally not helpful, for example, to have an accurate description at the molecular level - unless one considers digital twins in medicine or biology. Likewise, a 3D geometric model, or a behavioral model, is not inevitably necessary, or even useful, for all use cases of digital twins. In the end, a digital twin describes what is necessary for the intended use case(s).

A Digital Twin and its physical counterpart have a typical behavior in synergy, in a closed loop by which the observational data of the physical system will feed a digital twin, which will be able to analyze and use these data to emulate, test, compare scenarios by varying parameters, test “what-if” scenarios, assess candidate scenarios and pick an optimal one, and eventually push back these parameter configurations to the physical system. Multiple digital twins may be associated with the same (underlying) physical entity. Digital Twins can equally be used for educational purposes where particular procedures can be trained on in the digital twin and valuable experiences can be gathered before applying these to the real physical asset(s).

Typical usages of Digital Twin: Digital twins make it possible to maintain an up-to-date digital representation of entities of interest from the physical world in their environment, in order to supervise, orchestrate, and optimize the behavior of these entities and processes. They allow a global understanding for an optimal decision making. Digital twins aim to use historical and real-time data to represent the past and the present, to simulate or even predict possible futures. Note that many synchronization models may be considered to address specific use cases:

- Synchronization between a physical source and its virtual twin with continuous flows.
- Synchronization among virtual twin networks with occasional data exchange.

Typical usages of Digital Twins range from basic usages such as digitalization and visualization (e.g., 2D, 3D, Virtual Reality) to more advanced usages such as emulation, simulation, orchestration, management and control, or prediction (e.g., thanks to AI-based on historical information).

Digital Twins in IOWN Use Cases: Digital Twins are part of recurrent use cases which motivate beyond-5G networks, typically around the synchronization between digital twins and their physical counterparts which possibly necessitate efficient massive data transportation and low latency. Digital Twins are part of the IOWN vision and already included in most Cyber-Physical Systems use cases: Area Management (4D maps of buildings and city district), Mobility Management (digital twin of city traffic flow and smart grid), industry (digital twins of industrial sites/plants), smart grid management (electrical vehicle, houses/buildings and electrical network digital twins), and Health Management (public health digital twin).

Network Digital Twins for IOWN network infrastructure: Digital Twins are also emerging in the network area where they can be considered as an architectural element of future networks such as in IOWN, in which Network Digital Twins will help network management and automation together with other technologies such as AI and IoT.

A non-exhaustive list of envisioned categories of use cases where digital twins could apply and bring benefit to network management at large include:

- **Network planning and design:** there is a challenge for operators to maintain and share the knowledge on its networks. Various heterogeneous tools and applications are used all along the network lifecycle: modeling, planning, simulation, deployment, and operations, and for different kinds of networks and network segments (fix and mobile access, core networks, etc.). Digital twins could help with the inventory of network equipment and tracking of their configurations. A digital twin could federate together all these tools and give an accurate network inventory and keep track of configuration changes during the network lifecycle in a homogeneous way. The digital twin could also help in sharing (part of) information and knowledge between the different teams involved, or even between multiple actors/operators, and improve network management efficiency.
- **Telco site management and field service management:** data collected by sensors (proximity, image, touch, temperature, motion, and position) can be acquired from Telco sites. This data can then be pushed to a digital twin of the site to provide information to operations and field teams before they go on-site. When on-site, engineers can help field workers from the operations center by looking at the digital twin.

- **Network DevOps sandbox:** a digital twin of the network can become a DevOps sandbox, where new services are simulated, tested, and optimized before being deployed in production. It can also be used for testing the interoperability of multiple vendor devices and solutions.
- **Simulation:** a digital twin can be used as platform for “What-if” scenarios to emulate measures to mitigate large scale attacks, assess the resilience of the network, train teams to handle complex events that can’t be assessed directly using the operational network, etc.
- **Learning:** upgrade procedures can be tested and refined based on the learnings obtained from digital Twin testing.

