Open All-Photonic Network Functional Architecture

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1. Introduction

1.1. Market Dynamics and Needs

Today's world has experienced faster than ever growth, due 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.

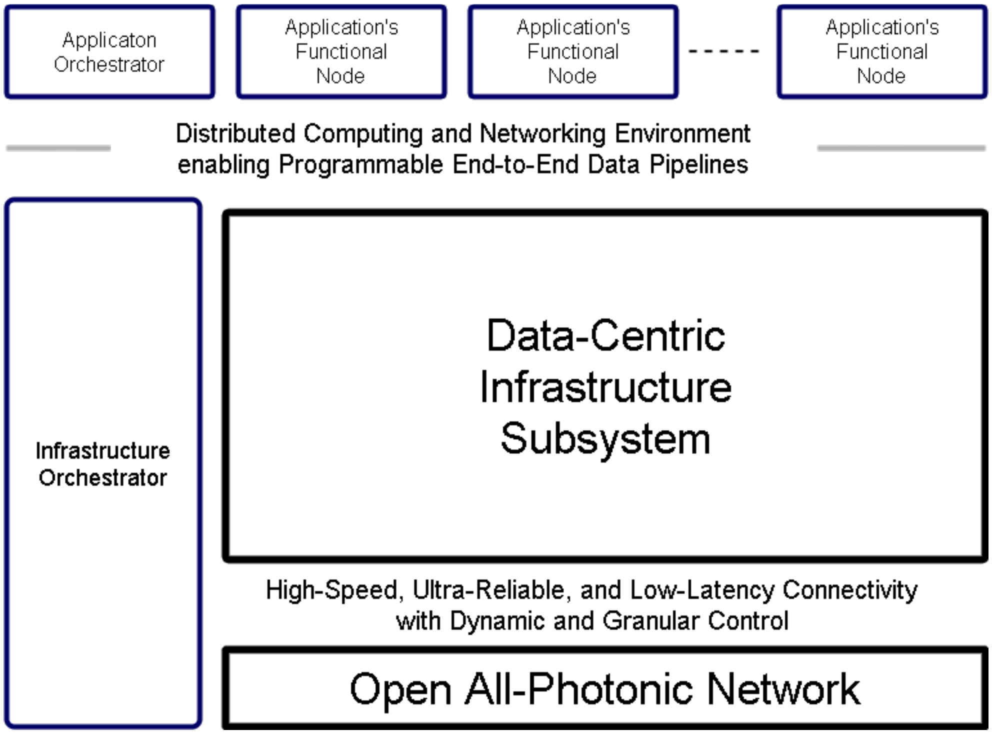
The Innovative Optical and Wireless Network Global Forum (IOWN GF) has released documents for two use cases, Cyber-Physical Systems (CPS) [IOWN GF CPS] and AI-Integrated Communications (AIC) [IOWN GF AIC]. The Area Management use case in CPS realized by many monitoring devices with beyond-human cognition will help people reduce the occurrence of incidents or respond to them more effectively when they occur. The Mobility Management CPS achieved by digital twin computing will enable Level 4 autonomous driving [SAE J3016]. The Industry Management use case in CPS modernizes the operation of factories and industrial plants by enabling AI-based monitoring/control and remote monitoring. AIC use cases will give businesses that once relied exclusively on in-person attendance for their services to endure in the face of difficulties such as the current pandemics. For example, future music concert halls and sports stadiums will have volumetric-capturing facilities so the performances of artists or athletes can be enjoyed remotely with a 6DoF view. Educational institutions and healthcare facilities will also be able to provide many services remotely.

The world has already started implementing these use cases at some level. However, the evolution of sensing/capture technologies suggests that the critical requirements of these use cases will be much higher than those achievable with existing technologies. CPS enhanced with beyond-human sensors should handle data at hundreds of Gbps and respond to events in the physical world within tens of msec, and in some advanced industry use cases, within a few msec. AIC enhanced with volumetric capturing should gather real-time streams at hundreds of Gbps and deliver the presentation data to the receiving users within tens of msec. What's more, some use cases will enable feedback within a few msec, providing super-rich user experiences (e.g., real-time haptic feedback). When the viewer is equipped for motion/posture capturing, the feedback should be achieved less than 10 msec motion-to-photon.

1.2. Overview of the IOWN Global Forum Architecture

IOWN GF aims to establish an end-to-end architecture for computing and networking that can support various data flows and workloads, as shown in Figure 1.2-1.

Open All-Photonic Network Functional Architecture



The **Open All-Photonic Network (APN)** is a network that connects endpoints directly with optical paths. It provides high-speed, ultra-reliable, and low-latency connections. In today's network, optical paths are disjointed and operated on a segment-by-segment basis, i.e., local area network (LAN), access network, and inter-data-center network. By contrast, the Open APN will enable one optical path to span across multiple segments. This will allow end-to-end communication with deterministic performance. However, this approach will require more dynamic and granular control.

Furthermore, as optical paths are dynamically created (making their performance demands impossible to predict until they are provisioned), a real-time performance measurement and monitoring mechanism is required that enables the infrastructure to set up new optical paths with the projected achievable transmission speed. The IOWN GF aims to establish an open architecture for photonic networking so that service providers can integrate photonic network functions with their entire computing and networking infrastructure with more granularity. The open architecture should also enable service providers to build an intelligent operations support system.

The **Data-Centric Infrastructure (DCI)** subsystem is intended to provide applications with a distributed and heterogeneous computing and networking environment that spans end-to-end, i.e., across clouds, edges, and customer premises. This end-to-end, heterogeneous, and distributed computing/networking will enable service providers to build end-to-end data pipelines, placing data processing and storage functions in desired places. Data processing functions include filtering, aggregation, and event brokerage. Data storage functions provide shared storage, such as object storage and database, for data pipelines with multiple data sources and sinks.

DCI's support of heterogeneous networking will allow service providers to select data transfer and network protocols on a pipe-by-pipe basis. For example, protocols supporting deterministic quality may be used for network paths connecting real-time sensors in a manufacturing setting, while traditional IP would be used for networking paths connecting external data consumers. In this way, service providers will be able to accelerate data flow without isolating their systems from today's Internet ecosystems.

DCI's support of function-dedicated computing (FDC) will enable service providers to add various types of computing resources for performing dedicated computing tasks such as image artificial intelligence (AI) inference, time-sensitive data processing, network function virtualization (NFV), and database acceleration. In this way, service providers will benefit from the ongoing evolution of computing acceleration technologies.

The DCI subsystem exposes service interfaces to the Application's Functional Nodes for applications such as cyber-physical systems (CPS) and AI-integrated communication (AIC). Application developers can then build applications leveraging the functions and features provided by DCI and the Open APN. The features for high quality-of-service (QoS) are provided by the Function Dedicated Network (FDN) layer and may be realized by underlying networks including an Open APN network.

The **Infrastructure Orchestrator** is the infrastructure's central management function that controls various types of infrastructure resources and exposes the single management interface. It is logically a single component but it may be implemented with multiple nodes.

The **Application Orchestrator** is the central manager of an application system, which controls multiple application processes, i.e., microservices, for the application. When it deploys an application process on an IOWN GF System, it should call the application programming interface (API) of the infrastructure orchestrator to create a runtime environment, e.g., a logical node.

This document focuses on the services and functional architecture of the Open APN.

1.3. Design Goals of Open All-Photonic Network (APN)

In response to the expectations in Section 1.1, there is a need to architect a new infrastructure Open APN based on the future optical technologies. Open APN aims at achieving the following concepts:

End-to-end lambda connection: Traditionally, a transponder was a huge special-purpose device in the central office of a service provider. In the future, users will have their transceivers that connect directly to remote sites via a service provider's network.

Dynamic optical path provisioning/control: Today, a high level of expertise is needed for optical path provisioning, and it takes several days to several weeks (including site surveys, design, and configuration) before the optical path is established. To provide optical transport services that directly connect users flexibly, a method to provision and control optical paths is required. In addition, the number of wavelengths is limited. Therefore, flexible and efficient optical path operation can be expected by adding, changing, or removing the optical path in real-time according to the performance requirements and quality of transport to be provided.

Energy efficiency: Today, with the increasing use of big data and AI processing of large amounts of data, the power consumption of network equipment and data centers tends to increase. Open APN based on an end-to-end direct optical connection can be expected to enable networking with less energy consumption by minimizing electrical processing. On the other hand, the actual power consumption differs depending on the network design and the technology choices. Therefore, the architecture and specifications of the Open APN should be defined in such a way that lower power consumption can be properly realized according to the policy.

Multi-operator's environment: The network will be an environment that accommodates multiple federated network operators. Each network operator can deploy end-to-end lambda connections seamlessly without annoying complicated resource-sharing procedures and any conflicts when isolating defects.

Computing-Networking Convergence: Computing, which performs calculations, and wide-area networks, which transfer data, have evolved independently of each other (Edge routers/switches are the demarcation point between the two facilities). To realize CPS and AIC use cases, new optical networking that is easily adaptable to distributed computing is needed. It connects computing resources in distant locations with high-capacity optical paths on-demand, with target quality of transport definable by computers.

Automated resource reallocation: The network will need to efficiently scale bandwidth up and down per Endpoint as user demands shift over time. During the day business parks may need more bandwidth, while during the evening concert venues may require more bandwidth. By redistributing these applications over distributed computational resources with variable bandwidth networks, latency and network traffic that impact user experience can be minimized.

Format-free optical communication: Open APN should allow a variety of optical modulation formats and upper-layer protocols. This will enable users to create new use cases with fiber infrastructures. Ideally, protocol-free and modulation-format-free communications should be allowed. However, this could not be achieved without detailed conformance specifications for admissible optical signals. The degree of freeness will improve as IOWN GF update the specifications of the Open APN.

Intelligent monitoring: To realize more dynamic operations of the Open APN, the network control, and management systems must obtain sufficient information from Open APN devices. The Open APN monitoring mechanism should be more granular and comprehensive to obtain enough information faster instead of the sluggish and monotonous monitoring mechanisms in current optical networks. Therefore, the network resources can be comprehensively managed and the resource allocations can be dynamically achieved. Furthermore, the monitoring information from various network administrative domains and various network operators can be leveraged to support the dynamic optical path provisioning/control of the Open APN. To handle such enormous pieces of monitoring data, Open APN control and management systems should be low latency and high security for data collecting, storing, processing, analyzing, and sharing.

1.4. Evolution of Optical Transport Technologies

In the recent router market, Software Defined Wide Area Network (SD-WAN) technology, which disaggregates the physical network and hardware equipment from its control plane and uses software to manage it, has become commercially available. On the other hand, for the optical transmission system market, it has been thought that automatic control by software like SD-WAN is difficult due to the barrier of complex physical phenomena such as wavelength dependency of optical amplifiers, chromatic dispersion, and nonlinear optical effects. As the commercialization of digital coherent transmission systems started around 2010, the downsizing, power saving, and control interface commonality of transmission systems were accelerated.

Figure 1.4-1: Evolution of Digital Coherent Transmission Systems and History of Openness

Figure 1.4-1 shows the evolution of digital coherent transmission systems and the history of openness activities. After the definition of the management interface specification for the C Form-factor Pluggable (CFP) [CFP], OpenConfig

[OpenConfig], which focuses on compiling a consistent set of vendor-neutral data models, began to define open configuration Yang models for optical transport. Open Networking Foundation (ONF) [ONF], which is a non-profit operator-led consortium driving a transformation of network infrastructure and carrier business models, proposed a standard Transport API (TAPI) [TAPI] for a northbound interface to a Transport SDN Controller. TAPI enables programmatic control of a service provider's transport network to support the faster and more flexible allocation of network resources to support application demands. In 2016, with the launch of Open ROADM [Open ROADM], which defines interfaces and specifications to make ROADM systems interoperable among vendors, and the Telecom Infra Project Open Optical & Packet Transport (TIP OOPT) [TIP OOPT], which aims to define open technologies, architectures, and interfaces in optical and IP networking, the openness of optical transmission technologies accelerated with the participation of telecom carriers and hyperscalers. CableLabs, which works with the suppliers to the cable industry to develop interoperable technologies, has adapted coherent technology for use in metro access networks. The Optical Internetworking Forum (OIF) published Implementation Agreements (IAs) for DCI edge coherent optical interface, network processing elements, component technologies, and the OpenZR+ MSA defined multiplex transmission of 100G/200G/400GbE for metro regional as well as DCI networks. The interface specifications and tools of each organization shown in Figure 1.4-1 are mapped in Figure 1.4-2.

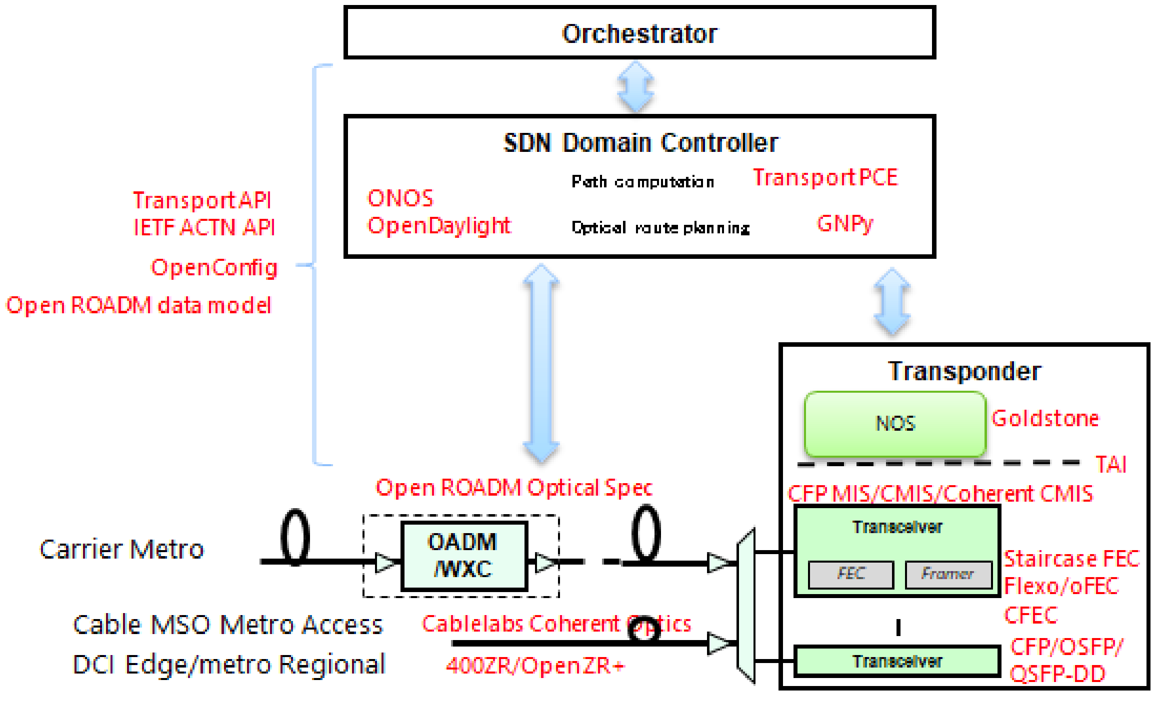


Figure 1.4-2: Interface Specifications and Tools of Each Organization

Through the activities of these organizations, international standards for coherent technology have been established by IEEE and ITU-T. IEEE802.3 defined 100GbE 80km DWDM optical interface based on coherent technologies. IEEE802.3 defined 100GbE 80km DWDM optical interface based on coherent technologies. Coherent 400GbE 80km DWDM interface is also being discussed in IEEE802.3cw (Work in progress). ITU-T specifies CFEC for FlexO-LR 80 km application and oFEC for 450 km application in G.709.3. Optical link parameters for 200G and 400G applications in G.698.2 are planned to be defined in 2022. Table 1.4-1 shows the status of compatibility in the data plane. Communicating transmission methods such as modulation, FEC, and baud rate of coherent DSPs among different vendors are necessary for data plane compatibility. Interconnection among different vendors is now possible in all bands from 100 to 400 Gbps as described in Table 1.4-1.

