



IOWN
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Open All-Photonic Network Functional Architecture

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[Open APN Functional Architecture]

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[Part-I] Overview, Services, and High-level Reference Architecture

1. Introduction

This series of documents supersedes Open APN Functional Architecture Release 2 [APN FA R2].

Part-I describes the introduction with needs and goals, services, and high-level architecture of Open APN.

Part-II describes the Control and Management plane, and User plane references of the Open APN. This part shows detailed information about the Open APN, including functions, network design, and operation.

Part-III provides Annexes. Each Annex provides a detailed description of Open APN Functional Architecture, focusing on a specific aspect, as well as additional information.

1.1. Market Dynamics and Needs

Today's world has experienced tremendous societal growth due to advancements in communication and computing technologies. Another quantum leap in communications and computing applications is expected to dramatically accelerate this continued growth and thus empower the world to reach new heights of interconnection and productivity.

This leap forward is powered by the research and innovation of the Innovative Optical and Wireless Network Global Forum (IOWN GF). The IOWN GF continues to conduct extensive research into the technologies required to power this new era of communications and compute. To guide such research and innovation, the Forum has released two advanced use cases as well as three early-adoption use cases so far; the former are Cyber-Physical Systems (CPS) [IOWN GF CPS] and AI-Integrated Communications (AIC) [IOWN GF AIC], and the latter are Remote Media Production for Broadcast Industry Use Case [IOWN GF RMP], Services Infrastructure for Financial Industry Use Case [IOWN GF FIN], and Green Computing with Remote GPU Service for Generative AI / LLM Use Case [IOWN GF GC].

However, today's widely deployed networks are packet-based and cannot meet the demanding performance and functional requirements of these use cases. They have delay and jitter in the order of tens of milliseconds, and the delay, jitter, and bandwidth are not guaranteed in the typical services [IOWN GF VISION 2030 ver.2].

Today, optical transport technologies are used primarily within the backbone of telecommunications networks. With these technologies, service providers can guarantee the bandwidth, delay, jitter, loss, and packet ordering. And by using optical-path routing technologies, routing by electrical processing of the packet routers can be reduced, and thus high-energy efficiency is expected.

Today, some Virtual Private Network (VPN) providers already offer dedicated optical connections for high-performance use cases such as data center interconnections. However, because their infrastructures are built with traditional integrated optical transmission systems, the service area is limited to those with high demands. It is highly expected that the service area will be expanded by disaggregating traditional integrated optical systems into multiple tiers.

To enable this shift, IOWN GF aims to develop the Open APN as an advanced form of the optical transport technologies to allow end-to-end and disaggregated optical networking.

1.2. Overview of the IOWN Global Forum Architecture

To meet these next-generation requirements, the 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.

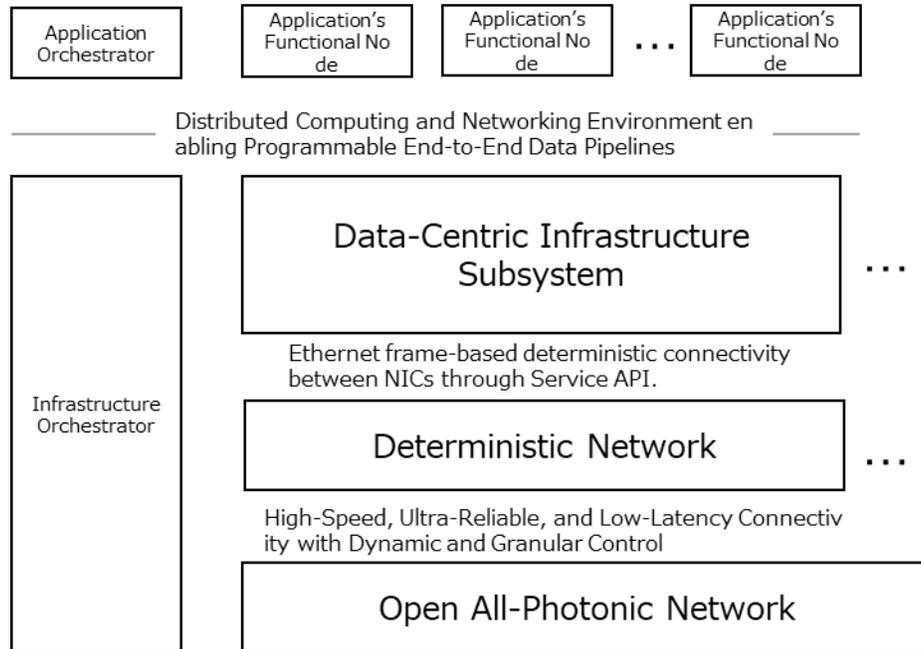


Figure 1.2-1: IOWN Global Forum Overall Architecture

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 that go far beyond the capabilities of today's network infrastructure. In today's network, optical paths are disjointed and operated segment-by-segment. Examples include the local area network (LAN), access network, and inter-data-center network. By contrast, the Open APN will enable one optical path to span multiple segments. This will allow end-to-end communication with deterministic performance. However, this approach will require more dynamic and granular control.

Moreover, since optical paths are established dynamically, making it possible to predict their performance requirements once they are provisioned, it becomes necessary to have a real-time performance measurement and monitoring mechanism. This mechanism allows the infrastructure to create new optical paths while considering the anticipated 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 databases, 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 pipe-by-pipe. For example, protocols supporting deterministic quality may be used for network paths connecting real-time sensors in a manufacturing setting. In contrast, traditional IP would be used for networking paths connecting external data consumers. In this way, service providers can 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 CPS and AIC applications. Application developers can then build applications leveraging the functions and features of 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 **Deterministic Network (DN)** is a network that provides network interface card (NIC)-to-NIC deterministic connections (connections with deterministic performance) as a Service across an Open APN that meet specified requirements with flexibility. It provides Ethernet frame-based logical connection with deterministic QoS (such as bandwidth and delay/jitter guaranteed) between NICs. Today's packet network is typically class-based and challenging to achieve deterministic connections. The DN provides deterministic connections across NIC, network within a site (e.g., data center network), and WAN, leveraging Open APN.

Moreover, the DN exposes a service API whereby the users can set up a connection, specifying parameters and capabilities for their requirements. Furthermore, it provides OAM functionalities (such as real-time performance monitoring and fault management) for establishing NIC-to-NIC deterministic connections. With this API, various use cases can be realized, which require computing resources across multiple data centers.

Note that Open APN provides high-speed, ultra-reliable, and low-latency connections. However, in typical deployment scenarios of Open APN, Open APN is deployed in the WAN connecting multiple sites. The DN intends to extend features of Open APN between NICs - across NIC, network within a site (e.g., data center network), and WAN. Also note that there is no restriction to deploy the DN only in the network within a site (e.g., data center network).

The **Infrastructure Orchestrator** is the infrastructure's central management function that controls various infrastructure resources and exposes a single management interface. It is logically a single component but 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 infrastructure orchestrator's application programming interface (API) 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 the Open All-Photonic Network (APN)

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

End-to-end lambda connection: To provide deterministic end-to-end communication, the path's endpoints should not be limited to the providers' central office but can be located on the user's premises. And in the future, users will have their transceivers* that connect directly to remote sites via a service provider's network. While end-to-end lambda connections already exist for users with high volume data requirements, the goal is to provide them as a network service to a wide range of users as well as to provide them with open specifications to allow multi-vendor implementations.

Dynamic optical path provisioning/control: To flexibly provide end-to-end optical path, the path should be established, modified, or removed in a real-time based on the customer's performance requirements. Therefore, methods to provide and control paths are required to provide optical transport services that directly connect users flexibly. In addition, the number of wavelengths is limited. The method to allocate network resources efficiently is also required. While dynamic optical path provisioning already exists in recent deployments, the goal is to realize it with open specifications to allow multi-vendor implementations.

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. An Open APN based on an end-to-end direct optical connection enables networking with less energy consumption by minimizing electrical processing. On the other hand, the actual power consumption differs depending on the network design and other technology choices.

Therefore, the architecture and specifications of the Open APN should be defined so that lower power consumption can be realized according to the policy.

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

Computing-networking convergence: Computing, which performs calculations, and wide-area networks, which transfer data, have evolved independently (Edge routers/switches are the demarcation point between the two facilities). To realize the use cases that IOWN GF published [IOWN GF CPS, IOWN GF AIC, IOWN GF RMP, IOWN GF FIN, IOWN GF GC], 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. While large Cloud operators already control both data centers and network infrastructure, the goal is to expand it to a wide range of computing resources, such as Edge and Fog, in addition to Cloud.

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 concert venues may require more bandwidth during the evening. By redistributing these applications over distributed computational resources with variable bandwidth networks, latency and network traffic that impact user experience can be minimized.

Format-agnostic optical signals: The 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-agnostic and modulation-format-agnostic communications should be allowed. However, this could only be achieved with detailed conformance specifications for admissible optical signals. The degree of freedom will improve as the IOWN GF updates 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 than 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 operators can be leveraged to support the dynamic optical path provisioning/control of the Open APN. To handle such enormous monitoring data, Open APN control and management systems should have low latency and high security for collecting, storing, processing, analyzing, and sharing data. While intelligent monitoring techniques with high granularity and speed already exist, their actual use varies from network operator to network operator. The goal is to create a common architecture to accelerate the development and deployment.

Coexistence of conventional ROADM network and Open APN: For smooth deployment of the Open APN in the real world, efficient coexistence with and migration from the conventional ROADM network is important. The migration scenario and the coexistence scheme should be developed.

(*The user's connection with their transceiver is an example case. There will be cases where the transceiver is installed within the carrier network or where the transceiver is owned by carriers but located at the user's site, as shown in Annex E.)

1.4. Gap Analysis

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

Disjointed 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 the Open APN aims to provide direct optical paths between any locations, including user premises on demand, the Open APN shall provide a function to provision and manage the wavelength resources throughout the network, i.e., from access to core. In addition, the Open APN shall provide a function to design the continuous optical paths from access to core, i.e., the end-to-end optical paths.

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. 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. The Open APN should allow for dynamic path creation, re-setup, and deletion, which require dynamic online optical path design. Anticipated technology evolutions 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 (BER) versus the optical signal to noise ratio (OSNR) characteristics of the receiver.
- Standard control signal.
Due to the downsizing and energy-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 K-1 in Annex K (in Part III). Still, 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 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 must be quickly carried out using production systems, which take a significant time to do 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 minimizing photo-electric conversion for lower latency and 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. Also, a user and a network operator should share an optical path endpoint address under a common addressing space to identify an endpoint device. Furthermore, a user should notify a network operator of the capabilities and parameters of an endpoint device, such as the supported wavelength range, 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, there are several gaps against the target Open APN.

Such gaps include (but may not be limited to) the following.

- In the conventional ROADM systems, optical transceivers under the same ROADM node are co-located, and there is no need to establish optical paths between them. Because of this, the current ROADM architecture doesn't support establishing optical paths between optical transceivers under the same ROADM node.
- A control/management channel is not supported for the remotely located transceivers 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 [G.986]) and its variation are not considered in the conventional ROADM-based network. As the loss induces the degradation of Signal-to-Noise Ratio (SNR) and the loss variation increases the

crosstalk from higher-power wavelength channels to lower-power ones after wavelength-division multiplexing, a system design to minimize these degradations must be carefully studied.

- Advanced control of optical amplifier chains will be needed to support wavelength reconfiguration, which 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, whose monitoring mechanisms are not efficient enough and insufficient in terms of the granularity of performance parameters. In the Open APN, when a management system detects failure or impairment on an optical path, it should dynamically re-set up an optical path to guarantee the designated Quality of Transmission (QoT) requirements, such as bandwidth, latency, jitter, and BER. Therefore, the 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 traffic. 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.

Lack of support for various optical signals: Today's optical network is designed to support specific optical signals, and is incapable of transmitting fiber-sensing or QKD (Quantum Key Distribution) signals, although these are promising IOWN use cases. CWDM (Coarse WDM) is also useful for cost-effective multiplexing, but the signal cannot pass through DWDM filters. Therefore, today's optical network does not support the simultaneous use of CWDM and DWDM. In today's broadband network, point-to-multipoint (PtMP) configuration is widely used, especially in the access network, because it is cost-effective. However, today's DWDM-based network does not support PtMP configuration either. The Open APN is expected to accommodate various optical signals to support multiple applications with an optimized cost.

2. Services of Open APN

The Open APN provides User plane services in the form of optical paths. Also, the Open APN provides Control plane and Management plane services to control and manage these optical paths.

The Open APN offers four types of optical paths to accommodate diverse optical requirements in two categories. The first category is a path that aligns with a DWDM grid and travels across a DWDM-based network. This is called a wavelength path. Two types of optical signal transport paths, Point-to-Point (PtP) Wavelength Path and Point-to-MultiPoint (PtMP) Wavelength Path, are defined in this category. The second category is a path equivalent to a direct fiber connection. This is called a fiber path. Two types of optical signal transport paths, Point-to-Point (PtP) Fiber Path and Point-to-MultiPoint (PtMP) Fiber Path, are defined in this category.

Figure 2-1 shows a summary of Open APN services based on various use cases described in Annex D. An Open APN endpoint is an optical path's transmission/termination point on an Open APN service. The Open APN endpoint may be located at user sites and be user-owned. Examples of user sites are enterprise user premises, cloud provider data centers, and mobile sites.