4.1.8. Network as a Service from the RAN to the Cloud

One of the primary factors driving the growth of the Network-as-a-Service (NaaS) market is an increase in new data center infrastructure worldwide. The increased adoption and implementation of the cloud for data storage and the introduction of big data analytics, as well as virtualization in the data center for workload mobility, have resulted in efficient resource utilization, increased availability, reduced overall costs, and ensured high reliability and security for mission-critical business applications. This rapid digitalization and cloudification transformation is driving a historic expansion of cloud services (private, hybrid, and multi-cloud), data center expansion (edge and core), and, as a consequence, connectivity between the enterprises and those data centers.

The majority of enterprises are moving their on-premise data storage and applications to cloud-based environments and transitioning their consumption model from a CAPEX-based model to an OPEX-based model, often with a pay-as-you-go arrangement. This mode of resource acquisition aligns very well with many business models, in particular for start-ups and fast-growing companies or companies that require variable amounts of compute/storage/capacities for undetermined usage time.

Connectivity still requires large amounts of specialty equipment that is expensive to acquire, share, and manage as well as specialized expensive expertise. However, few enterprises have the necessary experience, skillsets, and technical know-how to navigate the complex market offerings of products and services from a variety of suppliers. Fewer still can successfully recombine these offerings together to produce the desired outcomes in a timely acceptable manner.

Accordingly, a significant market opportunity exists for established Network Operators to transform and partner or for a novel ecosystem of partners to revolutionize the Neutral Hosts provider’s segment and offer Network-as-a-Service. NaaS is a market segment that has developed due to a confluence of semi-simultaneous events: massive fiber deployment by Neutral Host operators in metro areas driven by 5G small cell deployments and, in parallel, the massive growth of cloud computing applications requiring advanced network connectivity solutions.

The existing solutions available to Enterprises have limitations with respect to latency, security, outage resiliency, capacity agility, and data transfer expenses. These costs are not cheap. In addition, the complexity involved in achieving cloudification is overly onerous with significant delays in execution for cross-cloud computing. Additionally, the connectivity purchased options by enterprises is typically for long term lease terms, the contract conditions are rigid and fixed for the duration, and thus force operators to purchase non-optimal and fixed connectivity capacities. Shorter term leasing options are available but at very high costs.

NaaS offers Enterprises greater flexibility and performance gains in their network infrastructure. Enterprises can be more cost-conscious through on-demand purchasing and pay only for the networking services they need. NaaS can also enable enterprises that want greater flexibility in provisioning without having to rearchitect networks or redo contracts from the ground up. Using APN for Interconnect Core and Converged Optical Access as explained in section 4.1.2 and 4.1.3 will enable infrastructure resource sharing with dynamic and granular resource assignment.

The scope and vectors of interest are illustrated in Figure 12. The entities and sites of interest relevant to this opportunity to provide connectivity services between enterprises’ geographical locations and data centers, data centers (single-tenanted and multi-tenanted, edge, and core); are primarily the enterprises themselves, the cloud Service providers, the multi-tenanted data centers.

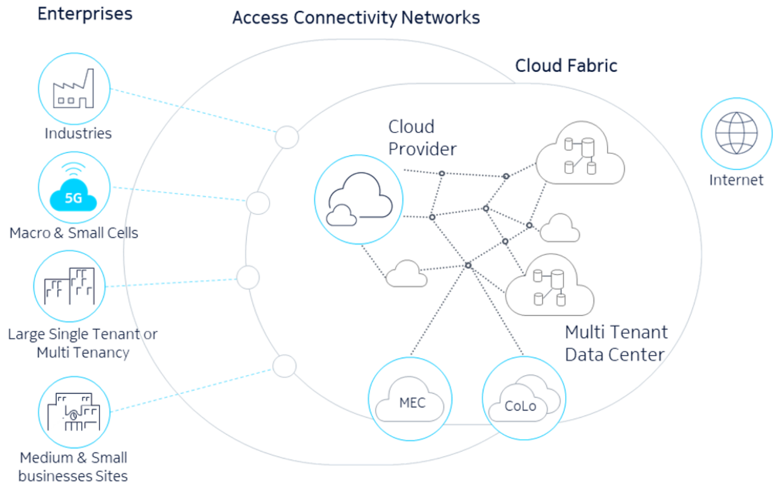


Figure 12. NaaS Domain Canvas

As hardware layers in networking technologies are being virtualized, setting the scene for Network virtualization is now being deployed. Underpinning the transformation to virtualized, programmable networks is the need for a highly scalable, flexible, and adaptive packet/photonic optical fabric. This allows the full benefits of software-defined programmability to be realized e2e across the data planes and physical transport layers across different ownership boundaries.