Table 1.4-1: Standardized Data Plane Modes

LINE RATE	MODULATION	FEC	BAUD RATE [GBD]	ORGANIZATION
100G	DP-QPSK	SC FEC	28.0	Open ROADM [Open ROADM spec], CableLabs [CableLabs spec], ITU-T [Y.1331][Y.1331.2], IEEE802.3 [IEEE802.3ct]
100G	DP-QPSK	oFEC	31.6	Open ROADM [Open ROADM spec]
100G	DP-QPSK	oFEC	30.0	OpenZR+ [OpenZR+ spec]
200G	DP-16QAM	oFEC	31.6	Open ROADM [Open ROADM spec], CableLabs [CableLabs spec]
200G	DP-QPSK	oFEC	63.1	Open ROADM [Open ROADM pec], CableLabs [CableLabs spec], ITU-T [Y.1331][Y.1331.3]
200G	DP-QPSK	oFEC	60.1	OpenZR+ [OpenZR+ spec]
300G	DP-8QAM	oFEC	63.1	Open ROADM [Open ROADM pec]
300G	DP-8QAM	oFEC	60.1	OpenZR+ [OpenZR+ spec]
400G	DP-16QAM	oFEC	63.1	Open ROADM [Open ROADM spec], ITU-T [Y.1331][Y.1331.3]
400G	DP-16QAM	oFEC	60.1	OpenZR+ [OpenZR+ spec]
400G	DP-16QAM	CFEC	59.8	OIF [OIF spec], ITU-T [Y.1331][Y.1331.3]

The application of digital technology provides the advantages as follow;

- Chromatic dispersion compensation circuits have made the transmission line and its design simple and flexible.
- Hardware and software have been disaggregated with a common hardware abstraction interface [TAI], allowing each to evolve independently.
- Real-time measurement of transmission quality (pre-FEC BER) without affecting the transmission quality (See 3.2.2.2).
- Gaussian noise model for rapid estimation of transmission line characteristics that determine transmission distance and capacity (See B.3.3) [GN model].

In the next decade, the convergence of computing and networking is expected to accelerate with the advent of co-packaged optics. Many technical gaps need to be overcome before digital coherent technology can be implemented closer to the user and further into the data center.

On the other hand, new technologies are also being introduced and developed in optical networks for Mobile Backhaul (MBH)/Mobile Fronthaul (MFH) as well as those for fixed broadband access. For example, in 4G-5G mobile networks, some mobile operators are applying WDM technologies to MFH to efficiently accommodate a large number of cells. The bitrate of the MFH link per antenna is enhanced to 10G to 25 Gbps. In addition, MOPA (Mobile Optical Pluggables), which aims to standardize optical modules for applying WDM technologies to MBH/MFH, is under discussion [MOPA]. At ITU-T SG15, discussions have begun on applying 25G NRZ WDM technologies to mobile networks [G.698.1][G.698.2][G.698.4][G.owdm].

For an enhancement of fixed broadband access, NG-PON2, which combines traditional TDM with a DWDM technology with 4 to 8 wavelengths, has been standardized and commercialized [NG-PON2]. Whereas, Super-PON aims to cover a wide range of customers with a small number of central offices through combining 2.5G to 10G class PON system with a DWDM technology (16 wavelengths or more) and thus realizing a long-distance (over 50-km) PON system. This is under standardization in IEEE 802.3 [Super-PON].

It is expected that common WDM networking will efficiently accommodate the traffic in the metro-access area. ITU-T G.698.2 defines parameters for single-channel optical interfaces at 2.5 Gbps and 10 Gbps (NRZ) and 100 Gbps (digital coherent) [G.698.2]. It adopts the black-link approach targeting point-to-point and ring DWDM systems with 50-GHz and 100-GHz wavelength spacings for metro applications. Given the progress of MFH, it is expected to add a 25-Gbps option. Open APN is expected to support 6G mobile and future FTTH as an evolution of these systems.

1.5. Gap Analysis

Realizing Open APN concepts described in Section 1.3 faces several technical challenges as follows:

Non-continuous optical paths: In today's optical transport networks, optical paths are non-continuous, and separated by frame-based switches. That is, optical paths are created for access, metro, and core networks, respectively. As Open APN aims to provide direct optical paths between any locations including user premises on demand, Open APN shall provide a function to provision and manage the wavelength resources throughout the network, i.e., from access to core.

Lack of dynamic online optical path design: In today's optical transport networks, optical paths are designed offline and configured statically with homogeneous transmission parameters (e.g., modulation format and baud rate) for optical paths of various distances along the longest path in the network. Open APN should allow for dynamic path creation, re-setup, and deletion, which require dynamic online optical path design. Anticipated technology gaps include the following.

- Automatic provisioning. Selecting the optimum transmission mode of a coherent module based on the quality of the fiber link system is a key factor in dynamically provisioning optical paths. It has been necessary to take into account the generation of a coherent Digital Signal Processing (DSP) LSI, the characteristics of Forward Error Correction (FEC) and the optical components installed, and the quality of the optical fiber path about the total required transmission capacity, and to have a skilled engineer carry out the optimum design of each of these conditions, taking into account the bit-error-rate versus the optical signal to noise ratio (OSNR) characteristics of the receiver.
- Standard control signal. Due to the downsizing and power saving of coherent modules, various types of modules have been developed and their applications are expanding. Standardization of the data plane mode has progressed over the past decade as shown in Table 1.4-1, but there is no standardization of control signals to interconnect modules of different types and vendors.
- Fast route planning/ensuring reliability. Path computation time would be limited, and the reliability of the communication service could be degraded due to the dynamic reconfiguration. An optimization algorithm that achieves fast and accurate route calculation while ensuring reliability is required. In addition to focusing on a single optical path, it is needed to maximize the reliability of the set of paths (primary and backup/restoration paths) from the network viewpoint. After finding the optimal optical path, communication tests are required to be carried out using production systems quickly, which currently takes a long time manually.
- Support for multi-environments. Online optical path design should consider the networking environment of multiple network operators, multiple administrative domains, and/or optical transport devices from multiple vendors, so it is multi-technology, multi-vendor, and across administrative or ownership boundaries. Also, online optical path design should consider the minimization of photo-electric conversion for lower latency and lower power consumption.

Lack of network attachment mechanisms for user-owned transceivers: When a user-owned transceiver requests network attachment to the Open APN, admission control functions are needed such as authentication of the transceiver and filtering of optical transmission using an illegal wavelength. And also, a user should notify a network operator of (1) optical path endpoint address so that the user and network operator can share a common addressing space for identifying an endpoint device and (2) wavelength range of an endpoint device so that the network operator can specify a wavelength to the optical path originating from the endpoint device.

Imperfect node architecture to support end-to-end and dynamic optical paths: While the end-to-end optical paths can be partially offered by the network based on conventional ROADM nodes with remotely located transceivers (TRxs), there are several gaps against the target Open APN. Such gaps include (but may not be limited to) the following.

- Optical paths (i.e., direct optical connections) cannot be set between TRxs under the same ROADM.
- A control/management channel is not supported for the remotely located TRxs in the conventional ROADM node.
- A typical loss of access fiber (e.g., 15 dB @ Class S and 20 dB @ Class A for point-to-point optical access in ITU-T G.986) and its variation cannot be supported in the network based on conventional ROADM nodes with the remote location of TRxs.
- Advanced control of optical amplifier chains will be needed to support wavelength reconfiguration that will happen more frequently.

Lack of real-time performance measurement and monitoring mechanism: In today's optical network, an optical path is configured statically and monitored by a management system, which monitoring mechanisms are not efficient enough and insufficient in granularity of performance parameters. In Open APN, when a management system detects failure or impairment on an optical path, it should re-setup an optical path dynamically to guarantee the designated Quality of Transmission (QoT) requirements such as bandwidth, latency, jitter, and bit-error-rate. Therefore, Open APN should provide a real-time performance measurement and monitoring mechanism that enables the infrastructure to set up new optical paths at the achievable transmission speed. Such new measurement and monitoring mechanisms can be conducted with advanced telemetry technology. The foreseeable technology gaps include the following.

- Faster response. Each measurement and monitoring should be achieved within a much shorter interval than ever, e.g., within seconds or even milliseconds.
- Better granularity. The monitoring parameters should be granular enough and various parameters across multiple domains of multiple operators should be leveraged together.
- High compatibility. The new mechanism should accommodate the current mechanism. Also, the monitoring operation should not affect the transmission quality of the service traffics. For instance, video streaming quality should not be affected during quality measurement.

Lack of secure transport mechanisms for the optical paths originating from user premises: The confidentiality of communications in the carrier's transmission service is currently guaranteed because transport systems are installed in the carrier's secure building. Development of technology to ensure secure transport such as Authentication, Authorization, and Accounting (AAA) without additional latency in connections between terminals installed in the customer's environment will be needed for the Open APN without additional latency.

2. Services of Open APN

2.1. User Plane Services

Open APN provides optical signal transport paths. An Open APN endpoint should have an optical transceiver to send data over the provided transport paths. A user device with an optical transceiver can directly terminate optical signal transport paths (known as direct connect service) or a user device can connect to an Open APN endpoint with a bridge function that provides QoS-aware mux/demux and forwarding services between external links and optical signal transport paths (known as flexible bridging service). Flexible bridging service maintains the benefits of optical transport, e.g., reserved bandwidth and bounded delay variation. See Annex A. IOWN Global Forum Flexible Bridging Services.

Optical interfaces for the Open APN are defined as the combination of the following two specifications.

1. Optical transmission/reception specification
2. Wavelength tunnel specification

For the optical transmission/reception specification, the following existing specifications are within the scope of Open APN in this document, while other interfaces are not excluded and are to be defined in a future document.

1. W 100-200G 31.6 Gbaud of Open ROADM MSA Optical Specification Version 5.0
2. W 200-400G 63.1 Gbaud of Open ROADM MSA Optical Specification Version 5.0
3. NRZ 10G (N, W) of ITU-T G.698.2
4. NRZ 2.5G (N, W) of ITU-T G.698.2

Given that it may be easier to design the digital-coherent and NRZ networks separately, Group of Optically Interconnectable Port (GOIP; see Section 3.3.1) for the two technologies may be designed separately in the initial stage (although an ultimate goal of Open APN is to provide direct optical connections for any types of signals).

The wavelength tunnel specification will provide the following information, but exact parameters and parameter values will be specified in future versions of Open APN.

- Physical information of the wavelength tunnel (e.g., used fibers, wavelengths, used bandwidth)
- Factors limiting the reachability over the tunnel including noise and impairments (e.g., optical signal to noise ratio (OSNR), generalized signal to noise ratio (GSNR), nonlinear noise, accumulated chromatic dispersion, polarization mode dispersion)

Section 3.3.4 describes further details for the characteristic of wavelength tunnels.

Figure 2.1-1 shows the image of the direct connect service.

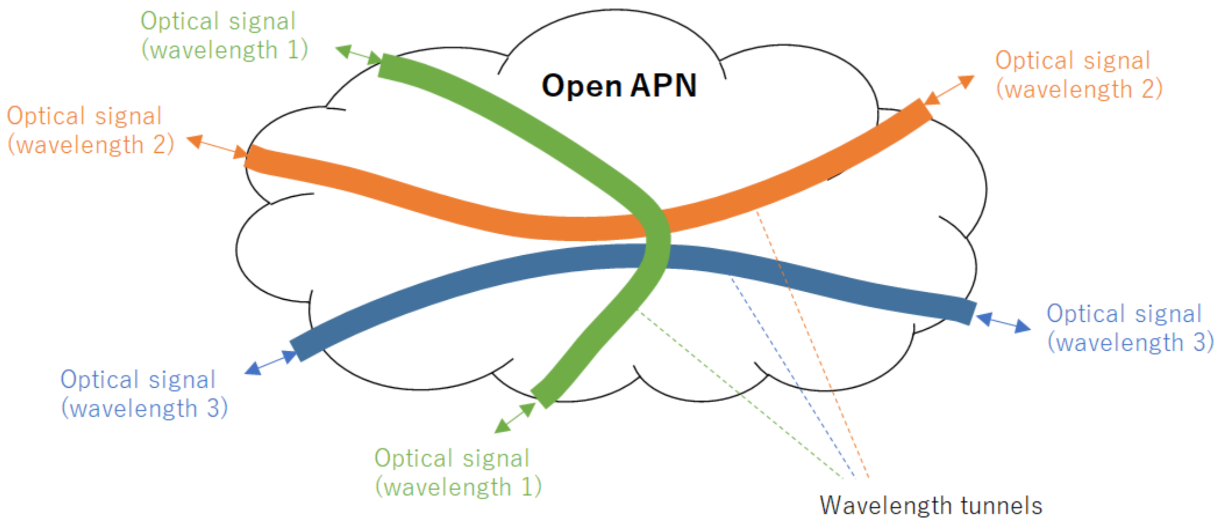


Figure 2.1-1: Image of the Direct Connect Service

2.2. Control Plane Services

The Open APN enables users to set up an optical signal transport path between authenticated and authorized Open APN endpoints. Open APN endpoints should be authenticated and authorized before path setup. For the setup of optical signal transport path, the following services are within the scope of the Open APN in this document, while other services are not excluded and are to be defined in a future document.

- The Open APN service provider should authenticate and authorize user-owned Open APN endpoint devices.
- Users can specify the following endpoint information before path setup request; (a) endpoint address and user ID, (b) supported wavelength range, and (c) supported transmission capability and parameters.
- Users can request the following path setup requests specifying path endpoint addresses; (a) path creation, (b) path deletion, and (c) path re-setup.
- Users can request the following requirements in a path setup request; (a) bandwidth, (b) latency, and (c) jitter.

Open APN provides an interface to expose Open APN control plane services to the Infrastructure Orchestrator or external management and orchestration systems. The Open APN provides user applications with an in-band or out-of-band interface. For the in-band interface, user applications send/receive control plane data to/from the Open APN controller through the connecting link between an Open APN endpoint and a neighboring Open APN device. For the out-of-band interface, user applications send/receive control plane data to/from the Open APN controller through a network external to the Open APN.

Figure 2.2-1 shows an object model for Open APN control plane services. The model shows logical instances of provided infrastructure resources as objects. They are called Open APN Control plane objects. The association among Open APN control plane objects is shown in Figure 2.2-1. Open APN Gateway, Interchange, and Transceiver are introduced in Section 3.1. Group of Optically Interconnectable Ports (GOIP) is introduced in Section 3.3.1.

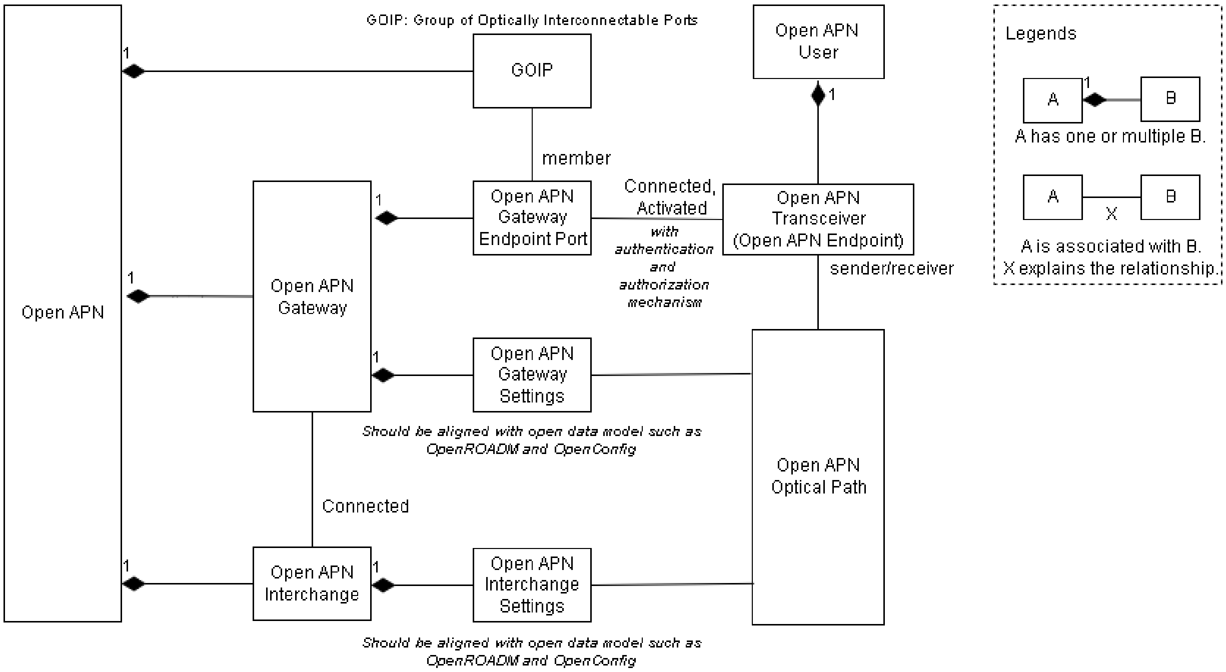


Figure 2.2-1: Object Model for Open APN Control Plane Services

2.3. Management Plane Services

The Open APN provides functions that enable the Open APN service provider to configure policies, including authentication and authorization of Open APN endpoint devices, specifying which user can access which Open APN ports, and specifying path setup allow/deny policies about pairs of Open APN endpoint. Open APN provides functions that enable the Open APN service provider to get Open APN device information and monitor the status of optical signal transport paths.