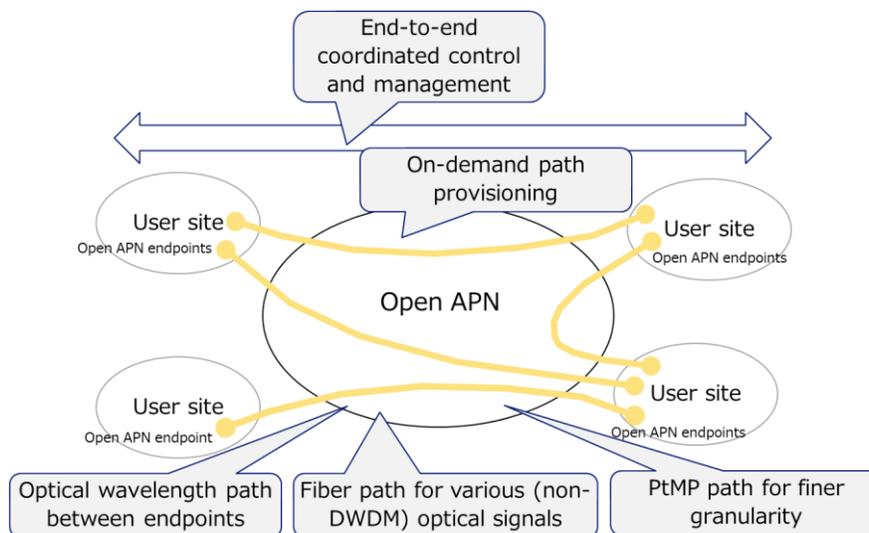


Figure 2-1: Brief Summary of Open APN Services

As for User plane services, an Open APN provides a wavelength path between Open APN endpoints for high-speed, ultra-reliable, and low-latency communication. Such wavelength paths may be provided on demand, allowing users to change destinations over time. Redundancy options may be provided. In addition, the Open APN provides a fiber path between Open APN endpoints for supporting non-DWDM optical signals.

In addition to the PtP path, Open APN provides a PtMP path for finer granularity (shared wavelength path or shared fiber path) from (or to) more than one leaf Open APN endpoints to (or from) a one hub Open APN endpoint.

As for Control plane and Management plane services, the Open APN, combined with related technologies, provides end-to-end coordinated control and management for automated operations (e.g., planning, provisioning, maintenance) and assures the quality of transmission (QoT) of end-to-end communication. QoT refers to transmission performance and reliability parameters, such as signal-to-noise ratio and bit-error rate (BER). Monitoring and maintaining QoT is crucial to ensure the reliable delivery of data across the Open APN. An example scenario is when QoT degradation is detected through monitoring and recovery is performed automatically.

2.1. Service Types

The Open APN provides the following four types of path services.

2.1.1. Point-to-Point (PtP) Wavelength Path Service

This service provides a dedicated wavelength path between two Open APN endpoints as shown in Fig. 2.1.1-1. The endpoint is an optical transceiver with DWDM transmission and reception capability and terminates the wavelength path. This is defined as Open APN Transceiver (APN-T). A set of optical parameters is used to ensure the connectivity at this endpoint.

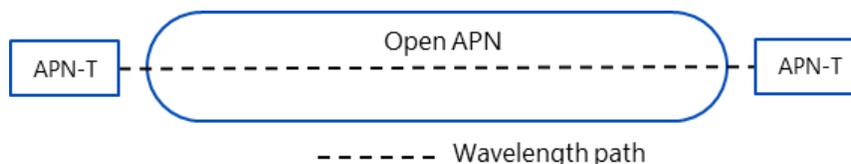


Figure 2.1.1-1: Point-to-point Wavelength Path Service

2.1.2. Point-to-MultiPoint (PtMP) Wavelength Path Service

This service provides a wavelength path shared by a set of endpoints connecting from (or to) more than one leaf Open APN endpoint to (or from) a one hub Open APN endpoint as shown in Figure 2.1.2-1. The endpoint is an optical transceiver with DWDM transmission and reception capability and terminates the wavelength path. This is defined as Open APN Transceiver (APN-T). (the leaf optical transceiver, and the hub optical transceiver are defined as APN-T(MP-L) and APN-T(MP-H), respectively; see Section 3.1.2). A set of optical parameters is used to ensure the connectivity at this endpoint.

This concept requires support of the P2MP aggregation by the Open APN. As power control loops to equalize the power of different APN-T(MP-L) may interact with power control loops in the Open APN.

Optical broadcast/multicast in Open APN.WX is a variant of PtMP Wavelength Path Service; see Annex I for the details.

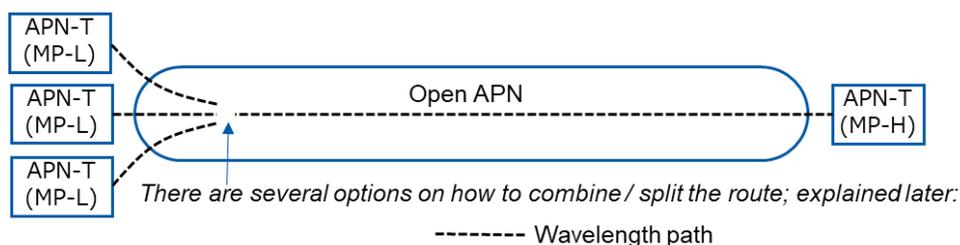


Figure 2.1.2-1: Point to Multi-point Wavelength Path Service

2.1.3. PtP Fiber Path Service

This service provides a dedicated fiber path between two Open APN endpoints as shown in Fig. 2.1.3-1. A fiber path is defined as a path of optical fibers connected in a fiber-exchanging manner. Ideally, it should carry the whole fiber bandwidth. However, as the supported bandwidth and other characteristics may depend on infrastructure implementations, we specify the user plane service of the fiber path in Section 2.2.

The endpoint of the fiber path is an optical transceiver, or another device; the case of using a device other than an optical transceiver at the endpoint of the fiber path is described in Section 3. The optical transceiver that terminates the fiber path is defined as APN-T(FX). This APN-T(FX) does not have to be a DWDM transceiver, while it should be compatible with the user plane specification of this service, defined in Section 2.2. A set of optical parameters is used to ensure the connectivity at this endpoint. The fiber path can be used in combination with the wavelength path; see Section 3 for the architecture.

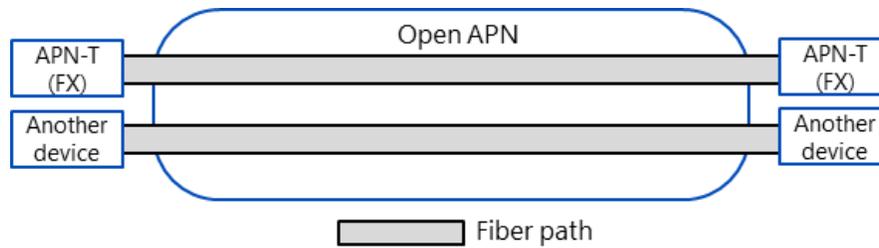


Figure 2.1.3-1: Point-to-point Fiber Path Service

2.1.4. PtMP Fiber Path Service

This service provides a shared fiber path from (or to) more than one endpoint to (or from) another via an optical splitter as shown in Fig. 2.1.4-1. Note that multiple optical splitters can be cascaded within a fiber path. The endpoint of the fiber path is an optical transceiver, or another device; the case of using a device other than an optical transceiver at the endpoint of the fiber path is described in Section 3. The optical transceiver that terminates the fiber path is defined as APN-T(FX). (the leaf optical transceiver and the hub optical transceiver are defined as APN-T(FX:MP-L) and APN-T(FX:MP-H), respectively). These APN-T(FX)s do not have to be a DWDM transceiver, while they should be compatible with the user plane specification of this service defined in Section 2.2. A set of optical parameters is used to ensure the connectivity at this endpoint. The fiber path can be used in combination with the wavelength path; see Section 3 for the architecture.

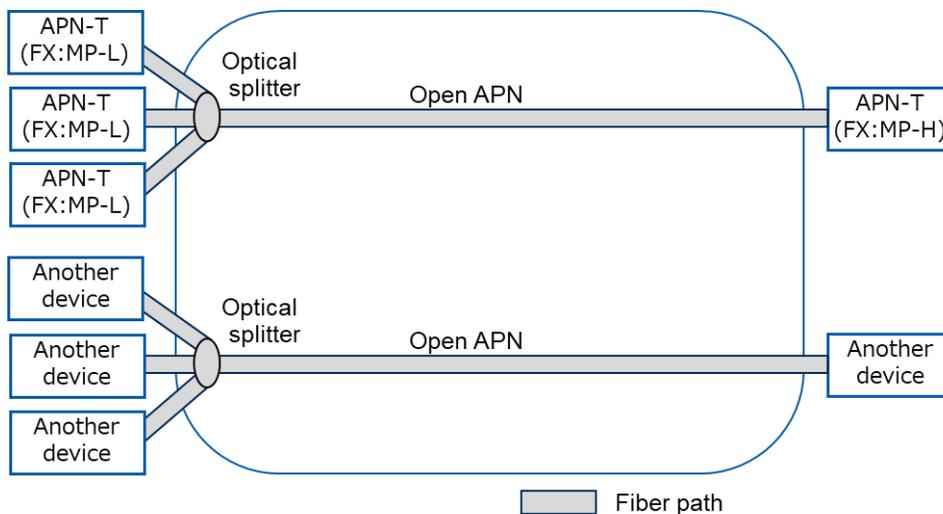


Figure 2.1.4-1: Point to Multi-point Fiber Path Service

2.2. User Plane Services

2.2.1. PtP Wavelength Path Service

The PtP wavelength path service offers optical signal transport paths that align with a DWDM grid and travel across a DWDM-based network (defined as Open APN Wavelength Exchange in Section 3).

The optical interface at each end of a PtP wavelength path is defined as the combination of the following two specifications when the endpoint of the wavelength path is APN-T (option 1 explained in Section 2.1.1).

1. Optical transmission/reception specification
2. Wavelength-path specification

The following existing specifications for the optical transmission/reception are within the scope of the Open APN.

1. W' 100-200G 31.6 Gbaud of OpenROADM MSA Optical Specification Version 7.0 [OpenROADM optical spec]
2. W' 200-400G 63.1 Gbaud of OpenROADM MSA Optical Specification Version 7.0 [OpenROADM optical spec]
3. W 400-800G 124 Gbaud of OpenROADM MSA Optical Specification Version 7.0 [OpenROADM optical spec]
4. W 600-800G 118- 131 Gbaud of OpenROADM MSA Optical Specification Version 7.0 [OpenROADM optical spec]
5. Open ZR+ MSA Technical Specifications Revision 3.0 [Open ZR+ spec]
6. NRZ 10G (N, W) of ITU-T G.698.2 [G.698.2]
7. NRZ 2.5G (N, W) of ITU-T G.698.2 [G.698.2]
8. NRZ 25G (N, W) of ITU-T G.698.1 [G.698.1]

Note that W' is the optical interface point for remotely located optical transponders, which is defined in the OpenROADM MSA after a careful study between IOWN GF and OpenROADM MSA [OpenROADM].

While the multi-vendor interoperability between the transmitter and the receiver through the use of standard optical specifications listed above is a mandatory requirement for APN-Ts to realize open and dynamic (i.e., on-demand) optical networking in Open APN, it is also allowed to deploy the same vendor's APN-Ts as a pair for some limited usage, that is, for providing static or semi-static wavelength paths for the purpose of maximizing transmission performance or reducing power consumption and latency in a limited part of Open APN, for example. In this case, the paired APN-Ts can be based on proprietary specification (e.g., that with a special modulation format), so that the transmission performance is maximized, or the power consumption is minimized. Note that basic optical parameters such as the power level, the frequency accuracy, and the out-of-band power suppression ratio must comply with a standard spec to avoid interference with other wavelength paths. To deploy the same vendor's APN-Ts as a pair is called "bookended mode", and is supported by the OpenROADM MSA specification as well [OpenROADM Device White Paper], [OpenROADM Network White Paper].

Given that it may be easier to design the digital-coherent and Non Return to Zero (NRZ) networks separately, Group of Optically Interconnectable Ports (GOIP; see Section 6.1 (in Part-II)) for the two technologies may be designed separately in the initial stage (although the ultimate goal of the Open APN is to provide direct optical paths for any types of signals).

The wavelength-path specification provides the following information.

- Physical information of the wavelength path (e.g., used fibers, wavelengths, and used bandwidth)
- Factors limiting the reachability over the path, 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 6.4 (in Part II) describes further details for the characteristic of wavelength paths.

2.2.2. PtMP Wavelength Path Service

For further study.

2.2.3. PtP and PtMP Fiber Path Services

The fiber path service offers optical transport paths equivalent to a direct fiber connection, so that it accepts optical signals that are not within a DWDM grid and those with very high (or very low) optical power and thus cannot be transmitted through a DWDM-based network.

The optical interface at each end of a PtP fiber path is defined as the PtP fiber-path specification. In addition, when the endpoint of fiber-path service is APN-T(FX) (see Section 2.1.3), the optical interface is defined as the combination

of an optical transmission/reception specification and the fiber-path specification. The following existing specifications for the optical transmission/reception are within the scope of the Open APN.