4.1.9. Non-terrestrial Networks with Free Space Optics-Based for communications networks everywhere

The Fifth Generation of mobile wireless communication systems (5G) introduced the concepts of enhanced Mobile Broadband (eMBB), massive Machine-Type Communications (mMTC), and Ultra-Reliable Low Latency Communications (URLLC) to accommodate the ever more demanding needs of emerging new services and applications. These drive and push the requirements of the terrestrial networks (TN) to be able to provision novel services in areas that currently cannot be serviced in a cost-efficient manner. As a result, new ways of offering services in these areas are being explored.

With the recent launches of e.g., SpaceX, Starlink, etc., delivering satellite broadband services in unreachable areas with low latency, opens up unprecedented possibilities.

Furthermore, the Sixth Generation (6G) technologies will revolutionize the wireless ecosystem by enabling the delivery of futuristic services through terrestrial and non-terrestrial transmissions. Non-terrestrial networks (NTN) refer to networks based on spaceborne vehicles or an airborne platform for communication transmission. The projected 6G wireless ecosystem will be essential to ensure service availability, continuity, ubiquity, and scalability. Since the terrestrial networks suffer from limitations in terms of deployment and coverage, Non-Terrestrial Networks are considered to be a complement to achieve global connectivity, e.g., through nano-satellite constellations. However, NTN distinguishing features (e.g., the orbit type, the altitude, the footprint size) strongly depend on the NTN platform type, spanning from Geostationary/Medium/Low Earth Orbit (with GEO, MEO, LEO) space born satellites to Unmanned Aircraft Systems (UAS), including airborne High Altitude Platform Systems (HAPS).

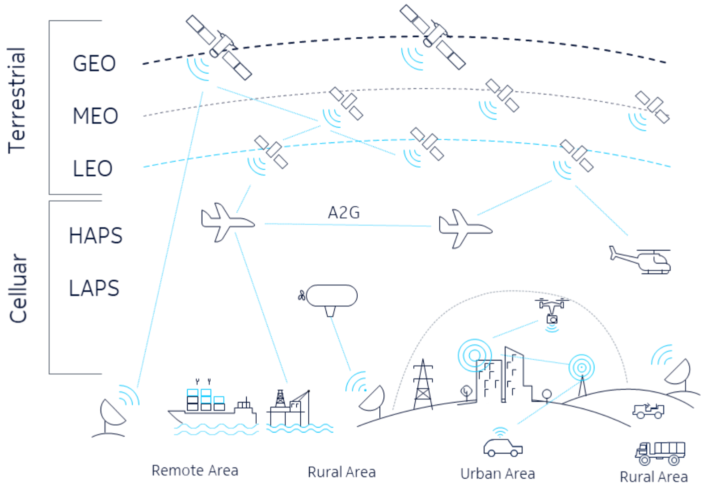


Figure 13. Examples of Non-Terrestrial Networks

The technical challenges and important issues for the alignment in tracking and acquisition using Free-Space Optical (FSO) communication links, such as the FSO unit precision alignment and the beam attenuation/fluctuation due to the atmosphere, must be studied. The availability of access to the network must equally be studied. Figure 13 shows the different aerial links between the different NTN platforms. The links between those platforms and their ground GW are not shown.

Many organizations recognize NTNs as a key component to provide cost-effective and high-capacity connectivity in future 6G wireless communication networks. Despite this premise, there are still many questions to be answered for proper network design, including those associated with latency and coverage constraints.