The following capabilities are within the scope of the Open APN in this document while other capabilities are not excluded and are to be defined in a future document.

- Open APN enables the Open APN service provider to get the following information: (a) QoT parameters such as bandwidth, latency, and bit-error-rate; (b) configuration parameters of Open APN devices, such as the endpoint address and assigned wavelength; (c) status parameters of Open APN devices, such as failure status of a device.
- Open APN provides three acquisition modes to get the above information, including (a) push-pull mode, in which the parameters are acquired on the demands of Open APN controller; (b) periodic mode, in which the parameters are acquired continuously within the subscription sessions; (c) threshold-trigged mode, in which the parameters are acquired on the defined thresholds are trigged within the subscription sessions.
- Open APN service providers may post collected data to the IOWN Data Hub and have some intelligent applications retrieving the data from the Data Hub. The Open APN supports a network configuration strategy to communicate with data processing units in the DCI subsystem. The collected QoT information can be sent to the data processing units in (a) raw-data manner or (b) selected-data manner. The configuration strategy can be received from the data processing units.

Open APN provides an interface to expose Open APN management plane services to the Infrastructure Orchestrator or external management and orchestration systems. Note: It is a future work when multiple Open APN service providers manage Open APN devices.

3. Functional Architecture of Open APN

3.1. High-level Reference Architecture

Figure 3.1-1 shows a high-level reference architecture of Open APN.

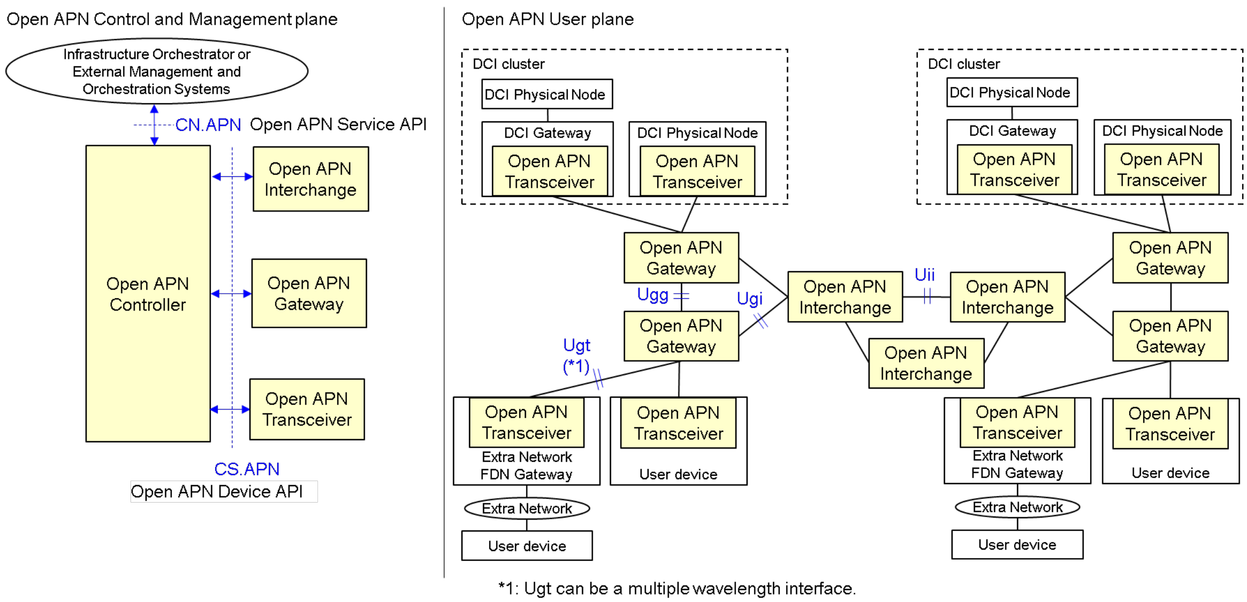


Figure 3.1-1: Open APN High-level Reference Architecture

Open APN User plane consists of Open APN Transceiver (APN-T), Open APN Gateway (APN-G), and Open APN Interchange (APN-I). Open APN Control and Management plane consists of Open APN Controller (APN-C) that communicates with APN-T, APN-G, and APN-I.

APN-T is an endpoint for an optical path. It transmits and receives optical signals on a path utilizing a designated wavelength. The APN-T might be placed as a WAN interface of Extra Network FDN Gateway or DCI Gateway defined in [IOWN GF DCI], which provides QoS-aware mux/demux and forwarding services between external links and optical signal transport paths (See Annex A. IOWN Global Forum Flexible Bridging Services). In another deployment pattern, the APN-T might be placed as a network interface of a user device. The functional split and interface between the APN-T and the remaining components of a user device or a gateway are for further study.

APN-G is a gateway for an optical path to permit optical transmission with the designated wavelength originating from APN-Ts. The connection between APN-G and the APN-Ts can be point-to-point or point-to-multipoint; in the latter case, the optical-path bandwidth is shared among multiple APN-Ts with a sub-lambda multiplexing technique. Note that the sub-lambda multiplexing technique is meant as any technique to share a wavelength channel among multiple APN-Ts, e.g., Time Division Multiple Access technique and Sub Carrier Multiplexing technique. APN-G shall have the following five functions: (1) provision of control channels to communicate with the connected APN-Ts, (2) admission control in U-plane, (3) multiplexing/demultiplexing, (4) turn back and (5) add/drop. The provision of control channels to communicate with the connected APN-Ts (1) is to enable various APN-T control (e.g., admission control, wavelength control) from APN-C through APN-G. APN-G generates and terminates the control-channel signal. The admission control function in U-plane (2) is to provide an entrance control in the physical layer. It passes the optical signals only when their wavelengths correspond to the assigned wavelengths. Meanwhile, it blocks optical signals with improper wavelength. The multiplexing/demultiplexing function (3) aggregates and de-aggregates optical paths. For upstream direction from APN-T to the trunk network, it aggregates optical paths. In case there are multi routes on a trunk network side, it aggregates optical paths route-by-route. The downstream direction from the trunk network to APN-T de-aggregates the optical paths and sends the appropriate wavelength for each APN-T. When APN-G passes a point-to-multipoint optical path on which plural downstream APN-Ts access a common upstream APN-T through a sub-lambda multiplexing technique, the bandwidth assignment to each downstream APN-T will be done by the cooperation between the upstream APN-T and a bandwidth assignment function in APN-C. The turn-back function (4) provides the shortest path between the APN-Ts connected to the same APN-G to realize low latency. The add/drop function (5) inserts the optical signal on a dedicated wavelength from an APN-T to an API-I and extracts the optical signal on a dedicated wavelength from an API-I to an APN-T. The APN-Ts are either located at the users' premise or at a part of DCI that may be located inside the operator's network. Together with (4), this function enables to provide a direct optical path through APN-G between an APN-T at the user's premise and that at DCI.

APN-I is an interchange for wavelength switching at the midpoint of an Open APN optical path. For providing a direct optical path between any two endpoints, APN-I shall have the following two functions; (1) wavelength cross-connect and (2) adaptation between interfaces of Ugi and Uii. The wavelength cross-connect function (1) enables each incoming optical path to be output to any direction (any port) without the need for electronic processing. The adaptation function (2) enables any combinations of APN-G and APN-I to be interconnected.

APN-C is a controller that has the functions of Open APN Control and Management plane. The APN-C has an admission control function that is invoked during the APN-T activation phase. This admission control authenticates the APN-T and configures the admission policy on the APN-G. The APN-C is a logical entity. The functions of APN-C can be aggregated at one location or distributed at multiple locations. Some functions of APN-C can be implemented on the same device as APN-I, APN-G, and APN-T or in separate boxes. All the functions of APN-C can be implemented together in a single box or separately in multiple boxes.

Interface reference points of Open APN are defined as follows:

- Ugt: User plane interface between APN-G and APN-T.
- Ugi: User plane interface between APN-G and APN-I.
- Ugg: User plane interface between APN-G and APN-G.
- Uii: User plane interface between APN-I and APN-I.
- CN.APN: Control and management plane interface to expose Open APN control and management plane services to the Infrastructure Orchestrator or external management and orchestration systems. It is defined as Open APN Service APIs.
- CS.APN: Control and management plane interface for the configuration and management of APN-T, APN-G, and APN-I. It is defined as Open APN Device APIs between APN-C and APN-T, APN-C and APN-G, APN-C and APN-I.

3.2. Control and Management Plane Reference Architecture

The Open APN provides a mechanism to authenticate an Open APN endpoint. After the authentication, the information from the Open APN endpoint is passed to APN-C. The Open APN enables a user to configure a path between the designated endpoints triggered by path setup requests on-demand. The APN-C calculates the wavelength path route, the wavelength to use, transmission/reception parameters for optical transmission devices, and the configuration of optical transmission devices accordingly to satisfy user requirements about the QoT. When user requirements are unsatisfied based on the real-time QoT monitoring, APN-C recalculates the above calculations and re-setup a path.

Open APN Service APIs for control purposes as a northbound interface of the APN-C consist of the following;

- Network attach API: The Infrastructure Orchestrator or user applications request APN-C to make a network attach of an APN-T to the Open APN. In response to the request, APN-C authenticates and authorizes APN-T and gets the APN-T information of (A) endpoint address and user ID, (B) supported wavelength range, and (C) supported transmission capability and parameters. Then the APN-T is activated.

- Path creation service API: The Infrastructure Orchestrator or user applications request APN-C to create a path between activated APN-Ts. The request specifies the addresses of path endpoints and the user requirements regarding bandwidth, latency, and jitter.
- Path deletion service API: The Infrastructure Orchestrator or user applications request APN-C to delete a path between activated APN-Ts. The request specifies the addresses of path endpoints.
- Path re-setup service API: The Infrastructure Orchestrator or user applications request APN-C to re-set up a path between activated APN-Ts. The request specifies the addresses of path endpoints and the user requirements regarding bandwidth, latency, and jitter.

Open APN Device APIs for control purposes as a southbound interface of the APN-C consist of the following;

- Path creation configuration API: APN-C notifies APN-T of the wavelength and transmission/reception parameters, and directs a path setup. APN-C notifies APN-G and APN-I of path route information and directs a setting of the configuration of path cross-connect.
- Path deletion configuration API: APN-C notifies APN-T of the wavelength and directs a path teardown. APN-C notifies APN-G and APN-I of path route information and directs a deletion of the configuration of path cross-connect.

Open APN also provides a mechanism to monitor QoT information in real-time and determine whether user requirements about QoT are satisfied for each wavelength path. When user requirements are unsatisfied based on the real-time QoT monitoring, the path re-setup is requested.

Also, Open APN provides a mechanism to support the analysis and strategy functions of Open APN. The information collected from Open APN devices can be quickly analyzed to support QoT assurance. The management-plane mechanism can communicate with the computing units of DCI by sending QoT parameters for advanced analysis and receiving the network configuration strategy conducted in those computing units. Open APN service providers may also choose to feed collected data to their network management systems with well-adopted telemetry tools.

Open APN Service APIs for management purposes as a northbound interface of the APN-C consist of the following;

- Network strategy request API: APN-C notifies DCI data processing units of the delivery of the QoT information. DCI data processing units conduct storage, processing, and all decisions based on the QoT information.
- Network strategy receiving API: DCI data processing units notify APN-C of the conducted network configuration strategy delivery.

Open APN Device APIs for management purposes as a northbound interface of the APN-C consist of the following;

- Quality monitoring API: APN-C requests APN-T, APN-G, and APN-I to send QoT information in a defined data model format.
- Quality assurance API: APN-C notifies APN-T, APN-G, and APN-I of the network configuration strategy in a defined data model format.

3.2.1. Example Procedures for Controllers

(1) Remote wavelength setup function

APN-C should support the remote wavelength setup function for APN-T according to the external control and management system or terminal request. An example of this processing method according to the request from the terminal is shown below.

1. APN-C gets candidates of QoT requirements from external control and management systems beforehand.
2. The terminal makes a connection request to the APN-C. The request includes the peer endpoint information and the required QoT.

3. APN-C decides the optical path route and wavelength using the endpoints and required QoT.
4. APN-C sets up the optical path route to APN-G. And APN-C also sets up a wavelength to APN-T.

(2) Real-time control to assure the QoT requirements

APN-C should support real-time control to assure an E2E QoT including a mobile network. An example of this processing method is shown below.

1. APN-C gets QoT information from APN-G.
2. APN-C compares the acquired QoT information with the QoT requirement and analyzes whether the quality is ensured or not. Here, the APN-C may also consider the quality of information of the wireless section of the network via extended Cooperative Transport Interface for Open APN (eCTI).
3. As a result of the comparison, if the QoT requirements are not met, the APN-C will perform optical path switching and/or wavelength control to the APN-G and/or APN-T.

This real-time control function is useful for services that require low latency, such as mobile edge computing.

3.2.2. Telemetry

For each Open APN device, the telemetry information can be transmitted in either of two modes. (a) out-band mode, via a dedicated link; (b) in-band mode, sharing the data traffic link. In (b) in-band mode, the dedicated link could be an optional implementation (Figure 3.2-1).

Figure 3.2-1: Two Modes for Telemetry

A collector will be implemented in APN-C to collect the telemetry information of Open APN devices (APN-T, APN-G, and APN-I). A telemetry engine will be implemented in Open APN devices (APN-T, APN-G, and APN-I) to send the telemetry information to APN-C (Figure 3.2-2).

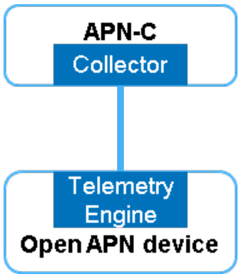


Figure 3.2-2: Collector and Telemetry Engine

A collector can accommodate multiple telemetry engines (Figure 3.2-3).

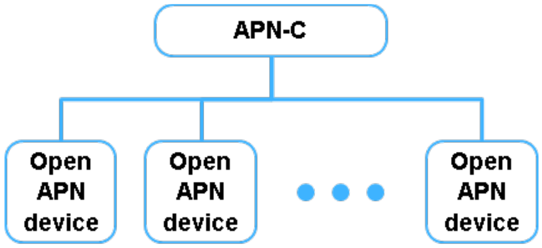


Figure 3.2-3: Accommodation of Multiple Telemetry Engines

3.2.2.1. Extended Cooperative Transport Interface for Open APN

Extended Cooperative Transport Interface for Open APN (eCTI) can be considered as a type of telemetry. This is because multiple kinds of mobile information delivered via eCTI play the same role as QoT information from telemetry in terms of data used by the Controller for analysis and control.

Figure 3.2-4 shows an example of controller configuration for eCTI. The eCTI between APN-C and mobile systems is defined as eCTI-APN. In this example configuration, APN-C includes a real-time control function, which plays the role of the real-time control of APN-G and/or APN-T respectively to assure QoT requirement.

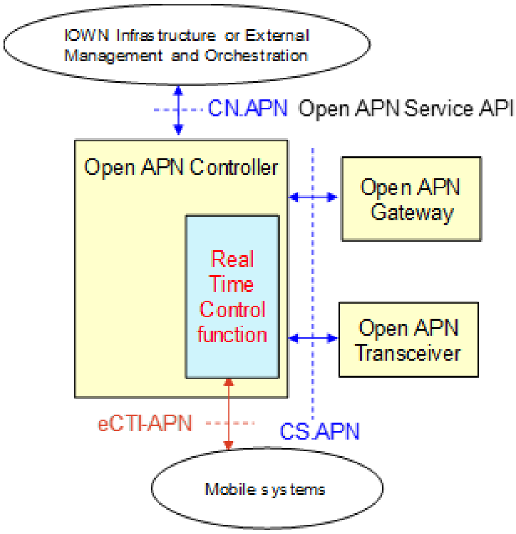


Figure 3.2-4: Example of Controller Configuration for eCTI

Table 3.2-1 shows the examples and expected benefits of the eCTI-APN.