1. Physical layer specification for 100 Gbit/s ONU and OLT in ITU-T G.9806 Amendment 3 [G.9806 Am3].

The optical interface at each end of a PtMP fiber path is defined as the PtMP fiber-path specification. In addition, when the endpoint of fiber-path service is APN-T(FX) (see Section 2.1.4), the optical interface is defined as the combination of an optical transmission/reception specification and the fiber-path specification. The following existing specifications for the optical transmission/reception specification are within the scope of the Open APN in this document. At the same time, other interfaces are not excluded and will be defined in a future document.

1. 100 Gbit/s symmetric Coherent PON in Cable Labs CPON-SP-ARCH-I01-230503 [CableLabs C-PON].

Each fiber-path specification provides the following information, but detailed parameters and parameter values will be specified in a future version of the Open APN.

- Physical information of the fiber path (e.g., insertion loss, return loss, polarization mode dispersion, input power range)

2.2.4. One-span PtP Wavelength Path Service

The one-span PtP wavelength path service offers a special form of PtP wavelength path between a pair of Open APN endpoints over one-span direct fiber. It supports transmission of optical signals not within a DWDM grid and signals with very high or very low optical power, which were accepted only over the fiber-path service in the Open APN Functional Architecture release 2. The endpoint of this service is an optical device such as an optical transceiver. A set of optical parameters is used to ensure the connectivity at this endpoint.

The optical signal is directly inserted into and extracted from the fibers connecting two APN nodes (i.e., APN-T/APN-G/APN-I), so that transmission of various optical signals that shall not be physically affected by functional elements of APN nodes (i.e., optical amplification, wavelength cross-connect, etc.) is supported.

2.2.5. Summary

Figure 2.2.5-1 shows a summary of Open APN User plane services. Optical interfaces provide an open interface for the Open APN, connecting Open APN endpoints by following optical specifications.

- For wavelength path service, optical signals must follow optical transmission/reception specifications, such as minimum/maximum frequency and optical power. Detailed specifications are mentioned in this section. This service's Open APN endpoint is named APN-T, which has DWDM transmission capability, as described in Section 2.1.1.
One-span PtP wavelength path service is newly defined as a special form of PtP wavelength path that supports optical signal transmission over one-span direct fiber. This service is useful for non-DWDM signal transmission even at the network segment where the fiber-path service is not deployed.
- For fiber path service, the optical signal has flexibility. Namely, the optical transceiver connected to an Open APN endpoint of this service does not have to be a DWDM transceiver, as described in Section 2.1.3.

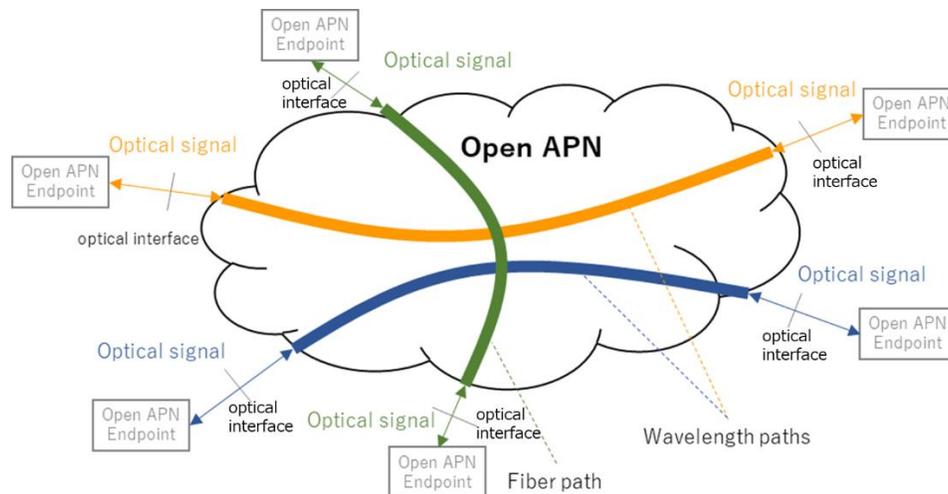


Figure 2.2.5-1: Open APN User Plane Service

For the wavelength path, an Open APN endpoint should be an optical transceiver to send and receive data over the provided paths. A user device with an optical transceiver can directly terminate the wavelength paths (known as direct connect service). In another case, 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 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.

2.3. Control Plane Services

The Open APN provides functions to set up wavelength paths or fiber paths for users to utilize Open APN services between Open APN endpoints. Open APN endpoints should be authenticated and authorized before path setup. For the setup of wavelength paths, 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.

<Control of Open APN endpoint devices>

- Open APN endpoint devices may be located at user sites and be user-owned. The Open APN should provide functions that enable the Open APN service provider to authenticate and authorize such an Open APN endpoint.
- Users can specify the following endpoint information before the path setup request: (a) endpoint address and user ID, (b) supported wavelength range, and (c) supported transmission capability and parameters. Such information is maintained within the Open APN for control and management purposes.

<On-demand path control>

1. Users can request the following path setup requests specifying Open APN endpoint addresses: (a) path creation, (b) path deletion, and (c) path re-setup.
2. Users can request the following requirements in a path setup request: (a) bandwidth, (b) latency, (c) jitter, and (d) redundancy.
3. Upon request, the Open APN service provider sets up a path satisfying requirements. The Open APN service provider could allow/deny the request between Open APN endpoints based on configuration policies. The Open APN service provider coordinates parameters (such as wavelength and transmission) to be configured with users. When the request is between Open APN endpoints belonging to different users, the Open APN service provider further coordinates the request between users (e.g., whether redundancy options are allowed between two users).

Users may request path setup on demand or request path setup as a reservation (actual path setup is executed later). For reservation, path setup requests include start-time and possibly end-time, and resources are reserved for these requests.

<Automatic path control driven by network>

- The Open APN monitors and analyzes QoT parameters, such as bandwidth, latency, jitter, and BER, through Management Plane Services described in Section 2.4.
- Once the Open APN finds that the QoT does/will not meet the requirement, it may automatically switch the path to satisfy the requirement continuously.

The 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 remote-site applications as user applications with an in-band or out-of-band interface. For the in-band interface, remote-site 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, remote-site applications send/receive control plane data to/from the Open APN controller through a network external to the Open APN.

2.4. 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 devices. The Open APN provides functions enabling the Open APN service provider to get Open APN device information and monitor the optical signal status.

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.

- The Open APN enables the Open APN service provider to get the following information: (a) QoT parameters such as bandwidth, latency, and BER; (b) configuration parameters of Open APN devices, such as the endpoint address and assigned wavelength; (c) status parameters of Open APN devices, such as the failure status of a device.
- The 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 the Open APN controller; (b) periodic mode, in which the parameters are acquired continuously within the subscription sessions; (c) threshold-triggered mode, in which the parameters are acquired on the defined thresholds are triggered within the subscription sessions.
- Open APN service providers may post collected data to the IOWN Data Hub and have some intelligent applications that retrieve the data from the Data Hub.
The Open APN supports a network configuration strategy to communicate with external entities.
The collected QoT information can be sent to the data processing units in (a) raw-data manner or (b) selected-data manner, based on the configuration strategy.

The Open APN provides an interface to expose Open APN management plane services to the Infrastructure Orchestrator or external management and orchestration systems. The case of multiple Open APN service providers managing Open APN devices will be considered in future work.

3. High-level Reference Architecture

To realize the wavelength-path and fiber-path services described in Section 2, we define the Open APN Wavelength Exchange (Open APN.WX) and the Open APN Fiber Exchange (Open APN.FX) as subsets of Open APN. Open APN.WX is a set of functions to realize the wavelength-path services while Open APN.FX is for fiber-path services.

Like Ethernet as Layer 2 and IP as Layer 3 in today’s packet networking, Open APN.FX and Open APN.WX can be combined in a layered structure to form a scalable multi-service network - i.e. Open APN.WX can be implemented on top of Open APN.FX.

Open APN.FX allows us to use a variety of optical transceivers, including non-DWDM-based ones, while it may not be suitable for long-distance communication. On the contrary, Open APN.WX will be suitable for long-distance transmission, while it narrows the choice of optical transceivers. Considering these merits and demerits of the two networks, using Open APN.FX as the underlying link layer of Open APN.WX (as shown below) will be a good approach. Figures 3-1(a) and (b) show the relationship between Open APN.FX and Open APN.WX in a shape of layer structure and network structure, respectively. The function blocks shown in Figure 3-1(b) (e.g., APN-T, APN-G, APN-I) are described in Section 3.1.1. Note that some fiber paths are provided by Open APN.FX between two of the functional blocks of Open APN.WX. In this case, a wavelength path provided on Open APN.WX passes through multiple fiber paths provided on Open APN.FX. Because each fiber path is a series of one or more sections (e.g., a fiber section plus an optical switching section plus another fiber section), identification of each section is needed.

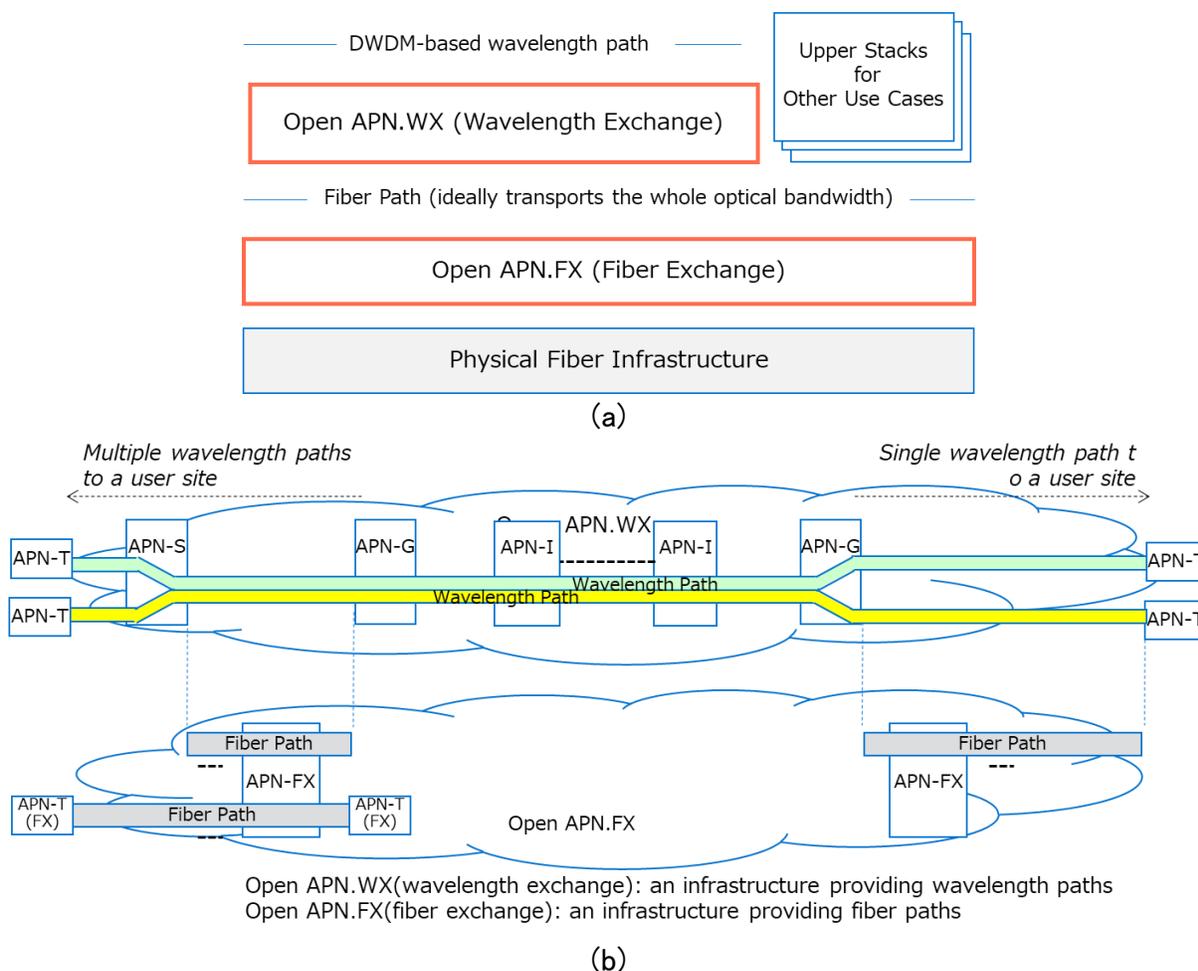


Figure 3-1: Relation between Open APN.WX and Open APN.FX: (a) layer structure, (b) network structure

Examples of service implementations that leverage Open APN.WX and Open APN.FX is shown in Annex I.

3.1. Basic Architecture

3.1.1. Open APN Wavelength Exchange (Open APN.WX)

Figure 3.1.1-1 shows a high-level reference architecture of Open APN.WX for PtP wavelength path services.