Current services congestion the conventionally deployed Radio Frequency (RF) spectrum. Free Space optics as an optical carrier has many advantages compared to RF communications and is considered to be the next frontier for high-speed broadband connections, as it offers extremely high bandwidth, ease of deployment, unlicensed spectrum allocation, reduced power consumption (~1/2 of RF), reduced size (~1/10 of the RF antenna diameter) and improved channel security. Additionally, contrary to an RF carrier where spectrum usage is restricted, an optical carrier does not require any spectrum licensing and therefore, is an attractive prospect for high bandwidth and capacity applications. The high directivity of the links, and their high sensitivity of the observed conditions on the propagation channel (in particular the weather conditions in the low layers of the atmosphere) must be studied to determine the availability of the service. Additionally, the identification of adequate use cases making use of the link directivity, challenges on the tracking performance for the optical links, cost, simplification, and miniaturization of optical sub-systems (particularly for the satellite segment), link availability, and link diversity (hybrid approach FSO/RF, etc.) should be studied. However, the implementation of Non-Terrestrial Networks (NTN) and free space optics has not yet been included in the IOWN GF current roadmap. In order to explore the potential benefits of these technologies, we plan to reach out to companies that specialize in providing NTN and free space optics solutions and gather information about their plans and progress in this field. By staying informed about the latest advancements and potential solutions, we can better evaluate the feasibility and potential benefits of incorporating NTN and free space optics into our future plans.

4.2. Expected Benefits

4.2.1. Benefits for Infrastructure Operators

Revenue Growth Acceleration with Express Fiber/Antenna Deployment: Optical branching will enable customers to add systems without having to wait for fiber deployment by carriers. This will increase customers' business velocity. In particular, future mobile networks will depend more on antenna site sharing, e.g., tower sharing, because millimeter radio requires antenna sites with good lines of sight, and the landowners of such sites often demand that mobile network operators should share the towers. Placing a splitter on a radio tower and letting the tower operator add a branch line for a new tenant mobile operator will reduce the lead time in mobile antenna deployment.

CAPEX/OPEX/Energy Saving with Infrastructure Sharing: As an APN connects sites, such as data centers and radio towers, with guaranteed bandwidth and bounded latency, it facilitates infrastructure sharing, e.g., radio tower or neutral host sharing, by multiple network operators. Besides radio tower or neutral host sharing, the combination of APN and DCI allows network operators to share other infrastructure resources, such as data centers and computing platforms for vRAN and edge computing.

CAPEX/OPEX/Energy Saving with Multi-access-area RAN Resource Pooling: Optical path-through will enable mobile network operators to create a common RAN resource pool for multiple access areas and dynamically assign resources in accordance with the hourly variation of the connectivity demands by areas. This will reduce the total amount of required RAN resources.

More Efficient and Resilient Network Operation with Network Digital Twins: Digital Twins will ease network operation and maintenance (we talk here about network infrastructures at large, including all telecommunications sites such as antenna sites, cabinets, data centers, etc.) through data aggregation for management at scale of complex networks**.** Digital Twins will also allow for the simulation of network evolutions before operational deployment, as it represents the state of a network in a more reliable way than a simulation platform, without the high risk of interfering with existing services and the higher cost of field trials. In addition, Digital Twin will help data sharing as managing networks is no more the exclusive concern of a single operator, but rather the opportunity of a collaboration between various actors within the organization of a single operator, or in an ecosystem gathering telecom operators, public organizations and territories, private service providers or contractors around shared digital twins.

Enhanced Resilience and Coverage with Non-Terrestrial Networks: Ability to provision reliable connectivity to areas otherwise difficult to connect or reach. Likewise, ubiquitous connectivity allows for service continuity and availability in a cost-effective and scalable manner.

4.2.2. Benefits for Enterprises and Application Providers

Business Digitalization with IT Decarbonization and Proper Data Residency: The network-wide disaggregated computing will help enterprises replace their servers with computing resources provided by Computing as a Service (aaS) providers. By selecting a CaaS service provider that excels in lowering CO2 emissions, enterprises will be able to advance their IT decarbonization while benefiting from service providers' latest computing systems. In addition, the separation of application and data will achieve proper data residency by allowing enterprises to maintain their data at their DC.

Mission-Critical Applications: Optical branching and optical path-through will enable customers to create high-speed and low-latency connections between devices on customer premises and applications in data centers. When the devices are mobile, such as in the case of drone control applications, the evolved infrastructure enables mobile operators to deploy millimeter radio spots quickly in response to customers' requests. In this way, the evolved infrastructure provides ultra-reliable, ultra-broadband, and low-latency connections that are necessary for mission-critical applications regardless of whether they are fixed or mobile.