Table 3.2-1: Examples of Applicable Targets for eCTI-APN

TARGET	WHAT TO CONTROL (EXPECTED BENEFITS)
Open APN Gateway (APN-G)	Optical path setting (low latency, priority control, bandwidth allocation)
	Optical path switching (congestion control, low latency, priority control)
Open APN Transceiver (APN-T)	ON/OFF control of optical transceiver (power saving)

3.2.2.2. Real-time Transmission Quality Measurement

As noted in Section 1.4, as one of the advantages of digital transmission technology, the transmission quality can be measured and monitored in a real-time fashion. There will be numerous parameters related to various transmission qualities. By employing the advanced telemetry technology to Open APN, such parameters can be measured and monitored for dynamic optical path provisioning.

One of the most critical parameters of transmission quality is BER, which straightforwardly reflects the transmission quality and fairly indicates the availability of the received signal. Currently, the transmission quality can be monitored by measuring the pre-forward error correction (pre-FEC) BER. As long as the measure pre-FEC BER is below the defined FEC limit, all error bits can be corrected. Otherwise, if the received signal quality cannot achieve the defined pre-FEC BER, the system will either trigger an alarm or detour the traffic to another optical path, i.e., re-setup the optical path.

3.3. User Plane Reference Architecture

3.3.1. Group of Optically Interconnectable Ports (GOIP)

For realizing a highly scalable and interoperable Open APN under physical constraints such as the limited number of wavelengths and reachable distance, Group of Optically Interconnectable Ports (GOIP) is defined in the Open APN architecture.

GOIP is defined as a group of optical ports for which a direct optical connection (open APN optical path) can be established (i.e., optical reachability is supported) between any two ports without an O/E/O repeater. Here, the port means a connection interface between an Open APN Transceiver and the access link. The connection can be point-to-point (PtP), point-to-multipoint (PtMP), while a multipoint-to-multipoint (MPtMP) connection is for further study.

In GOIP, there is at least one route that can establish a direct optical connection between ports. However, this doesn't guarantee that a direct optical connection between ports can be established by any route and at any time. It is because the transmission performance may not be guaranteed when choosing a detour path. It means that there is a possibility that you cannot establish a direct optical connection when the shortest route is not available due to any reason like the shortage of wavelength resources, a fiber cut, or an equipment failure. Given these, a GOIP may be designed with the following policies for example, but such design methods are for further study.

- to allow the direct optical transmission not only for the primary (i.e., shortest) route but also for one or several detour routes between any two ports from the viewpoint of the transmission characteristics,
- to keep the “call setup loss probability” (i.e., the probability to fail to set up an optical path due to the shortage of wavelength resources) under a predetermined value when assuming a predetermined utilization rate and a connection pattern given the number of available wavelengths.

Because the total distance of the connection depends upon bitrate and/or modulation methods, the guaranteed maximum performance of optical transmission/reception between ports in GOIP is presented for each GOIP individually.

Each optical port transmits/receives an optical signal with a specific bitrate (or less) with a wavelength pair (i.e., transmitted and received wavelength) assigned by a controller.

It is not supported to transmit a signal that has a bitrate over the assigned specification between any ports of GOIP, however, there is some possibility when the transmission distance is rather short. Therefore, after assigning wavelength and a route between the ports, if it is possible to establish a direct optical connection with a higher bitrate over the specified bitrate, the higher speed can be allowed under the conditions of the wavelength tunnel (i.e., as long as there is no impact on the other optical paths).

One optical port transmits one wavelength and receives one wavelength. Namely, each User Terminal (UT) needs to employ multiple optical ports to communicate with multiple UTs simultaneously. A realistic assumption is that each UT communicates with one or a few UTs simultaneously, so it has one or more optical ports.

Dynamic optical-path computation is done within a GOIP.

A connection of UTs that belong to different GOIPs is possible with the following approaches, but these are out of the scope of this document.

- Employ an O/E/O repeater to provide wavelength conversion and signal regeneration at the border of two neighboring GOIPs.
- Define an inter-GOIP wavelength set, and provide direct optical connections across GOIPs using it.

Because more studies need to be done in this area, the following items are out of the scope of this document.

- Configurations that to the APN-G, APN-I, and/or Link (fiber core) to be shared by plural GOIPs: For example, when plural GOIPs exist in the same area, and some wavelengths are not used, there is the possibility to share APN-Is and fiber cores. This needs further study.
- Network design technologies to establish optical paths for redundancy in GOIP: As described above, in GOIP, there is at least one route that can establish a direct optical connection between ports. However, it is not guaranteed that there is a second and/or third route for redundancy. This can be achieved by installing O/E/O repeaters in GOIP like in current trunk networks. Further studies are needed on this subject.
- Network design technologies to minimize the total power consumption of Open APN with a single GOIP as well as that with multiple GOIPs: For example, when a policy to limit the total power consumption in each time unit exists, it is needed to control the capacity and possibly the route in the GOIP(s)

Figure 3.3-1 shows a schematic diagram of GOIP, in which one GOIP is formed for the Data Center Interconnect and the other GOIP is created for the Radio Access Network.

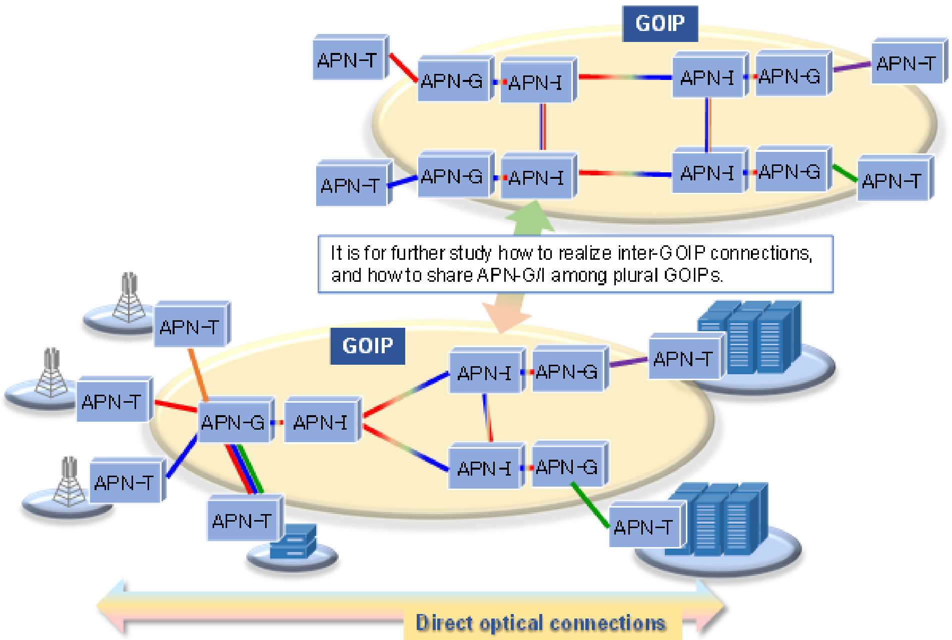


Figure 3.3-1: Schematic Diagram of GOIP

3.3.2. User Plane Reference Architecture within a GOIP

This section describes a single-GOIP network. Figure 3.3-2 shows the architectural diagram of GOIP.

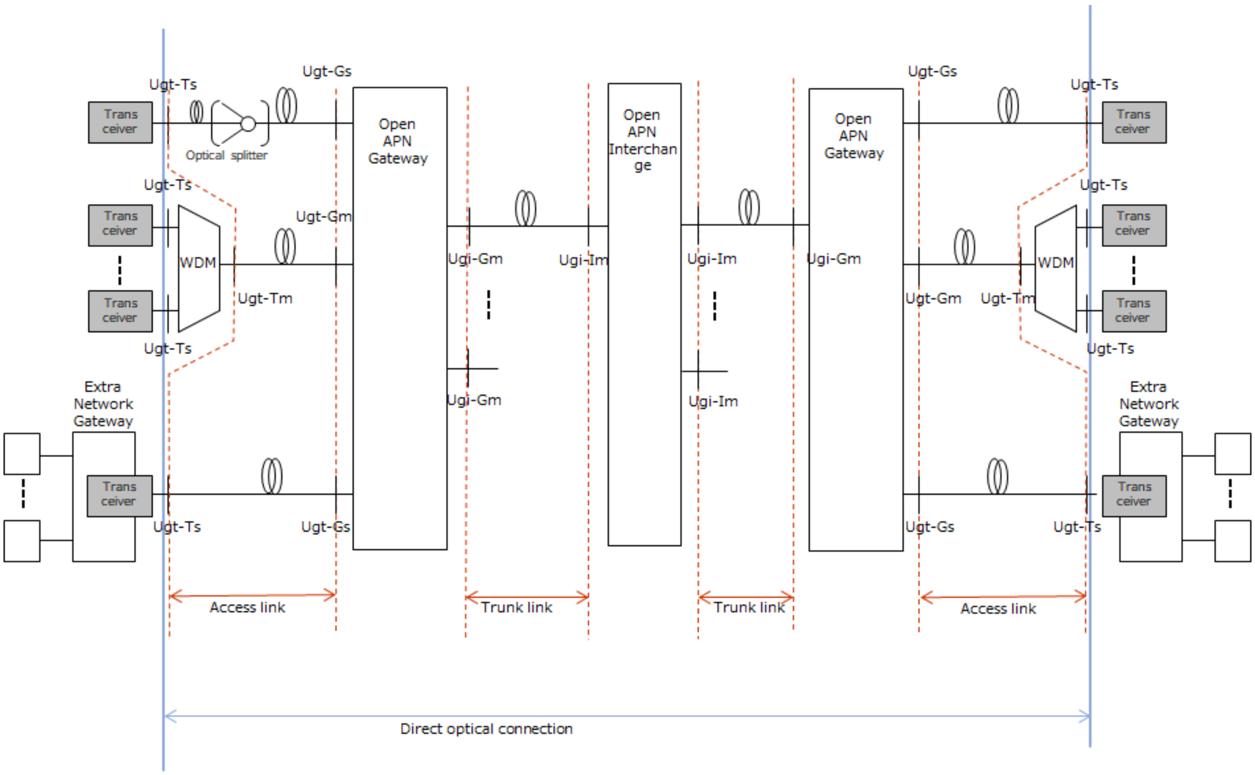


Figure 3.3-2: Architectural Diagram of GOIP

GOIP consists of APN-T, APN-G, APN-I, and optical fibers which connect those Open APN functions. APN-T roles as the Endpoint (i.e., port) for a direct optical connection in GOIP. The APN-G to which APN-Ts are connected controls and aggregates APN-Ts, and protects the network from unexpected optical signals. The APN-I connects APN-Gs and provides the cross-connection function for direct optical connections. There is a possibility to use multi-core optical fibers as optical fibers which connect those Open APN functions.

Regarding sending and receiving, bi-directional transmission is implemented with a single fiber (through the use of WDM for directional multiplexing), or with a dual fiber (in which upstream and downstream wavelengths can be the same). It is also possible to adopt multi-core fibers (MCFs) to realize the single-fiber bidirectional transmission without using WDM for directional multiplexing. In either case of using single-core fibers or MCFs, the fiber core number of Ugt-Ts, Ugt-Tm, Ugt-Gs, and Ugt-Gm shown in Figure 3.3-2 is one or two.

Two cases transmit a single wavelength by a single core (Ugt-Ts) and multi-wavelengths by a single core (Ugt-Tm). In the case of using multi-wavelengths, the WDM function which enables multiplexing/demultiplexing of Ugt-Ts of plural APN-Ts is needed between Ugt-Ts and Ugt-Tm.

Regarding low bitrate transmissions such as the 10 Gbps or less, it is required that one selects the higher efficiency method for wavelength resources to use the transmission capacity of the Open APN effectively. In the case of a low bitrate transmission of an Open APN optical path in APN-T, it may be a more efficient use of wavelength resources by using a flex grid. If there are two or more APN-Ts on the user premises, one wavelength made up of electrically multiplexed signals (e.g., 100 Gbps each) may be used instead of one wavelength for each APN-T. It is possible to establish an optical direct path for a point-to-multipoint transmission by multiplexing multiple signals to an optical sub-channel.

As mentioned in Section 3.1, the fiber connection between APN-G and the APN-Ts may be point-to-multipoint. In this case, an optical splitter(s) may be put between Ugt-G and Ugt-T.

Figure 3.3-3 shows an example configuration of APT-T, APT-G, and APT-I.

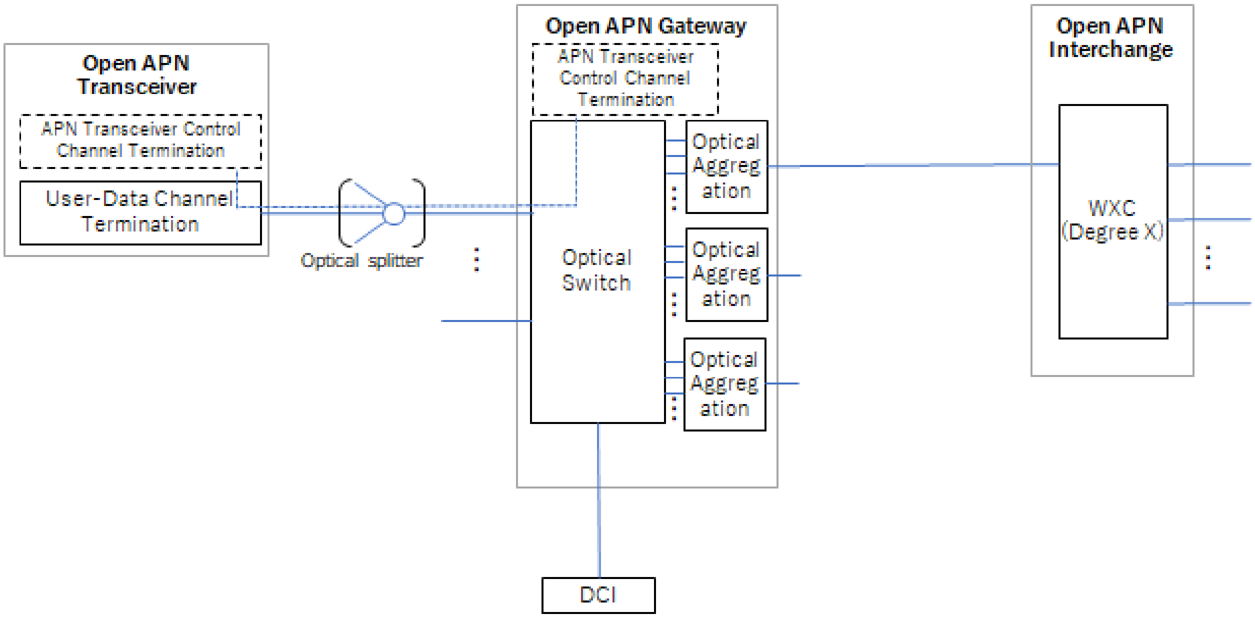


Figure 3.3-3: Example Configuration of APT-T, APT-G, and APT-I

APN-G provides a group of required functions for Open APN Edge to which APN-Ts are connected. APN-G should achieve five functions described in Section 3.1. Figure 3.3-3 shows an example of configuration and connections to APN-I and APN-T for this aim. APN-G consists of APN Transceiver Control Channel Termination, Optical Aggregation, and Optical Switch which connects and blocks DCI and APN-T so that APN-G can achieve its required functions. Open APN Transceiver Control channel termination is optional in the minimum version for implementing Open APN. Local Optical Interchange controls connection based on fiber cores. Even if two or more wavelengths are in one fiber core of the access link, it should be noted that the connection is selected based on fiber core, not wavelength.

APN-T consists of User-Data Termination and Open APN Transceiver Control Channel Termination. Open APN Transceiver Control channel termination is optional in the minimum version for implementing Open APN.

APN-I connects between APN-Gs. There are some cases that APN-Gs are directly connected. Connection topology for APN-G and APN-I can be linear, ring, mesh, and combinations of each, which is not specified in this document.

APN-I has the wavelength cross-connect (WXC) function to select the route by wavelength and may have wavelength and wavelength-band conversion functions for inter-GOIP connections. APN-I is not connected to APN-T directly. Because inter-GOIP connections are out of the scope of this document, wavelength conversion functions for APN-I are not described.

Figure 3.3-4 illustrates the relationship between the conventional ROADM, which comprises WXC, Add/drop, Transceivers (TRxs), and the Open APN function blocks.