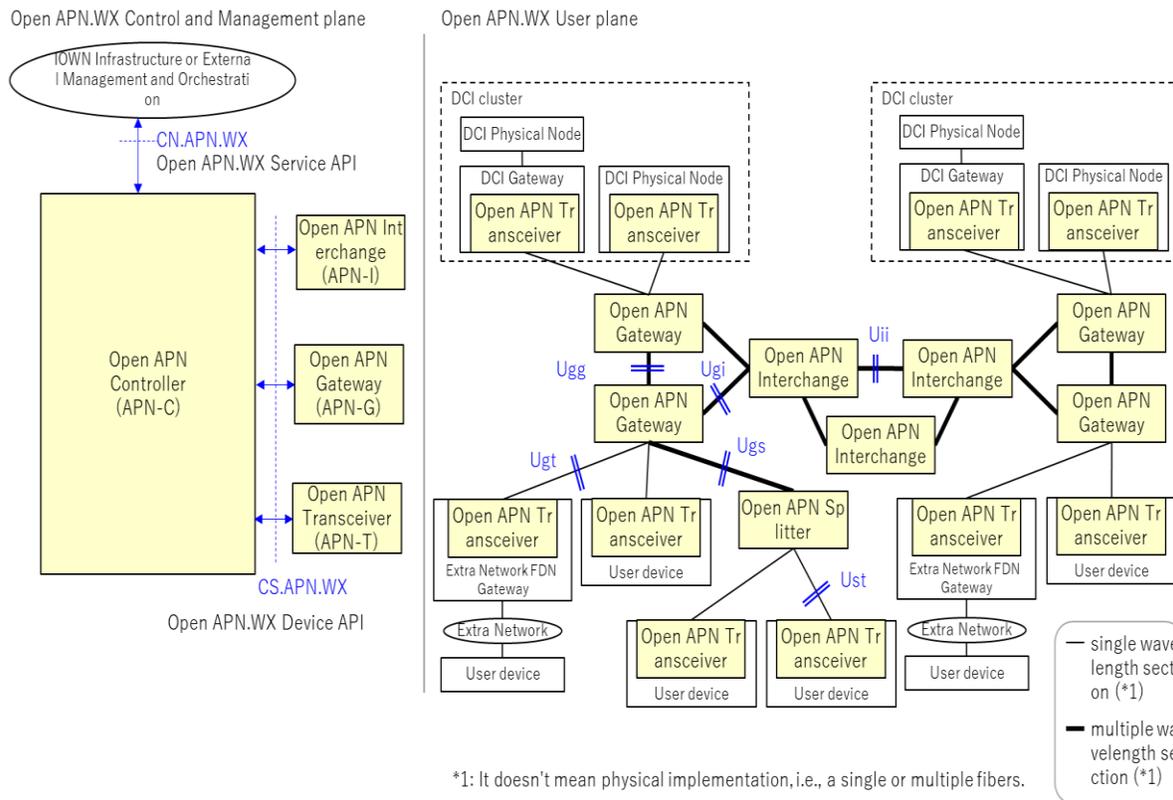


Figure 3.1.1-1: Open APN.WX High-level Reference Architecture for PtP Wavelength Path Services

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

APN-T is an endpoint for a wavelength path. It transmits and receives optical signals on a path utilizing a designated wavelength. The APN-T can be placed as a WAN interface of the 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. Note that APN-T is defined as an optical transceiver that terminates a wavelength path in Open APN.WX, and does not include APN-T(FX), APN-T(MP-H), or APN-T(MP-L) within its definition.

APN-G is a gateway on Open APN.WX for a wavelength path to permit optical transmission with the designated wavelength originating from APN-Ts. APN-G shall have (1) the provision of control channels to communicate with the connected APN-T or APN-S, and (2) admission control in the User plane. For wavelength path services, APN-G shall have (3) multiplexing/demultiplexing, (4) turn back, and (5) add/drop. The provision of control channels to communicate with the connected APN-T or APN-S (1) enables 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 the User plane (2) provides an entrance control of data transfer. It passes the optical signals only when their wavelengths correspond to the assigned wavelengths. Additionally, it blocks optical signals with an improper wavelength. The multiplexing/demultiplexing function (3) aggregates and de-aggregates optical paths. It aggregates optical paths from APN-T to the trunk network for the upstream direction. If there are multiple

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. Note that the multiplexing/demultiplexing function (3) may not be used to provide fiber paths. To realize low latency, the turn-back function (4) provides the shortest path between the APN-Ts connected to the same APN-G. The add/drop function (5) inserts the optical signal on a dedicated wavelength from an APN-T to an APN-I and extracts the optical signal on a dedicated wavelength from an APN-I to an APN-T. The APN-Ts are either located at the user's premises or a part of DCI that may be located inside the operator's network. Together with (4), this function provides a direct optical path through APN-G between an APN-T at the user's premise and that at DCI. The add/drop function optionally supports adding multiple wavelengths from an APN-S and dropping them to an APN-S.

APN-I is an interchange for wavelength switching at the midpoint of an Open APN optical path. To provide a direct optical path between any two endpoints, APN-I shall have (1) wavelength cross-connect and (2) amplification functions. The wavelength cross-connect function (1) enables each incoming optical path to be output to any direction (any port) without needing electronic processing. The amplification function (2) allows each incoming attenuated signal to be amplified to maintain transmission quality without needing electronic processing. Moreover, APN-I may have a (3) wavelength conversion function. The wavelength conversion (3) is an optional function that enables the assigned wavelengths of optical paths to be changed. Such conversion can mitigate the hurdles for providing direct optical paths. Please note that valid use cases and potential benefits of wavelength conversion are described in Section 6.1.5 (in Part II).

APN-S is a branch between APN-Ts and APN-G on Open APN.WX. This branching function enables APN-G to accommodate wavelength paths from APN-Ts by sharing the fiber path between APN-S and APN-G. The APN-S multiplexes the upstream optical signals from APN-Ts and forwards the downstream optical signals to reach their destination APN-Ts. By default, an APN-S should deliver only the assigned signal to each APN-T. However, in an implementation where the infrastructure operator can assure that each APN-T can't receive any unassigned signals or the communication of privacy is not required, the APN-S may not have the filtering capability. When APN-S has a wavelength multiplexing/demultiplexing function, whether APN-S supports only consecutive adjacent wavelength channels or any combination of wavelength channels between APN-S and APN-G is determined by the APN-S implementation selected according to the use case. APN-S might provide the function of in-line amplification of wavelength path, which compensates for the loss through the branching. APN-S in some implementations does not require an interface to be controlled and managed from APN-C.

APN-C is a controller with the functions of Open APN Control and Management plane. The APN-C has an admission control function 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.WX are defined as follows:

- Ugt: User plane interface between APN-G and APN-T.
- Ust: User plane interface between APN-S and APN-T.
- Ugs: User plane interface between APN-G and APN-S.
- 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.WX: 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.WX: Control and management plane interface for configuring and managing 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.

Ugs, Ugi, Ugg, and Uii are multi-wavelength interfaces for wavelength-path services. The Multi-Wavelength (MW) interface defined in OpenROADM MSA Optical Specification Version 5.1 is applied to Ugi, Ugg, and Uii.

Ugt is a single-wavelength interface.

The implementation examples of APN-I, APN-G, APN-S, and APN-T are shown in Annex C.

3.1.2. Open APN Fiber Exchange (Open APN.FX)

Figure 3.1.2-1 shows a high-level reference architecture of Open APN.FX for PtP fiber path services.

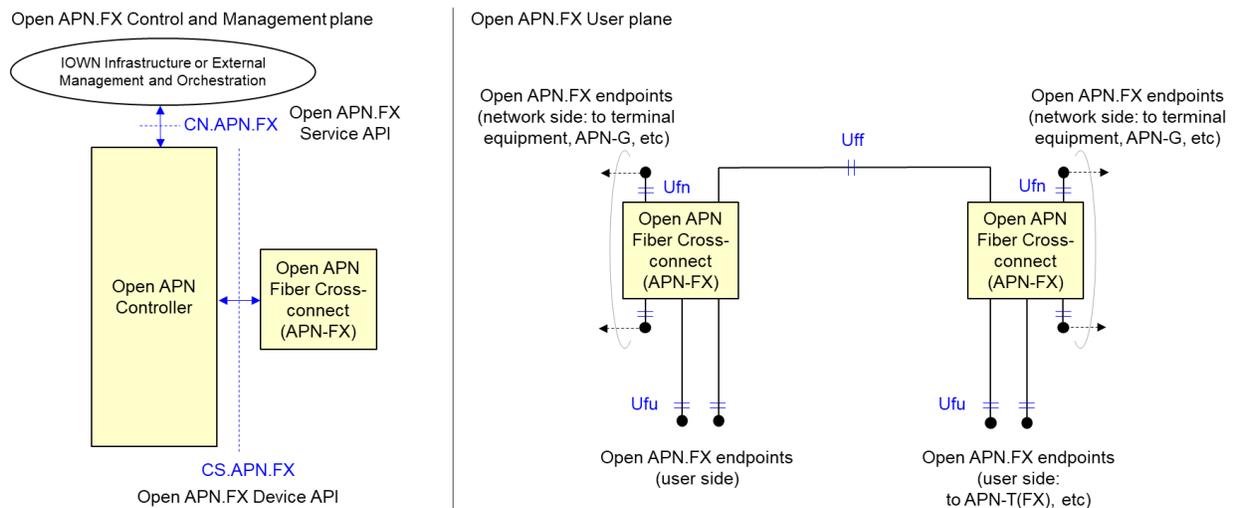


Figure 3.1.2-1: Open APN.FX High-level Reference Architecture for PtP Fiber Path Services

Open APN.FX consists of Open APN Fiber Cross-connect (APN-FX) and optical fibers.

APN-FX is a gateway for a fiber path to connect Open APN endpoints on Open APN.FX. APN-FX has two faces, the client side and the infrastructure side, and creates connections for pairs of ports on the client side and one on the infrastructure side. APN-FX may optionally provide a turn-back function, i.e., create connections between two client-side ports.

APN-T(FX) is an optical transceiver that terminates a fiber path. It can be a non-DWDM transceiver.

Interface reference points of Open APN.FX are defined as follows:

- Ufn: User plane interface at the network-side Open APN.FX endpoint.
- Ufu: User plane interface at the user-side Open APN.FX endpoint.
- Uff: User plane interface between APN-FX and APN-FX.
- CN.APN.FX: 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.FX: Control and management plane interface for the configuration and management of APN-FX. It is defined as Open APN Device APIs between APN-C and APN-FX.

Figure 3.1.2-2 shows an example of the Open APN in which Open APN.WX and Open APN.FX are structured in a layered manner. As shown in the upper side of the figure, Open APN.WX provides a wavelength path between two APN-Ts. Open APN.FX is located under the layer of the Open APN.WX, and it provides fiber paths. This shows three types of fiber path usage. The first one is between an APN-T to an APN-G. The second and third ones are between two APN-Ts or transceivers of the external functions. These fiber paths are established by APN-FX, which has a fiber cross-connect function.

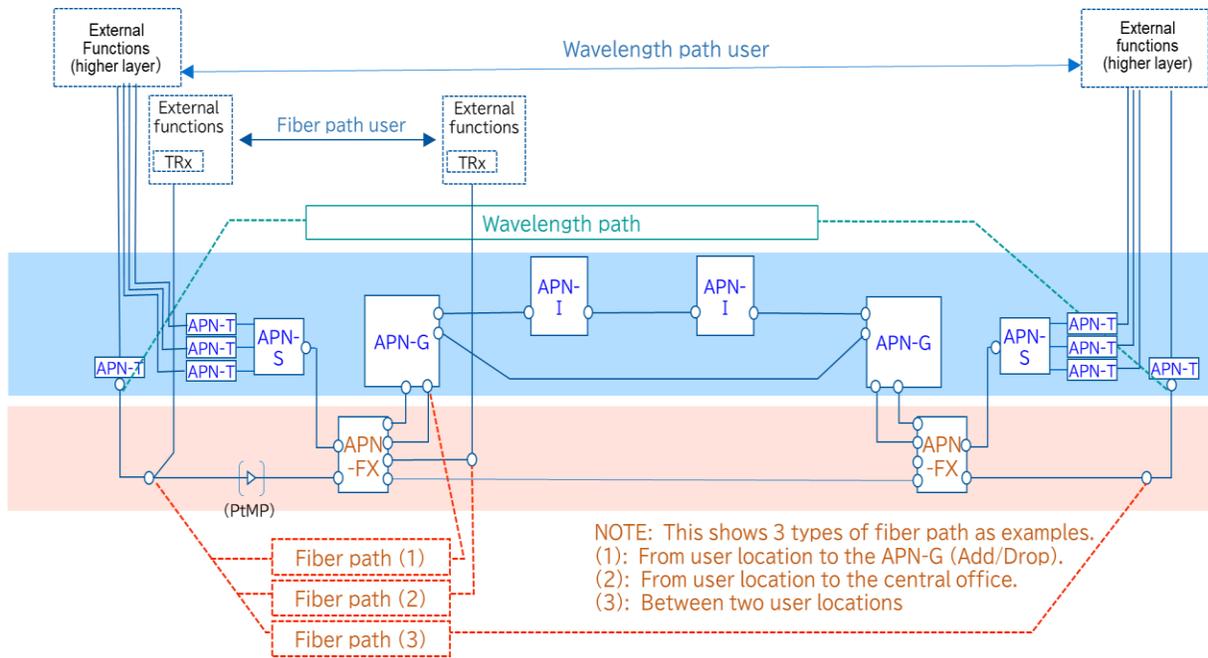


Figure 3.1.2-2: Example of the Relationship between Open APN.WX and Open APN.FX

3.2. PtMP Architecture

As explained in Sections 2.1.2 and 2.1.4, Open APN provides PtMP path services.