High-Resolution and Low-Latency Remote Working and Services: The evolved infrastructure will allow anyone to develop high-resolution and low-latency remote service applications by building their data pipelines over the Interconnect Core. Furthermore, the carrier-agnostic MEC stated below will make such services reachable to many sites and users.

Energy Consumption Reduction in Data Transport: The evolution of protocols for transport networks that consider energy consumption per bit on their design, as well as minimization of networking layers, can reduce the energy consumed due to the protocol overhead. Similarly, an optical transport solution is more energy efficient than an electric one and can allow for further reduction of energy consumption by minimizing electro-optical interchanges in the transport path

Carrier-Agnostic Multi-access Edge Computing: Many enterprises are eager to digitalize their business through connected services. Most of them require that their systems should not depend on a single network carrier. Hence, Multi-access Edge Computing (MEC) offering from a single carrier is not a perfect solution. Forming “the Internet of Data Centers” with the Interconnect Core will address this issue. If multiple carriers connect their MEC DCs to the Interconnect Core, any entity, which may be an enterprise or a DC provider, can become the owner of carrier-agnostic edge computing infrastructure just by connecting its DC to the Interconnect Core. Note that Open APN should allow multiple carriers to operate their Internet Core infrastructures and interconnect them. This would achieve perfect multi-carrier redundancy.

Infrastructure Cost Saving with Network-as-a-Service: Cloudification in the enterprise, and its resulting cloud connectivity requirements, compared to the current generation of transport solutions, command much greater capacity with symmetrical bandwidth, reduced, and stringent bounded service delivery service levels, and available when needed. However, current solutions can be costly, as well as architecturally and operationally complex in nature. Similarly, the latency and security of business-critical data is of great importance. To this end, APN and DCI will enable NaaS that can offer enterprises the required flexibility and performance gains in a cost-conscious manner through on-demand purchase models, minimizing the burden of cloudification.

4.2.3. Benefits for Societies

Society-Wide Optimization with High Data Velocity: Lightspeed data pipelines and data-oriented policy enforcement with Data Hub will allow enterprises to share their data without running a periodic batch process to produce a cleansed version. This will accelerate data velocities and enable societies to make short-term predictions.

“SNS of Artificial Intelligence” for Collaborative Autonomous Systems: Lightspeed data pipelines by a data hub will enable many autonomous systems, e.g., robots, to share their data in real-time as people exchange their tweets and photos through social network services (SNS). In this way, as the “SNS of AI”, the data hub will give birth to many innovations with collaborative autonomous systems.

“Internet of Data Centers” and Computing Function/Resource Marketplace: As the “Internet of Data Centers”, the interconnect core will realize network-wide disaggregated computing and create many aaS business opportunities. For example, AI accelerator product suppliers may connect their DCs to the Interconnect Core and provide services such as GPU-aaS and Inference-aaS. For another example, data warehouse companies may provide intelligent services such as Business Intelligence-aaS on their DCs, while selling the storage units to be placed in customers' DCs.

Data Center Decarbonization: The network-wide disaggregated computing with the Interconnect Core will enable us to build computing infrastructures with many acceptable-scale DCs that can run on locally available green energy.

5. IOWN GF Evolution Journey Plan

5.1. Roadmap

Striving toward 2030 envisioning growing adoption and deployment of the IOWN all photonic network, the IOWN GF has updated its phased roadmap toward 2025 (see Figure 14).

With immediate business needs requiring high volume and low latency network and with the progress being made at IOWN GF, pre-commercialization of IOWN is on the horizon targeting initial deployment of IOWN in the Phase-3 2023-2025 timeframe.