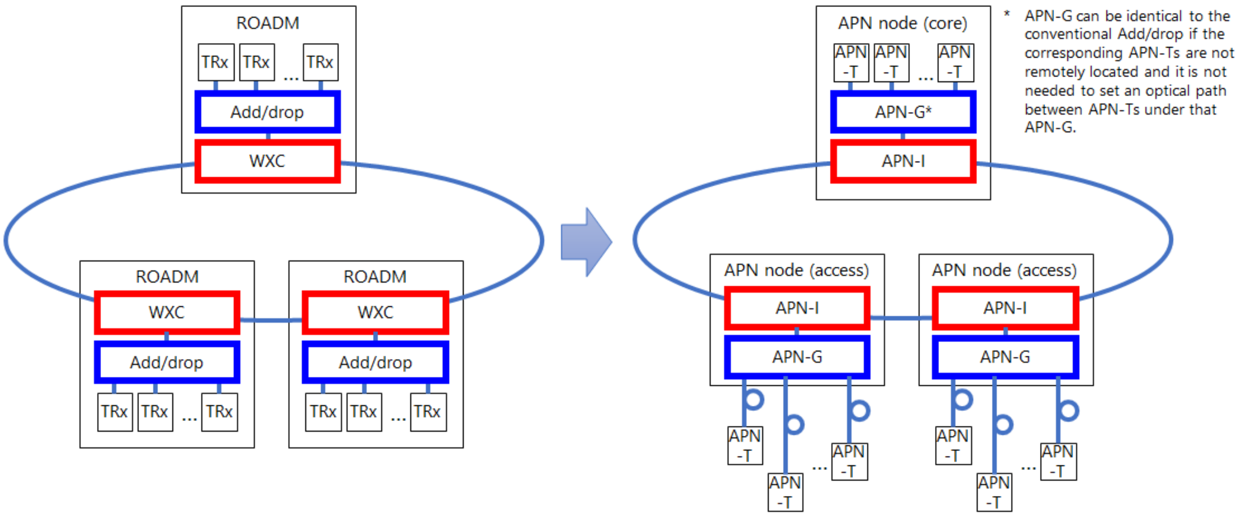


Figure 3.3-4: Relationship between ROADM and Open APN Function Blocks

WXC and Add/drop blocks of ROADM can be considered to evolve to APN-I and APN-G, respectively. Their functions are described in detail in Section 3.1. With the evolution, the following gaps stated in Section 1.5 will be filled.

1. Optical paths (i.e., direct optical connections) cannot be set between TRxs under the same ROADM in the conventional ROADM-based network.
2. A control/management channel is not supported for the remotely located TRxs in the conventional ROADM-based network.
3. A typical loss of access fiber (e.g., 15 dB @ Class S and 20 dB @ Class A for point-to-point optical access in ITU-T G.986) and its variation cannot be supported in the conventional ROADM-based network.

While the evolution from the conventional ROADM to Open APN to fill such gaps is highly encouraged, the minimum version for implementing Open APN allows us to consider that APN-I and APN-G are WXC and Add/drop of the conventional ROADM, respectively. Other functions for APN-I and APN-G defined in this document can be considered optional. For more clarification, Gaps 1 and 2 in the above will be filled by implementing APN-I and APN-G functions described in Section 3.1, and Gap 3 will be filled by reviewing the optical interfaces for the transceivers, i.e., Ugt-Ts, in the future.

3.3.3. Optical Interfaces

Ugt-Ts in Figure 3.3-2 corresponds to the optical transmission/reception interfaces listed in Section 2.1 (User plane services). Specifications of other optical interfaces in Figure 3.3-2 are for further study.

3.3.4. Wavelength Tunnels for End-to-end Optical Connections

3.3.4.1. Wavelength Tunnels Connecting Optical Interfaces

From the user perspective, the number of available wavelength tunnels shall be accessible for a given tunnel capacity and reachability. On the physical layer, information on the tunnel allocation is managed according to the reference architecture.

Considering a GOIP as defined in 3.3.1, the ability to establish optical ports shall be managed according to the network management system, based on physical layer information and network requirement. Therefore, establishing a port in the GOIP context will depend on the required bandwidth, on the bandwidth offered by the connected APN-T, on the required reachability between the connected APN-T, and on the characteristics of the wavelength tunnel between the

APN-T. If one or several wavelength tunnels are used to connect the APN-T, the physical references of these tunnels shall be managed in the GOIP, including:

- Requirements on the GOIP connection from the network
  - Required bandwidth
  - Locations of the connected APN-T
- Specification of the connected APN-T connected by the wavelength tunnels in the GOIP
  - Information relative to the compatibility of APN-T for connection through wavelength tunnel (e.g., modulation format, symbol rate, used FEC, etc.)
  - A bitrate of the APN-T connection
  - Specification for the error-free transmission of APNT-T including tolerance to noise and impairments (e.g., OSNR tolerance or generalized SNR tolerance, tolerance to chromatic dispersion)
- The physical reference of the wavelength tunnels
  - Physical information of the wavelength tunnel (e.g., used fibers, wavelengths, used bandwidth)
  - Factors limiting the reachability over the tunnel including noise and impairments (e.g., OSNR, generalized SNR, nonlinear noise, accumulated chromatic dispersion, polarization mode dispersion)

Considering the above information, the connected APN-T should be set within the constraint of compatibility and so that the bitrate of the connected APN-T satisfies the requirement in bandwidth. The optical path between the APN-T should be selected so that the characteristics of the factors limiting the reachability are within the specification of the connected APN-T for error-free operation for the setting of the APN-T. The information on such characteristics may be obtained through telemetry as described in Section 3.2.2.

3.3.4.2. Wavelength Tunnels for Ultra-Wideband Optical Transmission

Ultra-wideband optical transmission technologies include possible approaches to expand the wavelength resource of Open APN. This includes Wavelength-Division Multiplexing (WDM) and Space-Division Multiplexing (SDM) technologies. Bidirectional transmission can be used in conjunction with WDM and SDM technologies.

More specifically, WDM technologies consist in adding more wavelengths in the spectrum dimension.

- Increasing the number of wavelengths by adding new optical bands (e.g., U, S, E, and O bands in addition to C and L bands).
- Increasing the number of wavelengths through multiplexing of narrower grid channels

Similarly, SDM technologies consist of adding more wavelengths in parallel on the spatial dimension. Concretely, considering the time frame for the Open APN, two major technologies are being considered:

- Increasing the parallelization of wavelengths at the cable level with high-density cabling technology
- Increasing the parallelization of wavelengths at the fiber level with multicore fiber transmission technology.

Considering the reference architecture for the wavelength tunnel of 3.3.4.1, the specificities of ultra-wideband technologies apply as below:

- The physical reference of the wavelength tunnels using ultra-wideband technologies
  - Physical information of the wavelength tunnel using dimensions offered by ultra-wideband technologies
    - the wavelength dimension of the tunnel:
      - the optical band used for transmission
      - the central wavelength of the carrier and the bandwidth inside the band
    - the space dimension of the tunnel:

        - the fiber used inside a cable for transmission
        - the core inside the fiber.
    - ✧ the direction of the tunnel
- ➢ Factors limiting the reachability over the tunnel taking into account specificities of ultra-wideband technologies
    - ✧ Noise may depend on the characteristics of transmission on ultra-wideband signals or through components
    - ✧ Impairments may be caused by the transmission of ultra-wideband signals.

Details on the characteristics of ultra-wideband optical transmission as well as an example of QoT based on Generalized Signal to Noise Ratio (GSNR) are given in Section B.2.

Inside a single GOIP, an optical path shall be allocated without physical conversion. However, different GOIP may have different implementations and therefore different characteristics on the above dimensions, therefore regeneration or conversion is possible between different GOIPs. This difference in possible implementation is illustrated in Table 3.3-1 for several different cases. The characteristics given in Table 3.3-1 are examples of implementation. Specifications are to be given in future versions of Open APN. Furthermore, it is to be noted that the wavelength tunnels created in these examples are purely illustrative and that wavelength tunnels need to be established to meet the requirement of bandwidth and reachability described in 3.3.4.1.

Table 3.3-1: Examples of Architectures of Ultra-wide Bandwidth for Open APN

TUNNEL ALLOCATION POSSIBILITIES (PHYSICAL DIMENSION)	MINIMAL VIABLE VERSION	EXAMPLE A DESIRABLE VERSION BASED ON STATE OF THE ART DEPLOYED TECHNOLOGY	EXAMPLE A DESIRABLE VERSION BASED ON TECHNOLOGY TESTED BY SEVERAL VENDORS
Optical band	**Single-band (C)**	Dual-band (C+L)	more than three bands (C, L, and more)
Carrier wavelength and bandwidth	**16 wavelengths on C band**	~100 wavelengths on C and L bands	More than 100 wavelengths on C, L, and extended bands
Number of spatial channels (numbers of fibers in a cable, fiber type, and number of cores)	**Single**	100 to 300 channels (100 to 300 standard single mode fibers[1] in a cable)	More than 300 channels (more than 300 standard single mode fibers[1] in a cable) More than 400 channels (more than 100 4-core multicore fibers in a cable) Up to 7,000 channels (up to 7,000 standard single mode fibers[1] in a cable[2])
Number of wavelength tunnels	**16**	~10,000 to ~30,000	More than 30,000

1: “Standard single-mode fiber” intends to be optically compatible with existing international standards (e.g., ITU-T Recommendation G.65x).

2: Ultra-high fiber count cable, which accommodates 1000-7000 fibers, has been developed for the inter-connection of hyper-scale data centers.

The example of a minimal low bandwidth version can be considered as the minimum implementable version of 16-wavelength transmission over a fiber; it can be described inside the ultra-wideband transmission although it is likely to be insufficient to satisfy the requirements of end to end paths for Open APN. The second example is a desirable implementation offering significantly larger wavelength resources based on state-of-the-art deployed technology. It is fully described in the reference architecture. The third example is another desirable version offering still wider wavelength resources based on recently tested technologies, in the field or by several vendors. It is fully described on the ultra-wideband reference architecture.

Concerning the implementation of APN-T, APN-G, and APN-I in an ultra-wideband context, two options exist to match the characteristics of the wavelength tunnel. The first option is the minimum version for implementing Open APN; it relies on using standard APN-T, APN-G, and APN-I elements as described in Section 3.3.1 and interfacing these elements to match the physical characteristics of the wavelength tunnel. Concretely, this interface can be realized with physical conversion elements like wavelength conversion repeaters for extension of wavelength resource on WDM dimension or like fan-in fan-out elements for extension of the wavelength resource on SDM dimension. The second option is for future versions of Open APN and it requires the development of new APN-T, APN-I and APN-G optimized for the characteristics of the wavelength tunnel, i.e., optical transmission band, grid width, number of core, density, and direction.

Furthermore, as different wavelength tunnels may present different factors limiting reachability, this may be taken into account when connecting APN-T and different wavelength tunnels. For instance, in the context of additional bands, wavelength tunnels in the O band will have lower chromatic dispersion compared to wavelength tunnels in the C band or other bands. Therefore, it may appear advantageous to assign APN-T with analog signals or based on direct detection technology, i.e., without electrical compensation of chromatic dispersion, to such wavelength tunnels.

Scenarios based on an assumption of massive deployment of such tested technologies and future upcoming technologies are described in Section B.2.

4. Conclusion

Open APN is a network that connects endpoints directly with optical paths. It allows end-to-end communication with deterministic performance and high energy efficiency. There is a need to architect a new infrastructure toward the realization of Open APN.

In this document, a high-level reference architecture of Open APN has been described. The Open APN Transceiver, Gateway, Interchange, and Controller are introduced as components of the Open APN.

The IOWN GF will work to solve the technical challenges to realize the Open APN, as well as to refine the Open APN architecture and develop Open APN specifications.

Annexes

A. IOWN Global Forum Flexible Bridging Services

A.1. Introduction

Open APN provides optical paths at the Ugt interface. A user device or an Extra Network FDN Gateway (defined in [IOWN GF DCI]), which is connected to the Ugt interface, has an optical transceiver to send data over the provided optical paths.

However, many use cases require some mechanism to close the **granularity gap**. For example, according to the reference [IOWN GF IMN], the data rate of a single 5G mobile front haul would be about 25 Gbps for a 10 Gbps service bandwidth with the low-layer functional split. For a narrower bandwidth service or with the high-layer functional split, the data rate would be lower. For another example, according to the reference [IOWN GF RIM], the number of surveillance cameras and LiDAR sensors for a 10,000 square meter floor would be around 40. On average, one building would have about 25 floors. This would mean that an aggregate camera/sensor traffic data rate would be approximately 2.4 Gbps for one floor and 60 Gbps for one building (See Note at the end of A.1). On the other hand, the capacity of a single optical path with digital coherent optical communication is currently 100 or 400 Gbps and will keep increasing exponentially. Hence, a single 5G mobile front haul or a single building with dense sensors cannot fill up the capacity of a single optical path. While the data rate will increase multifold for 6G and beyond human sensing, the capacity of a single optical path will also increase exponentially. Therefore, the granularity gap will not diminish for a while.

As a solution, Annex A defines **Flexible Bridging Services (FlexBr)** as bridging services that aggregate and forward multiple data flows into a single optical path. FlexBr is provided by an extra network on the user side of the Ugt interface. Such a network may be a local network infrastructure on the customer's premises or a DCI gateway in a data center. The extra network may also exist between the Ugt interface and multiple DCI gateways in a data center. Unlike today's best-effort L3+L2 network nodes, FlexBr should achieve the **extreme QoS requirements** of the IOWN GF's use cases, e.g., including deterministic bandwidth and/or latency. In this way, FlexBr will enable IOWN GF's differentiated network services to be delivered to many endpoints in variable sizes. Furthermore, emerging co-packaged optics technologies are expected to facilitate the implementation of FlexBr.

The two last-mile networking methods should facilitate service providers to roll out the Open APN in various scenarios tailored to their early adoption use cases.

Note: The assumption is that one camera or sensor generates data at 60 Mbps. This metric comes from a base measurement of 500kB/Frame and 15 frames per second.

A.2. Flexible Bridging Services (FlexBr)

A.2.1. Definition

A **Flexible Bridging Service (FlexBr)** is a forwarding service that aggregates multiple data flows and sends them over an Open APN optical path. It is provided by extra network infrastructure connected with the Open APN Ugt interface. As defined in Section A.2.2, there are several types of forwarding services, and some of them support deterministic QoS requirements, e.g., deterministic bandwidth or delay/jitter.

A FlexBr Controller is a logical function that controls extra network infrastructures to create and maintain flexible bridging services. For the total infrastructure management, it should expose its northbound interface to the service-based interface bus of the Infrastructure Orchestrator.

Figure A.2-1 illustrates data flows enabled by Flexible Bridging Services. The data flows from multiple user devices under the left-side Extra Network FDN Gateway are aggregated and forwarded to the right-side Extra Network FDN

Gateway and then the data flows are disaggregated and forwarded to multiple user devices under the right-side Extra Network FDN Gateway. It is the same for the data flows of the reverse direction. Note that the data flows in Figure A.2-1 are an example of using a point-to-point optical path. A Mesh topology network using a multipoint-to-multipoint optical path is for further study.