Point-to-multipoint (PtMP) is a communication topology characterized by connecting the hub and leaf nodes in a 1:N (point-to-multipoint) configuration, rather than a 1:1 (point-to-point) configuration. Point-to-multipoint broadcasts downstream signals to multiple locations and aggregates upstream signals from multiple locations to a single location. This topology is commonly deployed in access networks that accommodate a large number of users and has recently been adopted in other fields due to its improved speed and robustness. While there may be bandwidth limitations compared to Point-to-point configurations, operators can reduce the number of optical fibers and hub nodes and efficiently provide a network between multiple bases by considering these performance factors. This enables users to utilize the network at a lower cost and power consumption. Detailed references regarding the multiplexing method and related topics of point-to-multipoint technology are described in Annex F.

Some considerations for energy saving are described in Annex G, including the line-rate selection function.

Figure 3.2-1 shows an Open APN.WX architecture for PtMP wavelength path services. In the case of Open APN.WX, a single APN-T(MP-H), sends signals to multiple APN-T(MP-L)s. An APN-T(MP-H) aggregates signals coming from multiple APN-T(MP-L)s.

If necessary, APN-Ts with selectable PtP/PtMP can be used.

For supporting the practical implementation of PtMP wavelength paths on top of an Open APN.WX system based on current industry specifications (i.e., OpenROADM specifications), the following considerations are needed.

- There are several options on how to provide the combine/split point(s) for PtMP wavelength path (see Annex I). Such combine/split point(s) must be managed by APN-C for provisioning PtMP wavelength path. In early-adoption cases, the combine/split points may be located under some specific add/drop ports of APN-G, so that the APN-C can handle PtMP wavelength paths almost independently.
- Optical power and its dynamic change of signals from PtMP optical transceivers, i.e., APN-T(MP-L) and APN-T(MP-H), must be considered because higher (lower) optical power causes crosstalk to (from) other

wavelength paths, and a rapid change of optical power may cause transient response in optical amplification. It may also affect the QoT estimation in the optical-path design.

- The in-band communication channel between APN-T and APN-C (described in Annex C.3) should be applied to that between APN-T(MP-L) and APN-C as well, and the specification, e.g., wavelength, of the in-band communication channel should be as common much as possible.

The relationship between APN-S and an optical combine/split device needed for the PtMP transmission is for further study. Thus, Figure 3.2-1 does not include APN-S.

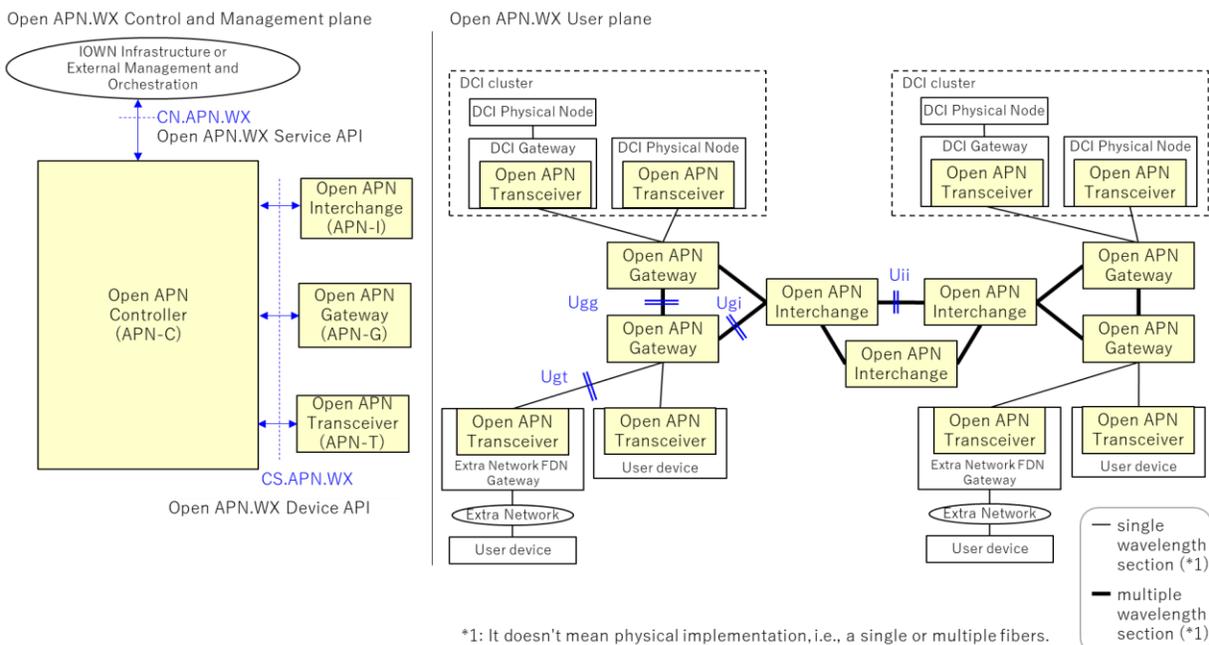


Figure 3.2-1: Open APN.WX High-level Reference Architecture for PtMP Wavelength Path Services

Figure 3.2-2 shows an Open APN.FX architecture for PtMP fiber path services. The fiber path between APN-FX and Open APN.FX endpoints (user side) is point-to-multipoint using one or more optical splitters. In the case of Open APN.FX, signals coming from one Open APN.FX endpoint (network side) are branched at a split point, such as a splitter, and sent to multiple Open APN.FX endpoints (user side). Signals sent from multiple Open APN.FX endpoints (user side) are aggregated at the split point and delivered to the Open APN.FX endpoint (network side). Interface reference points of Open APN.FX for PtMP are defined as follows:

- Ufn_mp: User plane interface at the network-side Open APN.FX with PtMP endpoint.
- Ufu_mp: User plane interface at the user-side Open APN.FX with PtMP endpoint.

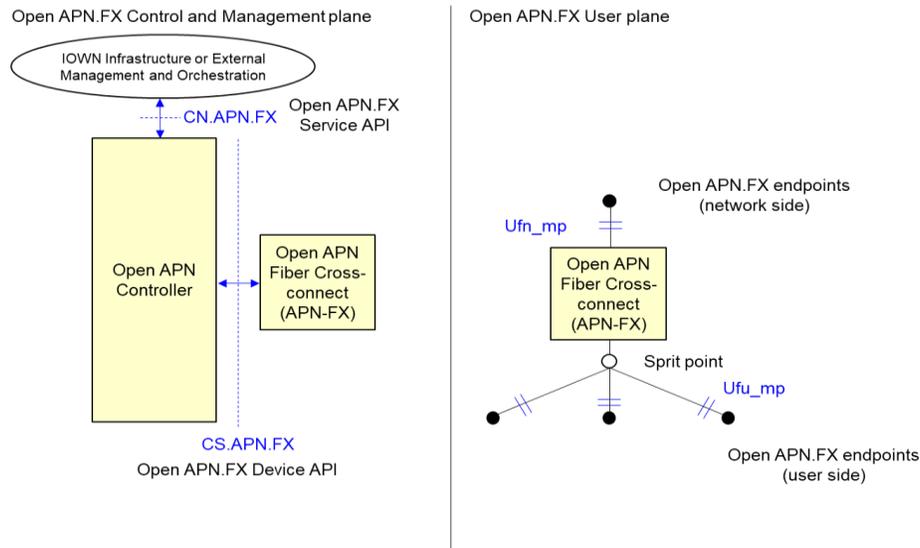


Figure 3.2-2: Open APN.FX High-level Reference Architecture for PtMP Fiber Path Services

In the PtMP wavelength path service, a PtMP wavelength path is assigned to multiple APN-Ts. The basic methodologies for constructing a PtMP wavelength path are the same as in Section 6.4.1 (in Part-II). A PtMP wavelength path assigning the same wavelength to multiple APN-Ts is required in some cases described in Annex I.1. In such a PtMP wavelength path, wavelength adjustments, including wavelength calibration, wavelength channel handover, and wavelength channel-locking, are required between a single APN-T(MP-H) and multiple APN-T(MP-L). In the PtMP fiber path service, the same wavelength assignment methodologies might be adopted for non-DWDM optical access.

Example implementation models of the PtMP architecture for Open APN.FX and Open APN.WX are described in Annex I.

3.3. Object Model for Control Plane Services

Figure 3.3-1 shows an object model for Open APN control plane services. The figure is focused on PtP wavelength path-related objects in Open APN.WX and PtP fiber path-related object in Open APN.FX. PtMP wavelength path-related objects in Open APN.WX and PtMP fiber path-related objects in Open APN.FX are for further study. 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 3.3-1. Open APN Interchange (APN-I), Gateway (APN-G), Splitter (APN-S), Transceiver (APN-T), and Fiber Cross-Connect (APN-FX) are introduced in Section 3.1. The Group of Optically Interconnectable Ports (GOIP) is introduced in Section 6.1 (in Part-II).

For Open APN.WX, an Open APN.WX user has one or more APN-Ts (Endpoints), which are authenticated and authorized before the Open APN wavelength path setup. An APN-T can send and receive an optical signal over an Open APN wavelength path. Furthermore, one GOIP is associated with a group of APN-G Endpoint Ports, and one APN-G Endpoint Port is associated with one or multiple GOIPs. APN-S is optionally introduced to provide multiple wavelength paths to a user site. In this case, APN-S Endpoint Ports are applied (instead of APN-G Endpoint Ports) to form the GOIP(s).

For Open APN.FX, an Open APN user, has one or more Open APN.FX Endpoints. An Open APN.FX Endpoints send/receive various (including non-DWDM) signals over an Open APN fiber path. Note that the Open APN wavelength path may use Open APN fiber path(s) as underlying fiber infrastructure. In this case, Open APN.WX User may connect to the Open APN.FX Endpoint to APN-G, APN-S, or APN-T (see Fig. 3.1.2-2).

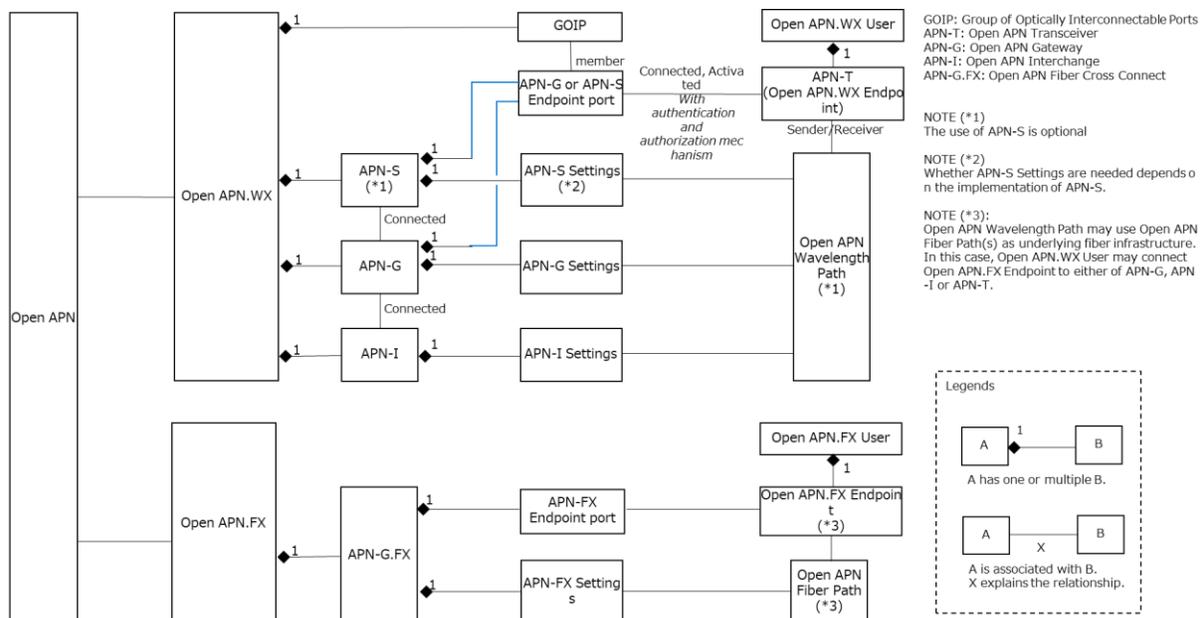


Figure 3.3-1: Object Model for Open APN Control Plane Service

3.4. Reference Network Models

Figure 3.4-1 shows a reference network model, where APN-S and APN-Ts are located at user sites. Such APN-S and APN-Ts may be user-owned. This figure focuses on PtP wavelength path service and PtP fiber path service. For the PtP wavelength path service type, the Open APN provides an optical wavelength path between APN-Ts. Such a wavelength path may be directly provided between user devices (direct connect service), or may be provided between gateways, which further enable QoS-aware mux/demux and forwarding (Flexible Bridging Service) over wavelength path(s).