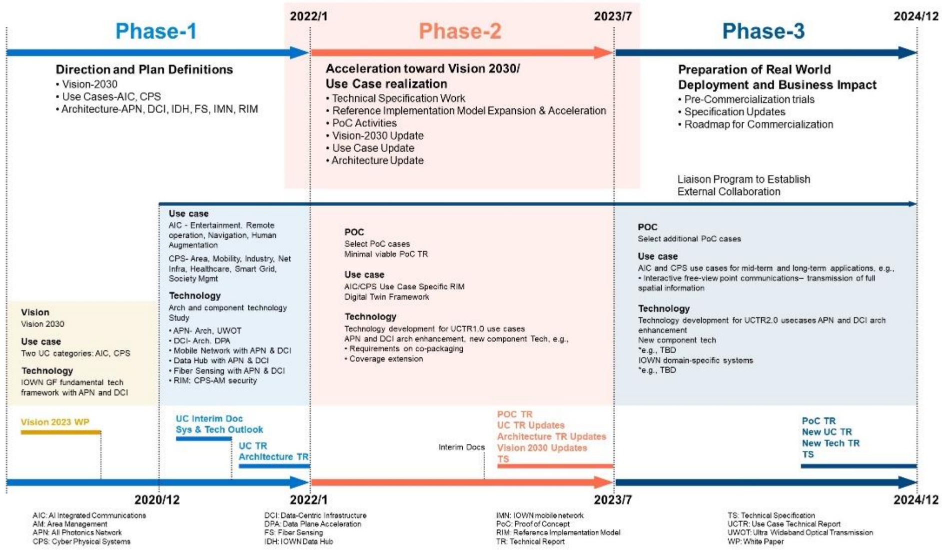


Figure 14. IOWN GF Roadmap

5.2. Work Plan

With the successful completion of Phase-1, the IOWN GF intends to keep its momentum toward Phase-2 work to accelerate toward the realization of Vision 2030.

While significant progress is being made in defining use case requirements and technology specifications, the current position of the documents being created remain as an early phase consensus. The IOWN GF believes in agile specification work by driving Proof-of-Concepts (PoCs) to iteratively improve the quality of the specifications.

The IOWN GF has initiated the creation of the set of documents called PoC Reference, which describe the objectives, scope, and metrics to be evaluated. The intention of the documents are to invite and call for participation for PoC execution from in-and-outside of the IOWN GF community. The creation of PoC Reference and feeding back the results of PoCs will be the essential work in 2023-24. The PoC scope will include applying IOWN technologies addressing contemporary use cases as well as step-by-step implementation of future-looking use cases defined in AIC/CPS.

Resilience is a key requirement. Therefore, the design of the IOWN system, and of each of its technology components, need to take into account their robustness against various types of adverse events, including natural disasters, equipment failure, software bugs, and cyberattacks.

5.3. Operation Principles

The IOWN GF should respect other communities' activities. The focus of the IOWN GF should be to define an end-to-end and full-stack system architecture that leads to quantum leaps in our key dimensions. Specifying technical details for a specific layer or component should be carried out by subject matter expert groups outside of this forum. However, if there is no such a group, we will work on the technical details.

The IOWN GF should also run use case exploration to fully understand users' requirements and to raise people's awareness about the IOWN GF's potential impact on future societies and businesses. In particular, use cases should be developed jointly with IOWN GF members representative of various industrial sectors (e.g., manufacturing, health, energy) in order to maximize the benefits of IOWN technology in these sectors. Also, the use cases feasibility assessment should include economic and environmental sustainability.

6. Conclusion

Emerging cyber-physical systems and remote services will help us solve the sustainability and resilience challenges. However, increasing pressure on carbon emissions implies that we should implement such application systems without increasing power consumption significantly. Hence, the world should develop a novel infrastructure that excels in capacity, latency, and energy efficiency. Since its foundation in 2020, the IOWN Global Forum has been addressing this new challenge and has defined new networking and computing infrastructures, Open All Photonics Networks (Open APN), and Data-Centric Infrastructure (DCI).

While today's Internet connects two sites with packet routing at layer 3, Open APN connects two sites with an optical wavelength connection at layer 1, achieving guaranteed bandwidth and bounded latency. This key difference enables us to add a data-center interconnection infrastructure, "Interconnect Core", to today's infrastructure. With the Interconnect Core, people will be able to build hybrid/multi-cloud infrastructure comprising multiple data centers interconnected with high-bandwidth and low-latency links.

DCI will enhance the value of such hybrid/multi-cloud infrastructures by enabling network-wide disaggregated computing. While the computer industry has been developing a variety of accelerators, such as GPU cards and FPGA-based processor cards, the host CPU often gets overwhelmed with the workload of moving data to accelerators in today's distributed computing. DCI solves this issue by composing a chain of modules including smart NICs and accelerators.