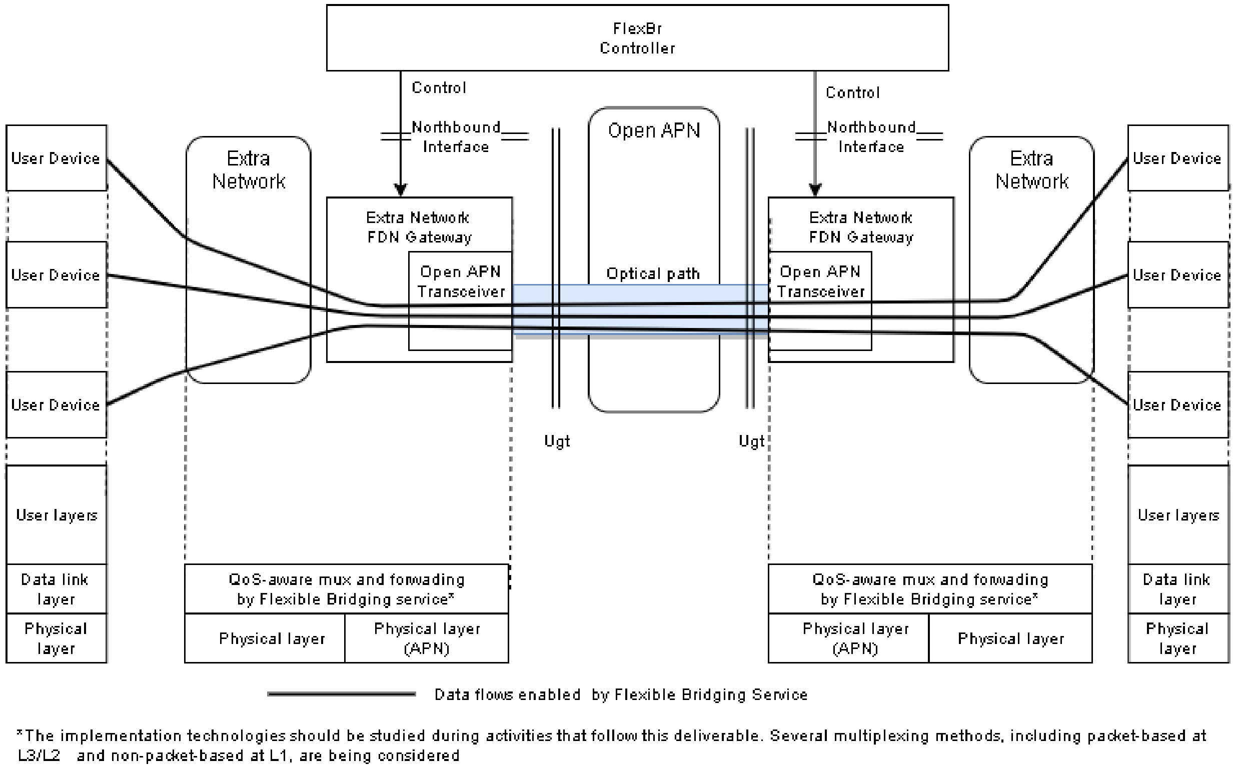


Figure A.2-1: Data Flows Enabled by Flexible Bridging Services

A.2.2. FlexBr Forwarding Service Types

Multiple types of FlexBr forwarding services are required since different use cases require different types of QoS. Table A.2-1 describes FlexBr forwarding service types. Service providers do not have to support all the service types. Service providers may start rolling out Open APN services with a limited set of service types for their roll-out scenarios.

Following are brief explanations about the service types:

- Types D1-D4 are for point-to-point communication, and types D5-D6 are for point-to-multipoint communication.
- Types D3-D4 do not reserve bandwidth for each connection. Instead, they should form bandwidth-sharing trees with some flow control mechanisms, as illustrated in Figure A.2-2. Examples of such flow control mechanisms are Peak Rate Limit and Priority-Based Flow Control. In particular, type D3 should provide bounded latency and congestion avoidance, i.e., no packet loss due to congestion.
- Types D1 and D5 should bound the latency under a minimal value to support data flow with very strict latency requirements, e.g., mobile front haul and SDI video distribution.
- The latency values, i.e., L1-L6, should indicate the latency of the forwarding by one bridge. IOWN GF should discuss whether IOWN GF needs to specify these values as requirements narrowly. If IOWN GF decides to do so, they should be described in implementation guidelines, separately from the functional architecture documents.

Table A.2-1: FlexBr Forwarding Service Types (Tentative Draft)

TYPE	BANDWIDTH MANAGEMENT & FLOW CONTROL	MAXIMUM LATENCY MANAGEMENT	P-TO-P / P-TO-MP	USE CASE EXAMPLES (NOT EXHAUSTIVE)
Type D1	Bandwidth reservation	Very Strict (< L1)	P-to-P	Mobile xHaul, SDI Video Transport, TSN LAN Interconnection
Type D2	Bandwidth reservation	Strict (< L2)	P-to-P	RDMA between large DCI Clusters
Type D3	Bandwidth sharing (see Figure A.2-2) with congestion avoidance	Strict (< L3)	P-to-P	Connecting small DCI Clusters with intermittent data transfer Event-driven sensor data aggregation
Type D4	Bandwidth sharing with best-effort quality	Undefined (Best Effort)	P-to-P	TCP/IP
Type D5	Bandwidth reservation	Very Strict (< L5)	P-to-MP	SDI Video Distribution, Multicast for TSN
Type D6	Bandwidth reservation	Strict (< L6)	P-to-MP	Compressed Video Distribution

(P-to-P: Point-to-Point, P-to-MP: Point-to-Multipoint)

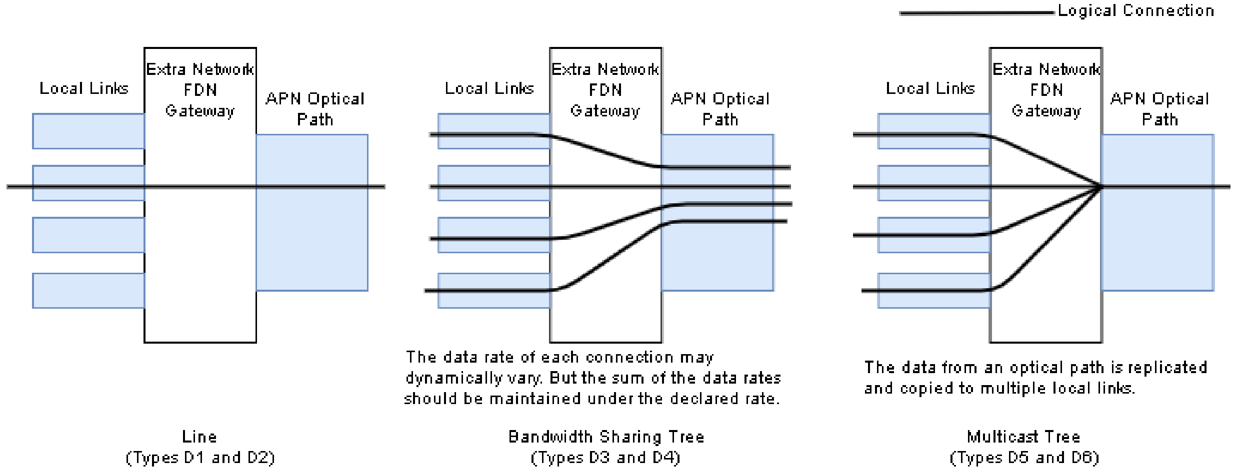


Figure A.2-2: Line, Bandwidth Sharing Tree, and Multicast Tree

There are several ways of implementing FlexBr services. Some take a packet-based approach, and others take a TDM-based approach. Implementation technologies are deferred to the technology evaluation and specification activities following this document. IOWN GF should look for approaches that can achieve the required QoS, e.g., deterministic latency/jitter and ultra-high energy efficiency. Approaches may vary with FlexBr forwarding service types.

A.3. Examples of Open APN Roll-out Use Cases

A.3.1. Converged Network Service for Campus/Town/Metro

Today, campuses, towns, and metropolitan cities have multiple network infrastructures such as fiber broadband for Internet access, carrier Ethernet for VPN, and CATV. However, the markets of these infrastructure types are converging. Moreover, each of them urgently needs to be upgraded because the technology is fully mature and, to improve, they must embrace new technologies for further growth. Hence, a converged network service that can fulfill existing demands and embrace new demands, such as a mobile front haul with low-latency and ultra-reliable connections would be very compelling. Open APN would be an ideal transport network for such converged network services.

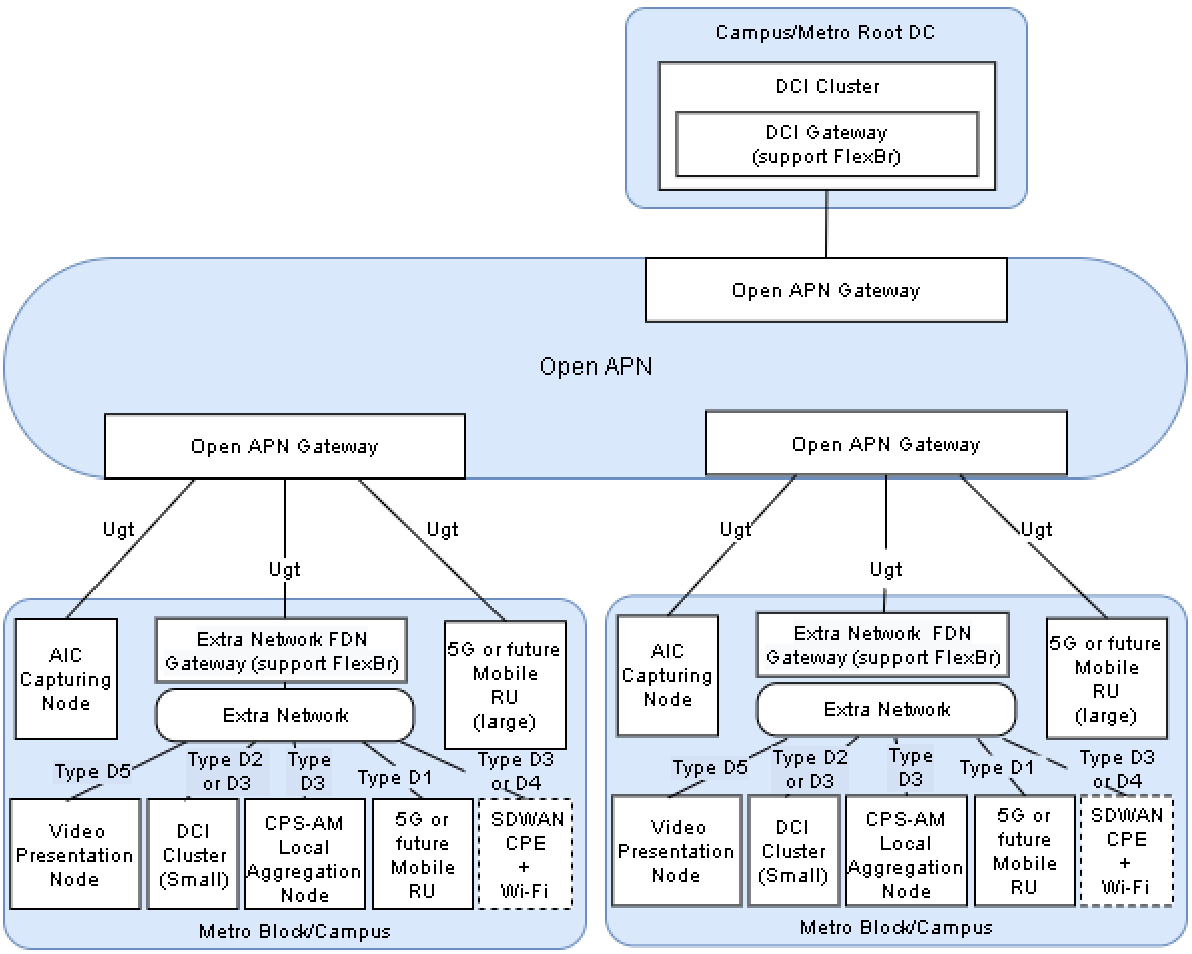


Figure A.3-1: Converged Network Service for Campus/Town/Metro

A.3.2. Data Center Interconnect Service

Many service providers and customers have multiple data centers even in a single regional area for various reasons, e.g., power capacity issues. Connecting these distributed data centers with ultra-high-speed, ultra-reliable, and low-latency interconnects would enable sharing computing resources across data centers and thus reduce the size of computing infrastructures and energy consumption. Open APN would be an ideal network for such data center interconnects.

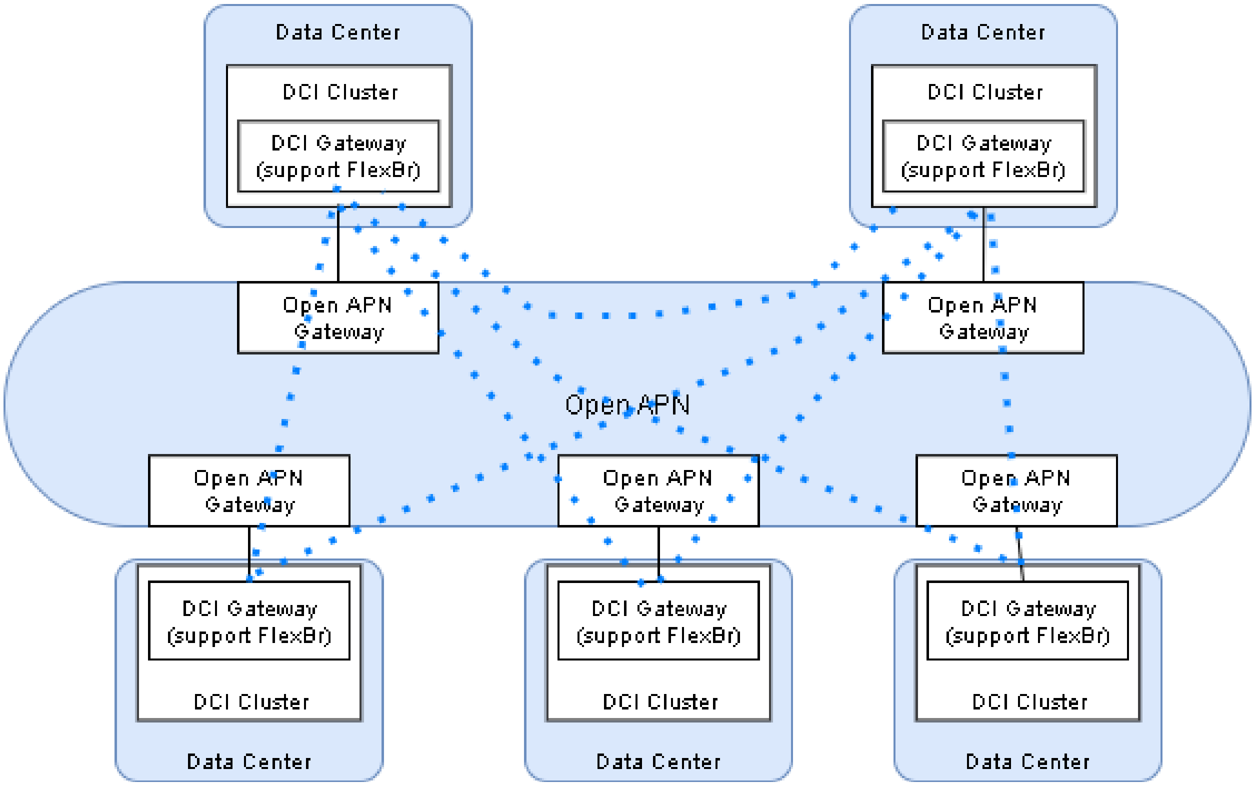


Figure A.3-2: Data Center Interconnect Service

B. Scenario to Expand Wavelength Resource

B.1. Introduction

In the context of expanding the wavelength resources to enable numerous end-to-end optical connections for the Open APN, two approaches can be taken. The first approach is to improve the utilization of existing wavelength resources through improvement in wavelength utilization. Network topologies as the one described in Section B.2 can therefore contribute to increasing the effective wavelength resource. The second approach is to create new wavelength resources to significantly increase the available wavelengths as enabled by ultra-wideband optical transmission technologies (UWOT). Details on such technologies are given in Section B.3.

In a scenario to expand the wavelength resource, network topologies can be used with current technologies for novel networks and also for future technologies to be deployed in the future for ultra-wideband optical transmission systems.

B.2. Reference Network Topologies to Improve Wavelength Utilization

Open APN provides direct optical path connections across domains/hierarchies between any user terminals, therefore the realization of the network topology that offers effective wavelength utilization and high scalability would be required. For the purpose of investigating how the network topology affects the scalability of the Open APN, the wavelength utilization in a two-tiered network model is shown in Figure B.2-1 (a) in which a metro-core ring interconnected with four metro-access rings comprising four access nodes are connected, are simulated. The path requests which are randomly occurred between two access nodes in the different access rings are assumed. The wavelength assignment tends to be more severe in terms of wavelength utilization in metro-core rings than in access rings because the optical path always passes through the metro-core ring. As a result, the wavelength utilization of the entire network is limited to only 53% when the first call loss occurs.

Adding links to the metro-core ring is an effective solution for relaxing the problem of wavelength assignment. For instance, the wavelength utilization can be improved to 55% by adding a link, and 60% by adding two links respectively (see Figure B.2-1 (b) and (c)). The numbers of the required optical paths that could achieve a call loss probability of 1% or less in each topology were 1,416, 1,614, and 1,881, respectively, which shows the effect of adding a link for accommodating the optical path.