The control channel between APN-T, located at a user site, and APN-C can be either (1) a communication channel provided by an external network, or (2) a communication channel that is multiplexed with the user-plane signal in the same fiber via WDM. The latter can be implemented based on OpenROADM optical specification 7.0 [OpenROADM optical spec], in which the optical specifications for the control signal as well as the user-plane signal have been defined between the network-side port of the remotely located transponder (i.e., the network-side port of APN-T in Open APN) and the user-side port of the ROADM node (i.e., the user-side port of APN-G in Open APN). See Section 6.7 for the relationship between the OpenROADM specification and Open APN Functional Architecture.

APN-S is either a passive element that does not require control/management from APN-C, or an active element that does require control/management from APN-C.

For the PtP fiber path service type, the Open APN provides an optical fiber path between two endpoints. The endpoint can be an optical transceiver defined as APN-T(FX) or another device, such as a sensing device.

Note that APN-FX is located between APN-G and APN-T or APN-S in Fig. 3.4-1. This means that APN-FX for providing fiber paths is used in combination with APN-G, APN-S, and APN-T for providing wavelength paths in this figure; Fig. 3.1.2-2 shows this relationship more clearly. However, it is not mandatory to use APN-FX to provide wavelength paths. Namely, APN-T can be connected to APN-G via APN-FX (as shown in Fig. 3.4-1) or directly connected to APN-G (not shown in the figure).

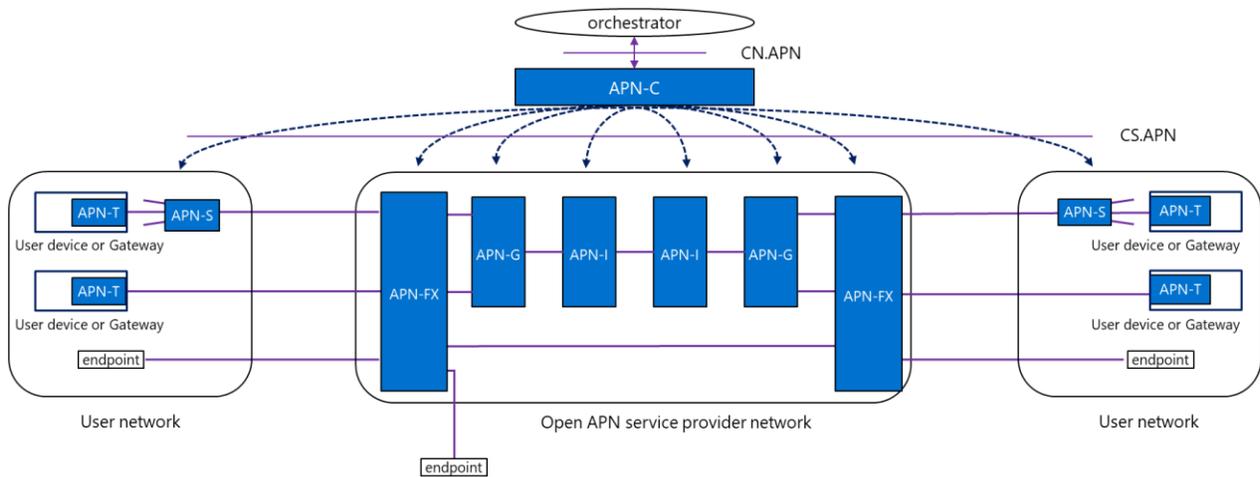


Figure 3.4-1: Example Network Reference Model

4. Conclusion

The 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. Architecting a new infrastructure is necessary to realize the Open APN.

This document describes overview, services, and high-level reference architecture of the Open APN. The Open APN architecture comprises Open APN Wavelength eXchange (Open APN.WX) for providing wavelength path service, Open APN Fiber eXchange (Open APN.FX) for providing fiber path services, and Open APN Controller (APN-C). The Open APN Transceiver, Gateway, Interchange, and Splitter (APN-T, APN-G, APN-I, and APN-S) are introduced as components of the Open APN.WX, while the Open APN Fiber-Exchange (APN-FX) and Transceiver for fiber path services (APN-T(FX)) are introduced as those of the Open APN.FX.

[Part-II] Control-and-Management-plane and User-plane Reference Architecture

Introduction of Part-II

This series of documents supersedes Open APN Functional Architecture Release 2 [APN FA R2].

Part-I describes the introduction with needs and goals, services, and high-level architecture of Open APN.

Based on Part-I, Part-II describes the Control and Management plane, and User plane reference of Open APN. This part shows detailed information about Open APN, including functions, network design, and operation.

Part-III provides Annexes. Each Annex provides a detailed description of the Open APN Functional Architecture, focusing on a specific aspect, as well as additional information.

5. Control and Management Plane Reference Architecture

APN-C is a controller that functions as the Open APN control and management plane. This section describes the control and management of PtP wavelength paths as well as PtP fiber paths. Future releases of this document will provide further details on the control and management of PtMP paths.

5.1. Control and Management Scope of APN-C

APN-C controls and manages APN-I, APN-G, APN-S, and APN-T, and sets up wavelength paths between two APN-Ts. It also controls and manages APN-FX and sets up fiber paths. APN-T and APN-S may be located at user sites and may be user-owned. In such cases, the Open APN service providers and users must coordinate to ensure QoT (Quality of Transmission) of wavelength paths. For path setup purposes, the Open APN service providers and users need to coordinate parameters (such as transmission mode on APN-T and wavelength) to be configured to set up a wavelength path between APN-Ts. The Open APN service providers and users must coordinate monitoring information (such as pre-FEC BER on APN-T and alarms) for fault and performance management of a wavelength path between APN-Ts.

This means that in addition to Open APN service provider network information, APN-C needs to maintain some user network information, as shown in Figure 5.1-1. APN-C must maintain APN-T-supported parameters and capabilities (such as supported wavelength range, transmission mode). Furthermore, APN-C must maintain access fiber parameters (such as OSNR) when part of the access fiber is located at a user's facility (not an Open APN service provider's facility). APN-C needs to maintain parameters to be configured on APN-Ts (and APN-S as needed) and maintain monitoring information of APN-Ts (and APN-S as needed). Note that APN-S can be either a passive element, which doesn't require remote control/monitoring, or an active element, which requires remote control/monitoring from APN-C. The vertical blue line in Figure 5.1-1 is the boundary between the user network (including user-owned access fiber) and the Open APN service provider network. This corresponds to Model#1 described in Annex E.1, with APN-T placed as the WAN interface of a gateway.

APN-C may directly control and manage APN-Ts (and APN-S as needed) for such a purpose. In other words, control and management of APN-T (and APN-S) are delegated to APN-C after network attachment and authentication. An alternative model is that a user network controller or application exists, and APN-C communicates through the user network controller or application.

As shown in the following list, when APN-C directly controls and manages APN-Ts (and APN-S), APN-C communicates with APN-Ts (and APN-S).

- APN-C obtains APN-T parameters/capabilities and access fiber parameters (and APN-S parameters/capabilities).
- APN-C configures APN-T (and APN-S).
- APN-C monitors APN-T (and APN-S).

Note that APN-T is typically implemented on a gateway, e.g., a DCI gateway or an extra network FDN gateway, which is defined in [IOWN GF DCI]. Unless there is a clear demarcation between APN-T and other parts of the gateway, authentication may be applied to the gateway as a whole, and APN-C may be privileged to control and manage the gateway as a whole.

Another option for the boundary between the user network and the Open APN service provider network is to place the boundary at the host interface of APN-T. This naturally allows direct control and management of APN-Ts from APN-C. This corresponds to Model#2 described in Annex E.1. This model requires a clear demarcation between APN-T and other parts of gateways. The APN-C mentioned in this section applies to both Model #1 and #2 in Annex E.1.

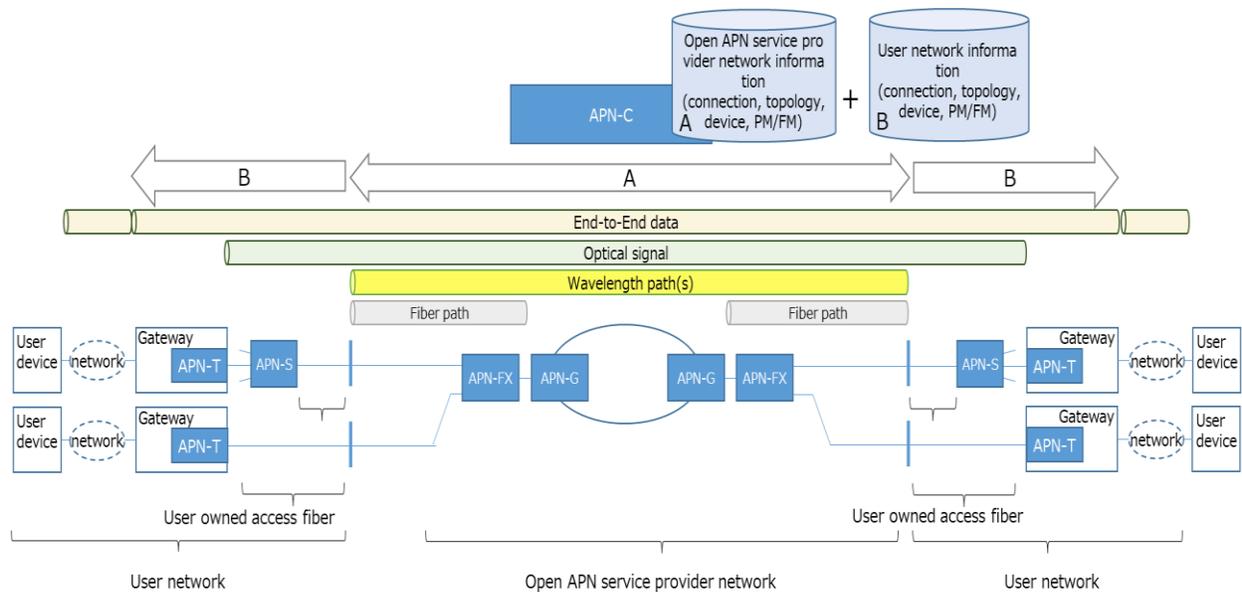


Figure 5.1-1: An Example Control and Management Scope of APN-C

Further work is required when APN-Is/APN-Gs/APN-FXs are in the user network, such as controlling and managing APN-Is/APN-Gs/APN-FXs located in user networks.

5.2. APN-C Functions and APIs

Figure 5.2-1 shows an example reference of the APN-C functional model. The APN-C is a logical entity. All the functions of APN-C can be implemented together in a single box or separately in multiple boxes. As described in Section 5.1, APN-C maintains not only Open APN service provider network information, but also user network information. APN-C may be privileged to control and manage user network devices directly. A user network device is APN-T, or it may be a gateway (FDN/DCI gateway) if there is no clear demarcation between APN-T and any other part of a gateway.

APN-T can be controlled and managed from APN-C via the gateway using an out-of-band or in-band communication channel between APN-C and the gateway. Or, if an optical transceiver for control signals is integrated in APN-T, it can be controlled and managed from APN-C directly by using an in-band communication channel between APN-C and APN-T. See Annex C.3 for examples of implementing the in-band communication channel for APN-T and the gateway. The out-of-band and in-band communication channels must be secure.

Depending on the implementation, APN-S may be a passive element without a control and management interface. In this case, APN-C doesn't control and manage APN-S.

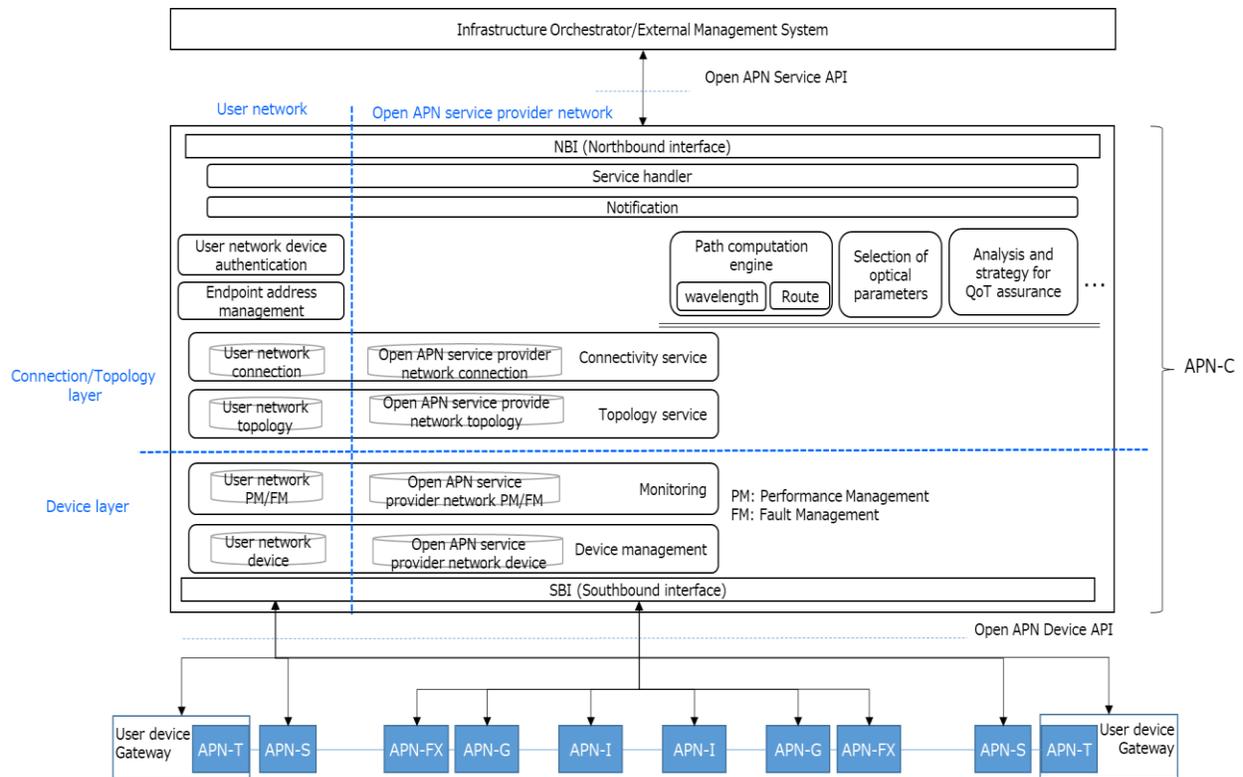


Figure 5.2-1: An Example Reference of APN-C Functional Model

Regarding Control and Management (C/M) using the in-band communication channel for APN-T in the user site, i.e., remote APN-T, the following features are required.