With Open APN and DCI, people will be able to build hybrid/multi-cloud infrastructures that can transfer and process data at the speed of optical communications. This will bring several benefits. First, such infrastructures will effectively support cyber-physical systems and remote services with extremely high QoS requirements. Second, enterprises will be able to store their data at their private data centers, while utilizing cloud service providers' up-to-date AI platforms for the analysis of data. Third, enterprises will be able to reduce the carbon emissions of their IT infrastructures by utilizing cloud service providers' highly efficient computing infrastructures.

The IOWN GF's Open APN and DCI will also play an important role in the evolution of mobile networks. As future mobile networks rely more on millimeter radio bands, whose coverage is very small, they cannot achieve their performance objectives without agile antenna deployment and elastic RAN resource management. This is where Open APN and DCI will come into play. Using Open APN as an infrastructure for mobile fronthaul, we can improve the agility of antenna deployment. In addition, using DCI as the NFV infrastructure of virtual radio access networks (vRANs), we can elastically assign computing resources in accordance with the hourly traffic variation. In addition, the Open APN will allow multiple mobile network operators to share a network infrastructure for mobile fronthaul. This will be very attractive because future mobile networks will rely more on tower sharing.

The IOWN GF considers that we should study the system's behavior and bottlenecks from the full-stack and end-to-end viewpoint and redefine the total system architecture to achieve high performance and energy efficiency. That's why the IOWN GF has also developed several complementary technologies including data hub, fiber sensing, and post-quantum security, and defined reference implementation models for some use cases. However, such works could not be practical without iterative test-and-refine activities. So, as the next step of the IOWN Infrastructure Evolution Journey, the IOWN GF will start testing and proof-of-concept activities. As a result of such test-driven activities, the IOWN GF's technologies will become truly viable and practically operable. More importantly, such activities will create opportunities for technology adopters and technology developers to recognize the value of the technologies.

The IOWN GF would be delighted to collaborate with many organizations in this exciting journey.

Appendix 1: List of Abbreviations

aaS	as a Service
AI	Artificial Intelligence
AR	Augmented Reality
AIC	Artificial Intelligence-Integrated Communications
APN	All Photonics Network
CAD	Computer Assisted Design
CAM	Computer Assisted Manufacturing
CDN	Content Delivery Network
CO-DBA	Cooperative Dynamic Bandwidth Assignment
CPS	Cyber Physical System
CTI	Cooperative Transport Interface
CWDM	Coarse Wavelength-Division Multiplexing
DC	Data Center
DCI	Data-Centric Infrastructure
DFOS	Distributed Fiber Optic Sensing
DPU	Data Processing Unit
DWDM	Dense Wavelength-Division Multiplexing
E2E	End-to-End
eMBB	enhanced Mobile Broadband
ESG	Environmental, Social and Governance
GEO	Geostationary Earth Orbit
GSIA	Global Sustainable Investment Alliance
HAPS	High Altitude Platform Systems
IoT	Internet of Things
IOWN GF	Innovative Optical Wireless Network Global Forum
IP	Internet Protocol
IPU	Infrastructure Processing Unit
ITU-R	International Telecommunication Union Radiocommunication Sector

LAN	Local Area Network
LEO	Low Earth Orbit
LSN	Logical Service Node
MEC	Multi-access Edge Computing
MEO	Medium Earth Orbit
MFS	Multi-Factor Security
ML	Machine Learning
mMTC	massive Machine-Type Communications
NaaS	Network as a Service
NIC	Network Interface Card
NTN	Non-Terrestrial Network
OAA	Open APN Architecture
OAF	Open APN Fiber Sensing
PLC	Production Lifecycle Management
PoC	Proof of Concept
RDMA	Remote Direct Memory Access
RF	Radio Frequency
RTT	Round Trip Time
RSA	Rivest–Shamir–Adleman
SDG	Sustainable Development Goals
SNS	Social Network Services
TCP	Transmission Control Protocol
TDM	Time-Division Multiplexing
TF	Task Force
TN	Terrestrial Network
TWDM	Time Wavelength-Division Multiplexing
UAS	Unmanned Aircraft Systems
UDP	User Datagram Protocol
URLLC	Ultra-Reliable Low Latency Communications
VR	Virtual Reality

WDM	Wavelength-Division Multiplexing
XR	eXtended Reality

Appendix 2: References

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