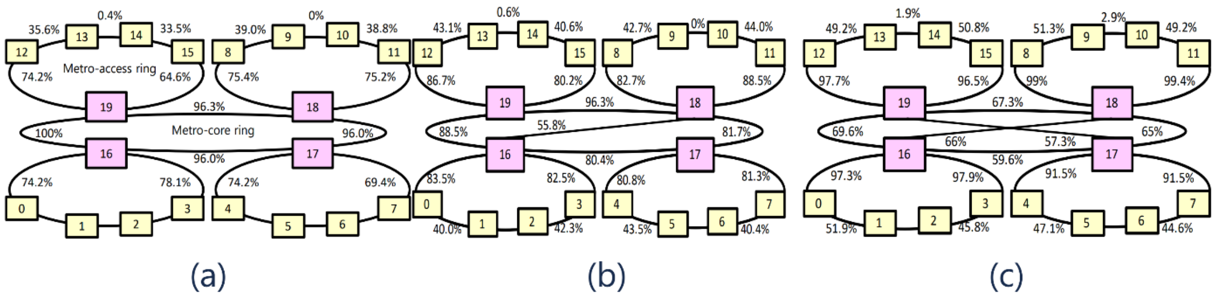


Figure B.2-1: Simulation Results of Wavelength Utilization in Two-tiered Ring Model; The Number of Wavelengths: 480, Routing and Wavelength Assignment (RWA): Shortest Path First (SPF) / FirstFit, No Wavelength Conversion.

Next, it has been calculated that the wavelength utilization of the specific model featuring the network deployed in Japan which is being studied by the Institute of Electronics, Information and Communication Engineers as a topology closer to the actual network (see Figure B.2-2). Several links with a wavelength utilization of 85% or more, as indicated by the red line in Figure B.2-2, occurred around node 25_KYOT, which is the center of the network. Therefore, it is assumed that all path requests for connecting the eastern side and western side in this model will lead to call losses.

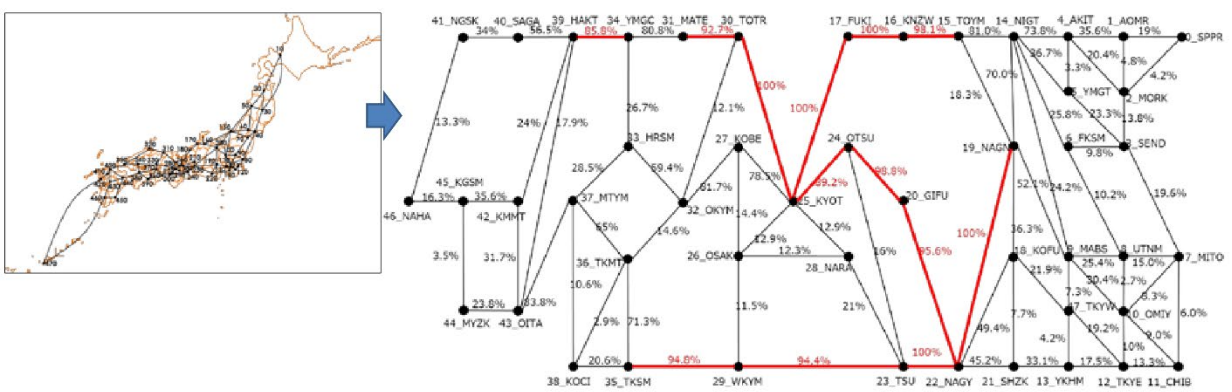


Figure B.2-2: Simulation Results of Wavelength Utilization in Japanese Network Model; The Number of Wavelengths: 480, RWA：SPF / FirstFit, No Wavelength Conversions, 3,000 Path Request

Adding links to certain areas with high wavelength utilization is an effective solution, and identifying these areas is relatively easy in such a multi-tiered ring model as shown in Figure B.2-1, however, with a complicated model as shown in Figure B.2-2, it would get more difficult.

In addition, unlike conventional static networks, Open APN allows users to freely make path connections on demand, so it is necessary to consider the following issues.

- A network topology without the limitation of the wavelength assignment should be designed by taking into consideration the probability of traffic occurrence and geographical restrictions.
- Route selection and wavelength management algorithms that maximize wavelength utilization in dynamic path demands and complex network topology configurations.

B.3. Scenario to Expand Capacity and Wavelength Resources Using Ultra-Wideband Optical Transmission

B.3.1. Ultra-Wideband Optical Transmission Technologies

Many service providers and customers have multiple data centers even in a single regional area for various reasons,

Ultra-wideband optical transmission technologies offer the possibility to expand the wavelength resources of the Open APN and cope with the fiber capacity limit stated in the gap analysis described in 1.4. In the future, the numerous end-to-end optical paths in the Open APN, along with ultra-wideband technologies, will enable scalable and sustainable networks.

According to the ultra-wideband framework defined in 3.3.4.2, the technological options considered in ultra-wideband optical transmission will be classified among Wavelength-Division Multiplexing (WDM) technologies and Space-Division Multiplexing (SDM) technologies. Bidirectional transmission technology can be used with WDM and SDM technologies to offer additional and more effective wavelength resources.

Technologies in this scope will be used depending on readiness for deployment, offered wavelength resource expansion, deployment cost, and impact on reachability. These technological options and the way they expand wavelength resources compared to current transmission technologies are described in Figure B.3-1.

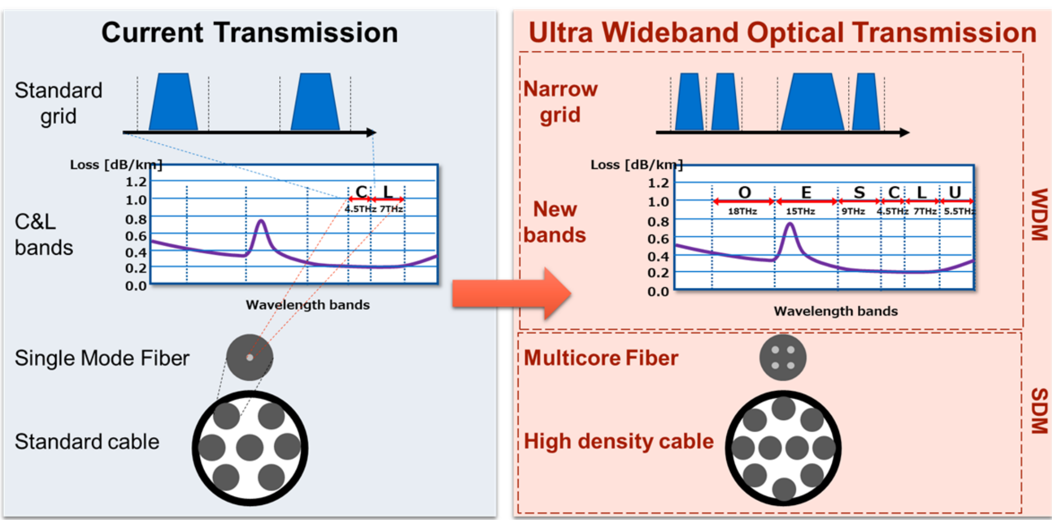


Figure B.3-1: Illustration of the Technological Options for Ultra-Wideband Optical Transmission

The four technologies illustrated in Figure B.3-1 in the UWOT section are not mandatory for the minimum implementation of the Open APN, although demand in a high number of wavelength tunnels will be a motivation for their adoption. These four technologies, i.e., narrow grid, new bands, multicore fiber, and high-density cable, can be used independently in any combination including current transmission technologies. Especially, in a scenario to increase wavelength resources, one or several technologies may be introduced first and progressively inside the network, depending on potential and challenges.

B.3.2. Reference Models for Ultra-Wideband Optical Transmission

To expand wavelength resources through creating newly available wavelengths using ultra-wideband optical transmission, it is required to establish models taking into account the technologies in this scope. Therefore, GOIP would make use of all dimensions offered by these technologies to add new bands, to split bands with narrower grids offering smaller granularity, to add more spatial paths parallelizing optical bands in a fiber and more fibers parallelizing optical bands in a cable. More details are described in Section 3.3.4.2.

The following reference models are intended to describe the transmission approaches for expansion of the wavelength resource and to discuss the technology gaps to be filled to expand the wavelength resource.

The reference models are designed as follows:

1. One model is set for each technology in scope. In the reference model, the reference points at Tx (S_s) and Rx (R_s) are to be set at the interface of APN-T.
2. The number of available wavelengths between the reference points Tx and Rx can be estimated according to any of the following options:
    A) Counting the number of wavelengths, for which for the defined bitrate supporting the required bandwidth, the characteristics of the wavelength tunnel are within the specification of the APN-T for error-free transmission. This condition can be verified using QoT or generalized signal to noise ratio (GSNR) as developed in B.3.3.
    This count can be performed on the following indices denoting each wavelength reference in the following order:
        i. (i): index of the wavelength carrier for the channel grid on a given band on a given core of a given in a cable
        ii. (m) index of the above-given band on a given core of a given fiber in a cable
        iii. (c) index of the above-given core in a given fiber in a cable
        iv. (f) index of the above-given fiber in a cable.
    B) Counting the available wavelength using a look-up table, which lists all the possible wavelengths and looks for the appropriate domain with several possible approaches (e.g., channel number, band, spatial channel, and fibers) for the complicated topology such as End to End path.
3. Examine the wavelength resource to characterize the reachability (QoT) of the following technologies in scopes according to the GSNR described in Section B.3.3.

While ultra-wideband optical transmission technologies enable to expand network capacity and wavelength resources, they present challenges, especially for APN-I. In particular, ultra-wideband technologies will make the optical layer more heterogeneous in terms of fiber type and transmission band. For providing end-to-end optical paths, APN-I should handle optical signals efficiently, even when several fibers and/or wavelength band configurations coexist. These challenges are detailed below among other technical gaps.

a) Additional bands

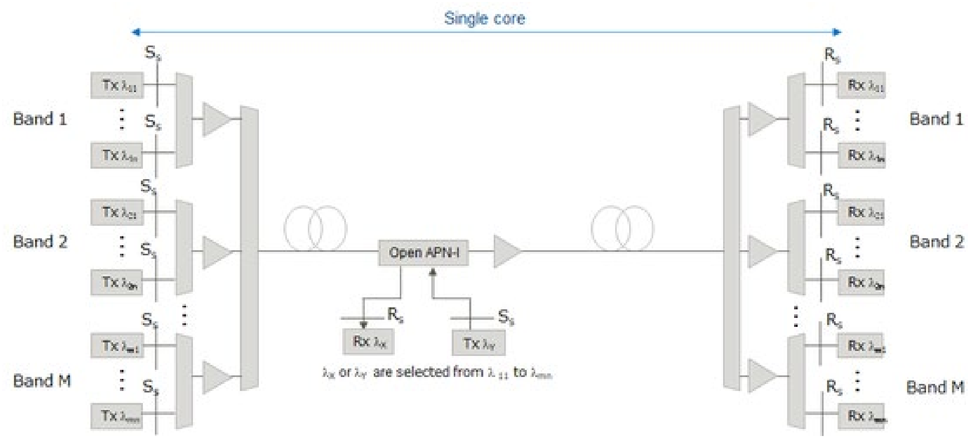


Figure B.3-2: The Additional Bands' Reference Model

One method to expand wavelength resources is to add the new bands to the conventional band. Hereafter, it is called the additional band. The transmission capacity could be drastically increased by adding the band, such as L-, S-, U-, E-, and O-bands. On the other hand, there are issues to overcome in utilizing the additional bands. The influence of the wavelength-dependent characteristics of deployed fibers on QoT should be considered which involves transmission loss, dispersion, nonlinearity, etc. In each band, QoT by considering GSNR should be examined where the interband effect of the stimulated Raman scattering should be treated appropriately. In addition, when the above reference model is considered, the following is a list of technical gaps that need to be filled.

- TRx used in the ultra-wideband range including tunable lasers and photo detectors
- Ultra-wideband fiber characteristics
- Ultra-wideband amplification by doped fiber amplification or Raman amplification
- Ultra-wideband optics
- Ultra-wideband APN-I including WSS and optical switches. The multiple-band operation presents a challenge in adaptation between interfaces of Uii and Ugi. Specifically, the difference in band operation will limit the interconnection pattern. For providing end-to-end optical connectivity efficiently, intra-connection (in APN-I) should be supported with no limitation. To address this issue, wavelength conversion technologies may be useful, and they may include all-optical conversion and O/E/O-type conversion.

b) Narrow grid

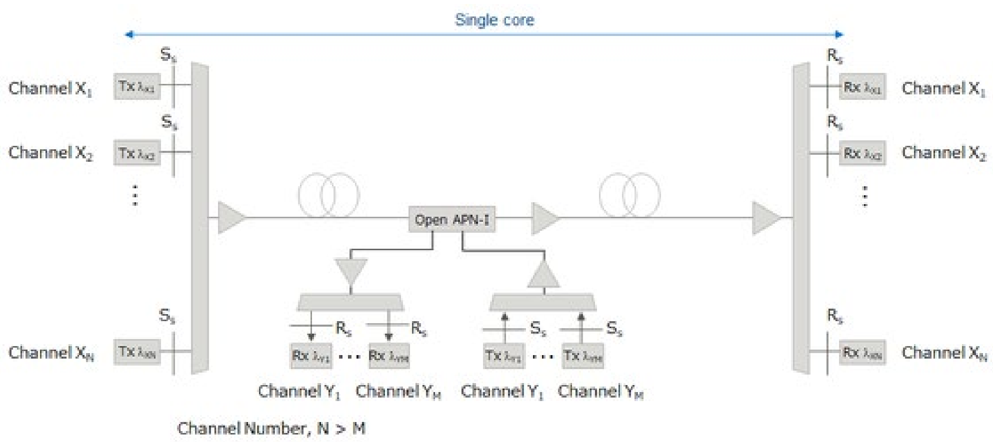


Figure B.3-3: The Narrow Grid Reference Model

The second method to expand wavelength resources is to narrow down the wavelength grid. Hereafter, it is called the narrow grid. The transmission capacity could be drastically increased by reducing the channel gird size and increasing the wavelength channels. When the reference model shown above is considered, the optical crosstalk impairment should be evaluated carefully. The following is a list of technical gaps that need to be filled.

- TRx with narrow grid
- Narrow grid fiber characteristics
- Narrow grid amplification
- Narrow gird optics
- Node configuration to maintain the moderate interface with the current network system

c) Multicore fiber transmission

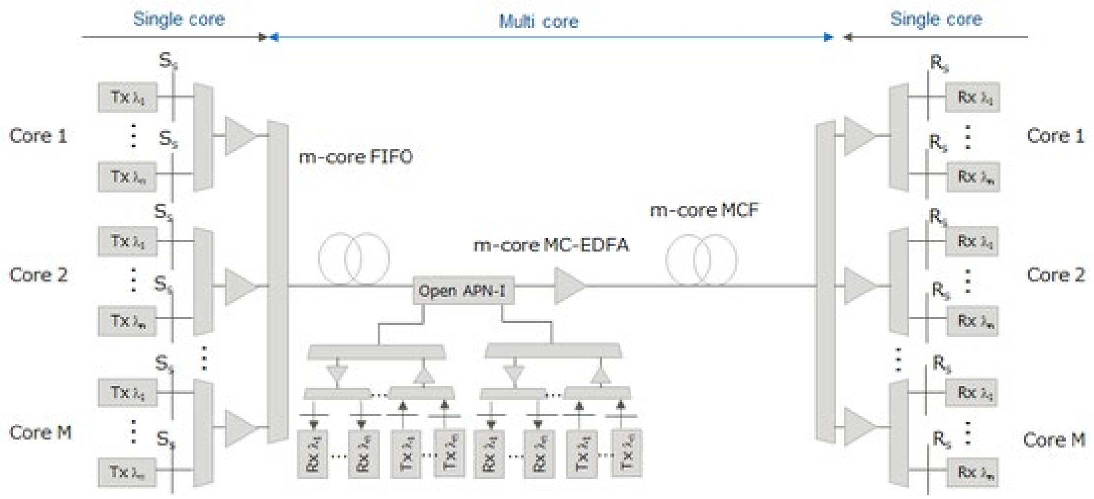


Figure B.3-4: The Multicore Fiber Transmission Reference Model

A third method to expand wavelength resources is to parallelize existing wavelength resources on the spatial dimension using multicore fiber transmission. The transmission capacity could be drastically increased using several cores, e.g., four cores in a standard cladding diameter fiber. On the other hand, there are technical issues to overcome in utilizing such technology. The influence of deployed multicore fibers on QoT should be considered, which involves transmission loss and crosstalk among cores. QoT by considering GSNR comprising the effect of linear crosstalk among cores should be treated appropriately.

In addition, the reference model in Figure B.3-4 involves the following gaps that need to be filled.