- Commonality with out-band C/M: Implementation of the remote APN-T C/M function shall be as common as possible between in-band and out-band.
- Independence from user-plane signal format: As the remote APN-T C/M must be applied to various types of user-plane optical signals, the C/M procedures must be independent of the user-plane optical signal. It is desirable to support single-fiber and dual-fiber transmissions in the same manner.
- Security: Since APN-T and the host device (i.e., the external gateway) are placed outside the service provider's building, ensuring security in the exchange of C/M information is necessary.

APN-C may have the extended Cooperative Transport Interface (eCTI) [IOWN GF IMN] as an interface for mobile systems, as shown in Section 5.5.1.

For control purposes, APN-C has the following functions.

- User network device authentication: a mechanism to authenticate the user network device.
- Endpoint address management: a mechanism to maintain endpoint addresses, which is in the common addressing space between the Open APN service provider and the user. The endpoint address is specified in a path setup request.
- Device management: a mechanism to maintain devices. The device management function should support the management of devices in the Open APN service provider network and the remote management of devices, such as APN-T and APN-S, in user sites, after authentication. The service provider or the user can own the devices in user sites. Device management includes management of device configuration and configuration history.
- Topology service: a mechanism to maintain topology and to provide topology information. The topology service function should maintain not only the Open APN service provider topology but also a part of the user

network topology after authentication, so that APN-C can control and manage end-to-end optical connectivity across service provider and user networks.

- **Connectivity service:** a mechanism to maintain connectivity service (i.e., service provided by connection through path setup request) and to provide connectivity information (e.g., information of connected endpoints). A connectivity service is provided based on path setup requests. Furthermore, updates may be performed to modify the parameters of existing paths or reroute the existing paths when QoT is unsatisfied using redundancy mechanisms. The update may be triggered by an external mobile system via eCTI; see Section 5.5.1 for how eCTI is used in Open APN.
- **Path computation engine:** a mechanism to compute the route and wavelength for wavelength paths. The path computation engine selects the transmission mode to satisfy the QoT of wavelength paths. Technologies such as GNP_y may be used to estimate the QoT of wavelength paths computed. Techniques to estimate QoT more accurately for network resource optimization are given in Annex E.5.
- **Selection of transmission mode:** a mechanism to select transmission/reception parameters for optical transmission devices (APN-T).

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

- **Network attach API:** The Infrastructure Orchestrator or user applications request APN-C to make a network attach of a user network device to the Open APN. In response to the request, APN-C authenticates and authorizes the user network device and gets information of (A) endpoint address and user ID, (B) supported wavelength range, and (C) supported transmission capability and parameters. Then the network attach of a user network device is complete.
- **Path design service API:** The Infrastructure Orchestrator or user applications request APN-C to design a path before creating it. The actual path setup is not executed. The request specifies the addresses of path endpoints and the user requirements regarding bandwidth, latency, jitter, and redundancy.
- **Path creation service API:** The Infrastructure Orchestrator or user applications request APN-C to create a path between attached user network devices. The request specifies the addresses of path endpoints and the user requirements regarding bandwidth, latency, jitter, and redundancy. For reservation (actual path-setup is executed later), the request includes start and possibly end times.
- **Path deletion service API:** The Infrastructure Orchestrator or user applications request APN-C to delete a path. The request specifies the addresses of path endpoints.
- **Path update service API:** The Infrastructure Orchestrator or user applications request APN-C to update a path. The request specifies the addresses of path endpoints and the user requirements regarding bandwidth, latency, jitter, and redundancy. This is used to modify a path according to new requirements or to reroute the path.

Open APN Device APIs for control purposes as a southbound interface of the APN-C consists 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-FX, APN-G, and/or APN-I of the path route information and directs the 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-FX, APN-G, and/or APN-I of the path route information and directs a deletion of the configuration of path cross-connect.
- **Path update configuration API:** APN-C notifies APN-G and/or APN-I of path route information and directs the setting of the configuration of path cross-connect. In addition, APN-C may notify APN-T of the wavelength and transmission/reception parameters if the wavelength changes.

For management purposes, APN-C has the following functions.

- **Monitoring:** a mechanism to monitor QoT information in real-time and determine whether user requirements about QoT are satisfied for each wavelength path. Path update is requested when user requirements are not satisfied based on real-time QoT monitoring.
- **Closed loop for QoT assurance:** a mechanism to support collection, analysis, decision, and execution, as a closed loop (including monitoring) for assuring QoT in the 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 result of analysis, e.g., optimized network configuration and settings. Open APN service providers may also 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 consists of the following.

- QoT management API: APN-C notifies an external entity of the QoT information. The external entity conducts storage, processing, and all decisions based on the QoT information. An external entity notifies APN-C of the analysis result, e.g., optimized network configuration and settings for QoT assurance.

Open APN Device APIs for management purposes as a southbound interface of the APN-C, which consists of the following.

- Quality monitoring API: APN-C requests APN-T, APN-S (if it is an active element), APN-G, APN-I, and APN-FX to send QoT information in a defined data model format.
- Quality assurance API: APN-C notifies APN-T, APN-S (if it is an active element), APN-G, APN-I, and APN-FX of the device configuration and settings for QoT assurance in a defined data model format.

5.3. A Recommendation Set of Southbound Interfaces

Figure 5.3-1 shows a recommended set of Southbound interfaces (SBIs) of APN-C. The APN-C sends/receives information through the SBIs to/from APN-I, APN-G, APN-FX, APN-S (if it is an active element), and APN-T for control and management of them. As a part of the Open APN architecture, APN-C should have open interfaces as SBIs with a fully or partially disaggregated architecture [Partial Disaggregation]. Given the existing open interfaces (OpenConfig [OpenConfig], OpenROADM [OpenROADM], and TAPI [TAPI]) and the current technical trend of disaggregated architectures, there are three options for SBIs as shown in Figure 5.3-1.

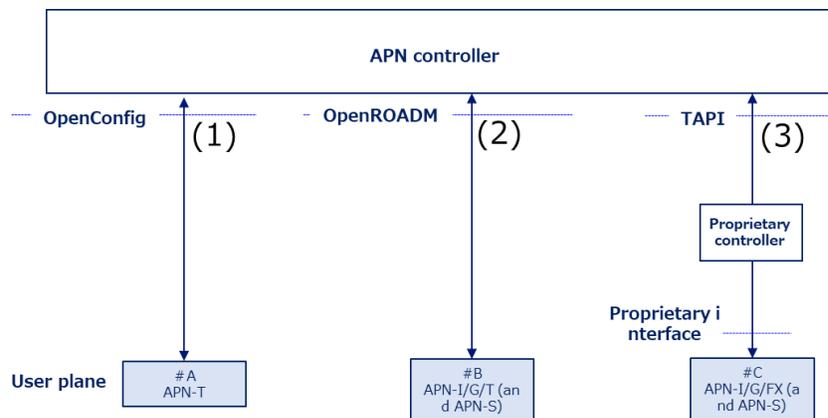


Figure 5.3-1: Recommendation Set of Southbound Interfaces (SBIs) for APN-C

- Option (1): OpenConfig (OC) for APN-T

OC-compliant APN-T is controlled and managed through OC. Since OC covers protocols of RESTCONF (JSON encoding) and gRPC (ProtoBuf encoding) that can provide shorter processing time than NETCONF (XML encoding) [gRPC SDN], it may have an advantage for streaming telemetry.

- Option (2): OpenROADM (OR) for APN-I, APN-G, APN-S, and APN-T

OR-compliant APN-I, APN-G, APN-S, and APN-T are controlled and managed through OR. This option can be expected to have a simple implementation due to the single open interface at SBI.

For those who need to control and manage OC-compliant APN-T through OR, it could be done with the help of a data model translation layer, which translates data models between OR and OC. The data model translation layer could be implemented in the APN-C or APN-T. In the use of the OR data model, APN-C shall comply with OR Yang model version 13.0 (or a later version) as it supports IOWN requirements; see the latter part of Section 6.2.

- Option (3): TAPI with proprietary controller for APN-I and APN-G

APN-I, APN-G, APN-FX, and APN-S with a proprietary interface are controlled and managed through TAPI with the help of a proprietary controller, which mediates TAPI and the proprietary interface. This option assumes a partially disaggregated architecture and could apply to migration or as a near-term solution. However, from the viewpoint of an Open APN architecture, APN-I, APN-G, APN-FX, and APN-S should have open interfaces as Options (1), (2), and (3). Note that APN-S may be a passive element without a controller interface or an active element with a controller interface.

5.4. Example Procedures for Controllers

Ideally, APN-C should manage all procedures within the lifecycle of APN services, such as designing, path provisioning, monitoring, and device management.

The following are some typical procedures of APN service lifecycle management supported by APN-C:

(1) Network designing

Before new network devices (APN-T/G/I) are deployed and physically connected, APN-C should support network designing functions to estimate if future APN.WX paths with certain QoS grades can be established after these deployments.

This should be an individual function using a specific calculating tool or simulation environment and should work without connecting to a real network environment.

Note: The result of network designing may not be accurate in some cases, and the design model can be improved by real network operating data in the long term.

(2) Registration of the user network device

Once user network devices are attached to the Open APN, APN-C should authenticate user network devices, register user network devices and links, and maintain endpoint addresses. Note that the user network device is APN-T or may be a gateway. While further consideration of details is required, an outline of the setup procedure could look as follows.

Note: Secure control channel between APN-C and the user network device must be established.

1. APN-C receives user network device registration and authentication requests.
2. APN-C authenticates user network devices.
3. APN-C obtains user network device capabilities and access fiber parameters (where necessary).
4. APN-C registers user network devices and links to its database, as well as assigns relevant addresses/IDs, including endpoint addresses.
5. APN-C replies, including the endpoint address

Registration should be automatically performed when APN-C controls the user network device through an in-band communication channel. This plug-and-play feature eliminates the necessity of sending technicians to the user site and shortens the lead time for starting the service. See Annex E for the detailed sequence to realize this.

(3) Wavelength path setup

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

Note: APN-C may get candidates for QoT requirements from external control and management systems beforehand.

1. APN-C receives path setup requests, including a pair of endpoint addresses, as well as bandwidth, delay, jitter, and redundancy requirements.
2. APN-C mediates parameters between endpoints. APN-C performs path computation and transmission mode selection. APN-C selects route, wavelength, and transmission mode to meet service requirements.
3. APN-C configures APN-G//FX (route/wavelength) and user network device (wavelength/transmission mode) and establishes a path.
4. APN-C confirms that a path is established correctly and starts monitoring.
5. APN-C replies, including path ID.

When APN-C controls the user network device with an in-band communication channel, it is desirable that the path setup and update requests can be sent via the communication channel, eliminating the necessity of using an external network to send such requests. See Annex E for an example sequence to realize this.

(4) Real-time control to ensure the QoT requirements

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

1. APN-C gets QoT information from APN-G/FX.
2. APN-C compares the acquired QoT information with the QoT requirement and analyzes whether the quality is ensured. Here, the APN-C may also consider the quality of information of the wireless section of the network via the extended Cooperative Transport Interface for Open APN (eCTI) [IOWN GF IMN].
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 the user network device.

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

(5) Advanced lifecycle management by Network Digital Twin (NDT)

APN-C may use NDT to support lifecycle management of the Open APN service.

NDT is a digital representation of Open APN; it contains (but is not limited to) information of physical and logical topology, device configuration, performance-monitoring data of the current network, and specification of new components to be deployed.

It could enhance other APN-C functions, such as QoT estimation and network optimization, and could also be used as a visualization and monitoring method of Open APN.

The following key features are considered to be included in the NDT of Open APN.

1. NDT should continuously synchronize with the real Open APN and provide a high-fidelity simulation environment.
2. Before making any changes on the real network, the performance of new paths and their effect on the current network should be simulated in the NDT environment.
3. After the physical link of a new path is established, the QoT data of the physical link should be measured and fed back to the NDT environment to improve future design accuracy.
4. If a future failure is predicted to occur with techniques like (but not limited to) measured time validation of QoT and a simulation in NDT environment, a recovering action that is validated in NDT should be triggered through the NDT on the real network before the failure occurs to prevent a service impact in advance by (manually or automatically) modifying configurations or do a re-designing of path.
The failure here includes, but is not limited to, equipment issues, link down, and QoT deterioration.