- Fan in Fan Out (FIFO) devices for connecting MCF to single-mode fiber. There exist several technologies for realizing such devices, as listed in Section B.3.4. Especially, one must consider the additional loss and crosstalk of such devices, which may have an impact on QoT.
- MCF characteristics. The MCF still needs to be standardized. Furthermore, one must consider crosstalk inside the fibers, which may have an impact on QoT.
- Multicore fiber erbium doped fiber amplifier (MC-EDFA). Several technologies have been reported to realize MC-EDFA. One must consider the crosstalk and noise figure of such amplifiers, which may have an impact on QoT.
- Impact of the number of connections in the link. The number of connectors or splices in the transmission line may have a loss and therefore an impact on QoT.
- Multicore APN-I. When SDM fibers such as multicore fibers are used, the required port count tends to be increased. Therefore, wavelength cross-connect and adaptation functions (described in Section 3.1) provided by APN-I need to be scaled in a hardware efficient manner. For instance, multi-granularity optical switching (e.g., fiber-level and wavelength-level) may be a useful solution. In addition, APN-I may support spatial multiplexing/demultiplexing for efficiently handling optical signals when using SDM fibers.

Finally, compatibility between systems using multicore fiber transmission and legacy systems can be simply assured with the FIFO interface, provided the number of used single-core fibers and the number of used cores of MCF match at the interface.

d) High-density cable

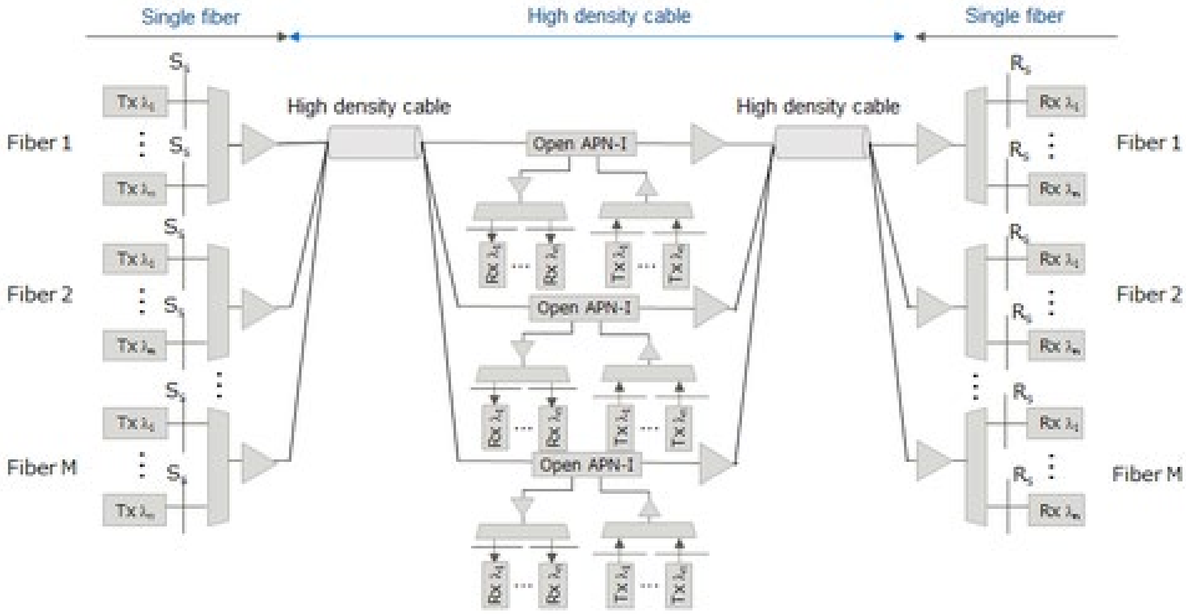


Figure B.3-5: The High-density Cable Reference Model

A fourth method to expand wavelength resources is to parallelize existing wavelength resources on the spatial dimension using several fibers in a high-density cable. The transmission capacity could be drastically increased by using more fibers inside a constant cable diameter.

The compatibility between systems using high capacity cables and legacy systems can be assured by simply using the fiber interface and connecting fibers among cables of different densities, provided the number of used fibers matches at the interface between cables.

In addition, the reference model in Figure B.3-5 involves the following gaps that need to be filled:

- Diameter of the cable. Some cables with high core counts may have large diameter filling ducts and making them more difficult to deploy. Therefore, one should also consider the diameter of the cable in addition to the cable density, to consider areas of the network where it can be deployed.

e) Bidirectional transmission

Finally, as an additional technology in the scope of ultra-wideband optical transmission, bidirectional transmission can be used in conjunction with any of the other four technologies. For instance, combining bidirectional transmission with additional bands would result in solutions where one optical band is transmitted in one direction and an adjacent band in the opposite direction. Combining bidirectional transmission with a narrow grid would result in solutions where one wavelength is transmitted in one direction and an adjacent one in the opposite direction. Combining bidirectional transmission with multicore fiber transmission would result in solutions where one core is used for transmission in one direction and an adjacent core in the opposite direction. Using bidirectional transmission with high-density cable would consist in using different fibers for each direction, which is widely used in present systems.

B.3.3. QoT for Ultra-Wideband Optical Transmission

The QoT can be estimated based on the GSNR parameter which has been defined by the Physical Simulation Environment (PSE) of the Telecom Infra Project (TIP). It appears that SNR is an important parameter to understand the advantages and constraints on additional wavelength resources enabled by technologies in the scope of UWOT. Therefore, the question of SNR should be discussed in upcoming versions of the Open APN to generalize it according to the properties of technologies in the scope.

The generalized signal-to-noise ratio (GSNR) is defined as

$$GSNR = \frac{P_{ch}}{P_{ASE} + P_{NLI}}$$

Where P_{ch} is the channel power, P_{ASE} and P_{NLI} are the power level of the disturbances in the channel bandwidth for ASE noise and NLI (Non-Linear Interference).

The approximated closed form in the expression enables to reduce dramatically computation resources and time compared to the conventional split-step-Fourier-based computation method. Therefore, the adoption of GSNR in the scope of Open APN and ultra-wideband optical transmission will enable to rapidly estimate the characteristics of a wavelength tunnel, determine the achievable capacity and reachability, which will become a key feature as the number of tunnels grows with the number of end-to-end optical connections.

Notably, to take into account the influence of the technologies in the scope of UWOT, additional nonlinear impairments resulting from using additional bands should be added, potentially within P_{NLI} or in an additional noise term and linear crosstalk resulting from using multicore fiber transmission should also be included, potentially as an additional noise term (P_{XT}) to be added to P_{ASE} and P_{NLI} at the denominator of GSNR.

B.3.4. Components to Expand Capacity and Wavelength Resources

To expand the capacity and wavelength resources using technologies described in Section B.2, multiple considerations and discussions would be required regarding components.

One of the critical discussions with components is around density and space. UWOT considers adding more bandwidth by adding more wavelength options and/or more TRx. This would require more transceiver ports at UWOT equipment and more fibers and channels at the WDM/FIFO module. If existing components are used, there will be more space required in a rack to accommodate such port/fiber increases compared to the current networking rack (Figure B.3-6). However, there can be limited space in central offices which UWOT solutions shall consider to avoid the space and size increase.

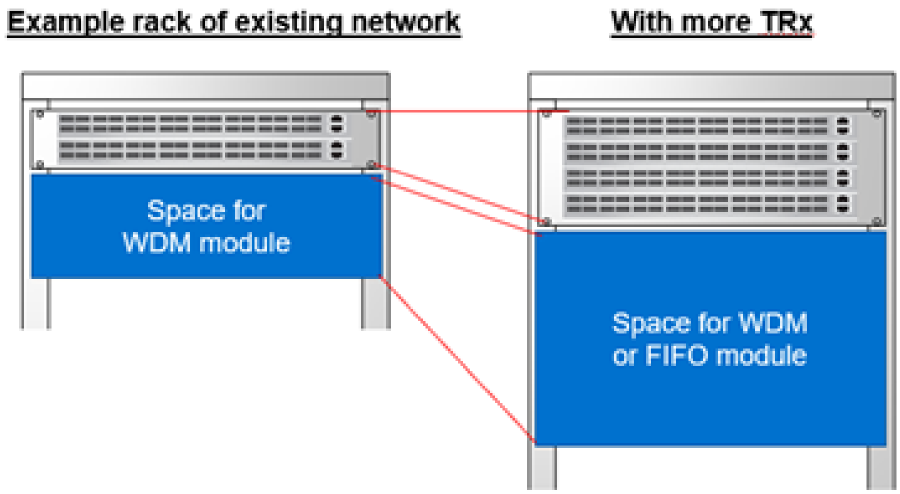
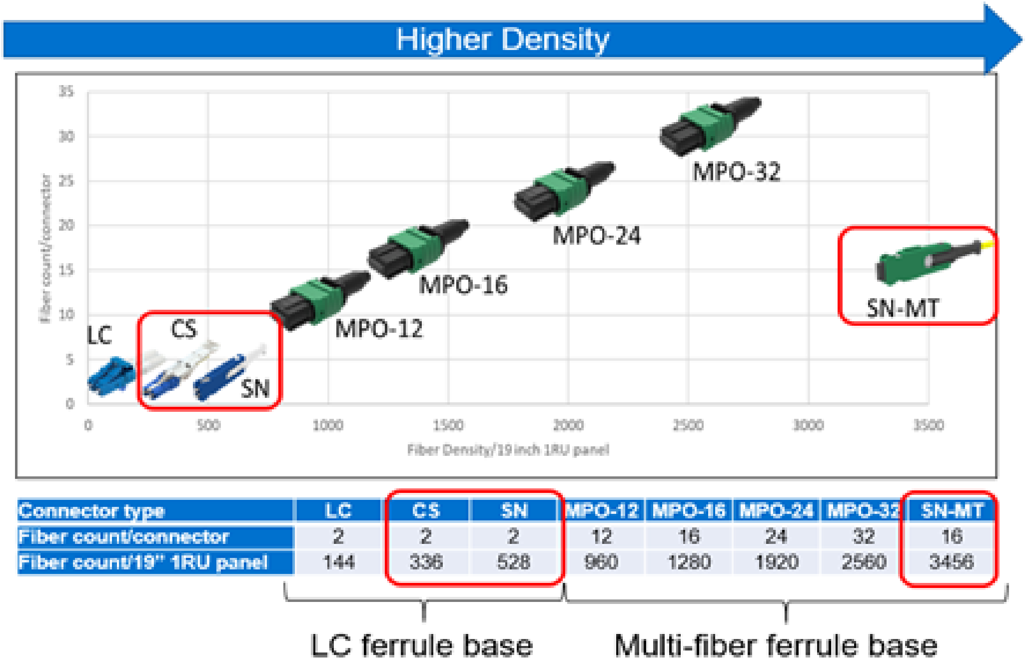


Figure B.3-6: Illustration of Rack Space Required for TRx Ports and WDM/FIFO Module Using Existing Components

The use of new high-density optical connectors can be a viable solution to overcome this space issue. There are a few fiber optic connectors that have been released recently. CS and SN connectors are LC ferrule-based duplex connectors, achieving better density over an LC duplex connector adopted by the new generation transceivers such as QSFP-DD and OSFP MSAs. For multi-fiber ferrule connector type, SN-MT connector has a significant density increase over MPO. Figure B.3-7 shows the density comparison among those connectors. Those new connectors can improve the module density, and reduce the space requirement for WDM/FIFO modules while increasing the channel capacity.



Connector type	LC	CS	SN	MPO-12	MPO-16	MPO-24	MPO-32	SN-MT
Fiber count/connector	2	2	2	12	16	24	32	16
Fiber count/19" 1RU panel	144	336	528	960	1280	1920	2560	3456

Figure B.3-7: Graph of Fiber Optic Connector Density Comparisons among LC, CS, SN, MPO, and SN-MT Connectors

SN connector mentioned previously can be a viable option to improve the transceiver port density. Legacy SFP and QSFP transceiver modules can accommodate only one LC duplex interface due to the size. SN connector having a reduced size, it can fit two duplex connectors in SFP-DD, and four connectors in QSFP-DD. Compared with duplex LC in SFP+, SN can increase density by two to four times more (Figure B.3-8).

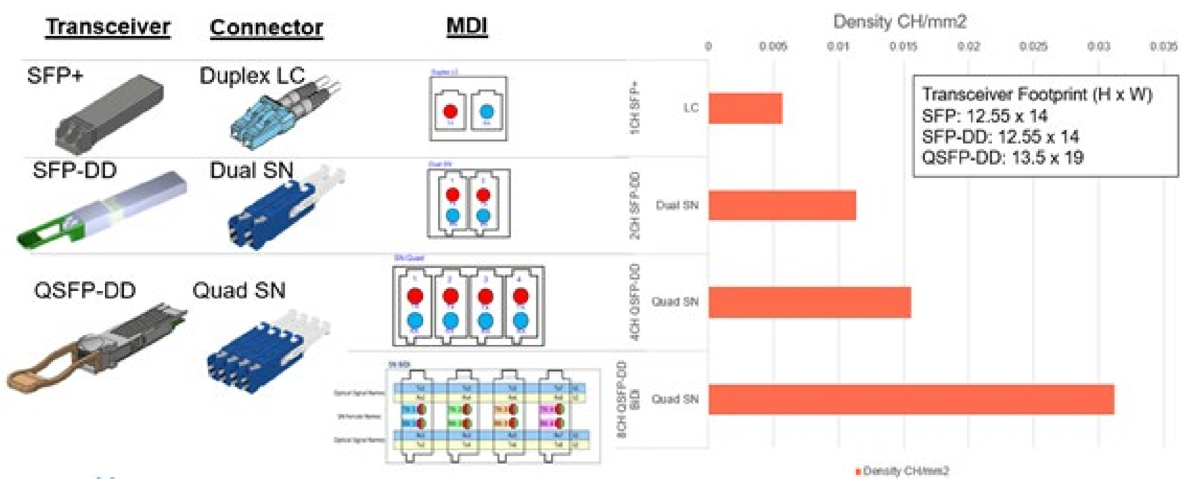


Figure B.3-8: Comparison Chart of Transceiver Density among Different Transceiver and Connector Types

In addition to the connectors described above, compatibility is a crucial consideration for the future integration of UWOT systems with conventional systems and for expanding the use of UWOT systems. The compatibility of multi-fiber connectors depends on whether the new connectors for UWOT equipment can use the traditional MT ferrule interface or new solutions applicable to the interface. As a viable solution for overcoming the space issue with the conventional

MT interface, MTCOMPACT(MTCT) ferrule with half-size or a quarter-size of the standard MT geometry can be considered. The MTCT ferrule applied connector applied with MTCT ferrule should be considered because it may be compatible with the conventional MPO connector and could overcome the space issue of UWOT equipment as well. Both would accelerate the dissemination of UWOT.

In this section, adopting a new high-density optical connector is discussed as one of the viable component solutions to expand capacity and wavelength in UWOT. However, some topics remain to be updated and clarified in future versions of Open APN. Notably, this includes:

- MCF connectors and MCF. Such connectors and fibers still need to be standardized, although there has been some report of a few hundreds of kilometer-long low loss 4-core linked formed using MCF provided by three manufacturers.
- Suitable Fan-in and Fan-out devices for MCF. Indeed, some FIFO devices are available for deployment such as, for example, devices realized using free space connection with lenses, waveguides drawn by laser, fusing fibers, or bundling fibers.
- Optimized devices like transceivers for ultra-wideband optical transmission. Two options for APN-T are discussed in 3.3.4.2, one based on legacy APN-T devices with interfaces and the other one related to optimized devices left for future versions of Open APN.
- The benefits of APN-T based on co-packaged optics technology. Such technologies are expected to increase density, reduce system space and power consumption in the future.

Abbreviations

AI	Artificial Intelligence
AIC	AI-Integrated Communication
API	Application Programming Interface
APN	All-Photonic Network
APN-C	Open APN Controller
APN-G	Open APN Gateway
APN-I	Open APN Interchange
APN-T	Open APN Transceiver
CPS	Cyber-Physical Systems
DCI	Data-Centric Infrastructure
FDC	Function-Dedicated Computing
FDN	Function Dedicated Network
GOIP	Group of Optically Interconnectable Ports
GSNR	Generalized Signal to Noise Ratio
OSNR	Optical Signal to Noise Ratio
pre-FEC BER	pre-Forward Error Correction Bit Error Rate
QoS	Quality of Service
QoT	Quality of Transmission
ROADM	Reconfigurable Optical Add-Drop Multiplexer
SDM	Space Division Multiplexing
SDN	Software Defined Network
WDM	Wavelength Division Multiplexing

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History

Revision	Release Date	Summary of Changes
1.0	January 27, 2022	Initial Release