5.5. Telemetry

The streaming telemetry function can be implemented in the Open APN controller and Open APN devices, and the information of attached devices can be collected using this streaming telemetry function. Compared with conventional monitoring schemes, streaming telemetry can access the device information much more efficiently, including shorter monitoring periods and more relieved workloads for the Open APN controller.

For each Open APN device, the telemetry information can be transmitted in either of two modes. (a) out-of-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 optional (See Figure 5.5-1).



Figure 5.5-1: 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, APN-I, and APN-FX). A telemetry engine will be implemented in Open APN devices (APN-T, APN-G, APN-I, and APN-FX) to send the telemetry information to APN-C (See Figure 5.5-2). Note that APN-C collects the telemetry information of APN-S when APN-S is implemented as an active element.

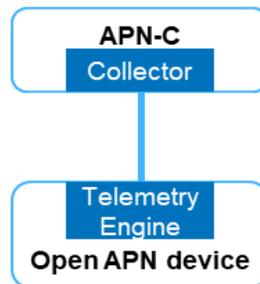


Figure 5.5-2: Collector and Telemetry Engine

Figure 5.5-3 depicts two reference models of streaming telemetry in an Open APN controller and attached Open APN devices. As one of the functions of an Open APN controller, streaming telemetry can collect information from Open APN devices via open interfaces.



Figure 5.5-3: Streaming Telemetry and Two Collector Configurations

In Figure 5.5-3(a), a streaming telemetry collector is installed in the Open APN controller. Such a collector is responsible for sending subscriptions to the related Open APN devices to start a monitoring session, and it is also responsible for collecting the data obtained from the devices. On the other hand, in Figure 5.5-3(b), another

streaming telemetry collector is depicted. Such a collector is composed of two parts. The left part is responsible for sending subscriptions to the related Open APN devices to start a monitoring session. The right part (server) is responsible for collecting the data obtained from the devices. The configuration functionality is installed in the Open APN controller, and the data server section can either be installed in the Open APN controller or another server.

The details of the above reference models are listed.

- The open interface protocols include gNMI and gRPC. [gNMI][gRPC]
- The operation modes include sampled mode and on-change mode. With the sampled mode, the monitored Open APN devices deliver data regularly and repeatedly. With the on-change mode, the monitored Open APN devices deliver data only when the defined threshold is triggered.
- The monitoring interval can be second-level (with state-of-the-art technology).
- A collector can accommodate multiple telemetry engines, as Figure 5.5-4 shows.

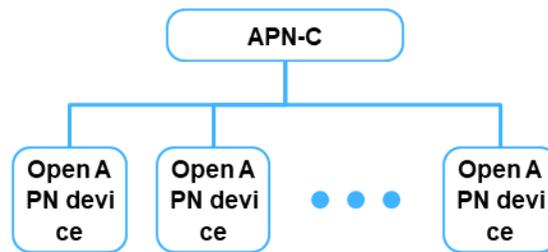


Figure 5.5-4: CAPTION HERE

5.5.1. Extended Cooperative Transport Interface for Open APN

Extended Cooperative Transport Interface for Open APN (eCTI) [IOWN GF IMN] can be considered a telemetry type. This is because multiple kinds of mobile information delivered via eCTI play the same role as QoT information from telemetry regarding data that the Controller uses for analysis and control.

Figure 5.5.1-1 shows a configuration using eCTI between APN-C and mobile systems. For APN-C, the actual equipment to connect via eCTI depends on the requirement of real-time control. As an example configuration, APN-C includes a real-time control function, which plays the role of the real-time control of APN-G, APN-FX, and/or APN-T, respectively, to assure QoT. Annex D.3 shows an example of eCTI applications and configurations.

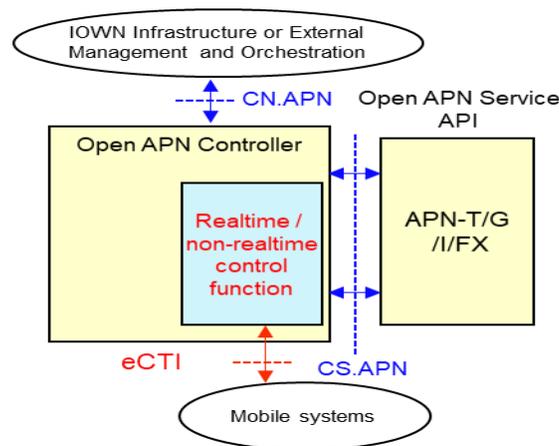


Figure 5.5.1-1: Example of Controller Configuration for eCTI

Table 5-1 shows the examples and expected benefits of the eCTI.

Table 5-1: Examples of Applicable Targets for eCTI

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

5.5.2. Real-time Transmission Quality Measurement

As noted in Annex K, one of the advantages of digital transmission technology is that 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 in the Open APN, such parameters can be measured and monitored for dynamic optical path provisioning.

One of the most critical transmission quality parameters is BER, which straightforwardly reflects the transmission quality and indicates the availability of the received signal. Transmission quality can be monitored by measuring the pre-forward error correction (pre-FEC) BER. All error bits can be corrected if the measured pre-FEC BER is below the defined FEC limit. 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-set up the optical path.

6. User Plane Reference Architecture and Wavelength Management Framework

As the aim of the Open APN is to provide end-to-end optical paths (i.e., wavelength paths and fiber paths), its User plane must be carefully designed considering constraints in the physical layer (e.g., maximum transmission distance of each optical signal and maximum available number of wavelengths in each optical fiber). In other words, defining the User plane architecture is essential to take full advantage of Open APN features. Section 6.1 defines the Group of Optically Interconnectable Ports (GOIP) in Open APN.WX for such a purpose. It then describes the User plane reference architecture of the Open APN.WX using GOIP and how to leverage the ultra-wideband optical transmission technologies in Sections 6.2 to 6.4. Section 6.5 describes the support of the one-span PtP wavelength path service.

6.1. Group of Optically Interconnectable Ports (GOIP)

To realize a highly scalable and interoperable Open APN.WX under physical constraints such as the limited number of wavelengths and reachable distance, the Group of Optically Interconnectable Ports (GOIP) is defined in the Open APN.WX User plane architecture. The relationship between GOIP(s) and APN-C is flexible. Typical cases include the following.

- A relatively small network (e.g., within a city) is constructed with a single GOIP. It is controlled by an independent APN-C (owned by a local operator in the city, for example).
- An APN-C takes care of several GOIPs (e.g., covering several cities). This makes it easier to optimize inter-GOIP connections.

6.1.1. Purpose and Definition

GOIP is defined as a group of optical ports for which a direct optical connection through a wavelength path can be established (i.e., reachability is supported) between any two ports. Here, the port means a connection interface between an Open APN Transceiver (APN-T) and the access link, and the direct optical connection means an optical connection without any opto-electro-opto (OEO) conversion in the middle. The connection can be point-to-point (PtP) or point-to-multipoint (PtMP), while a multipoint-to-multipoint (MPTMP) connection is for further study.

The purpose of defining GOIP is to clarify where direct optical connections are available without being limited by the current network segmentation (i.e., access, metro, and core). The following benefits are expected through the use of GOIP for designing and managing Open APN.WX.

- To guarantee the following properties for any intra-GOIP connections.
 - Minimum (i.e., light-speed) latency
- Minimum power consumption (i.e., no regeneration that causes additional power)
 - Pure wavelength path (to carry various types of signals independently from the modulation format, as long as the signal meets the wavelength-path characteristics)
- To minimize the power and latency of the network that comprises multiple GOIPs.
 - This will be realized by visualizing and optimizing additional power and latency at inter-GOIP connections (i.e., 3R and/or wavelength conversion).
- To limit the area of path computation to a practical size.

In GOIP, at least one route 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. The transmission performance may not be guaranteed when choosing a detour path. There is a possibility that you cannot establish a direct optical connection when the shortest route is not available due to any reason, such as a shortage of wavelength resources, a fiber cut, or an equipment failure. Given these events, a GOIP may be designed with the following policies, 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,
- Keep the “call setup loss probability” (i.e., the probability of failing 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 signals with a bitrate over the assigned specification between any ports of GOIP. However, this is still possible when the transmission distance is relatively short. Therefore, after assigning the wavelength and 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 path (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 device (or extra-network FDN gateway) must employ multiple optical ports to communicate with multiple user devices simultaneously. A realistic assumption is that each user device communicates with one or a few user devices simultaneously, so it has one or more optical ports.

Dynamic optical-path computation is done within a GOIP.

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

- Network design technologies to minimize the total power consumption of the 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 6.1.1-1 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.

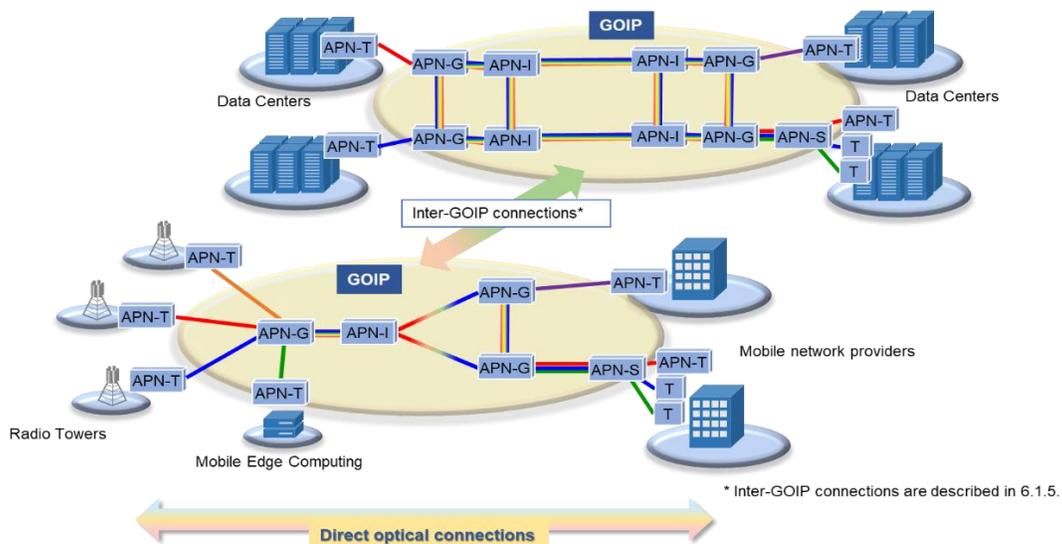


Figure 6.1.1-1: Schematic Diagram of GOIP

6.1.2. Grouping Types of GOIP

The previous section introduced the concept of GOIPs. This section discusses the two grouping types for GOIPs: "geography-oriented grouping" and "APN-T-oriented grouping."

- "Geography-oriented grouping" divides the Open APN into several regions geographically. This is similar to conventional optical networks offered by several vendors, and it has the advantage that operators can easily manage the wavelength resources of the Open APN in multi-vendor environments. For example, one can imagine a ring network with six nodes, each distant from 80 km [ITU-T G.Sup39].
- "APN-T-oriented grouping," on the other hand, is defined by the set of ports that an APN-T can transmit to, and is a grouping method that aims for the ultimate and ideal direct optical path management of the Open APN in multivendor environments. It is possible to achieve ideal wavelength resource utilization at any time without dependence on the bitrates of APN-T and geographic factors.

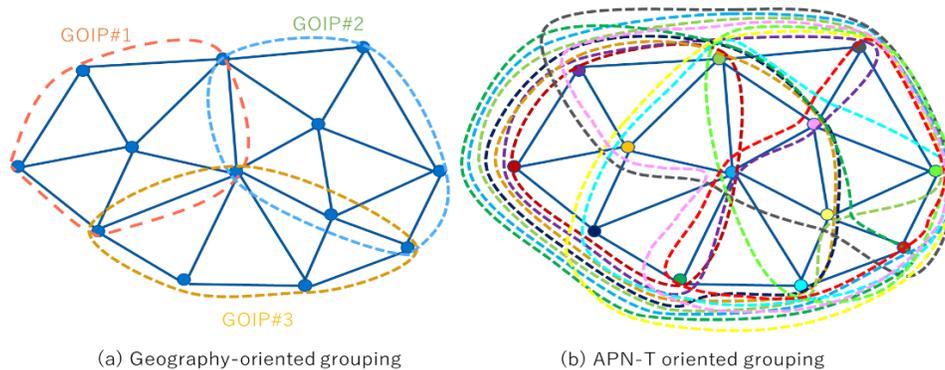


Figure 6.1.2-1: Grouping Types of GOIP

Table 6-1: Comparison of the grouping types of GOIP

	GEOGRAPHY-ORIENTED GROUPING	APN-T-ORIENTED GROUPING
Path Computing Complexity	Can be calculated within a single GOIP.	Need to consider other GOIPs' path status.
Transmission Restriction	Restricted not only by transmission performance, but also by the border of GOIP. An optical connection may be terminated once at the border of GOIP to resolve wavelength assignment.	Restricted only by transmission performance.
GOIP for multiple bitrates	Geographic boundaries may be different depending on the bitrates. If you want the same boundary regardless of the bitrates, the maximum transmission distance may not be obtained. However, the maximum distance at each bitrate can be obtained if direct optical paths can be connected in Inter-GOIP, as discussed in Section 6.1.3.	GOIP can be considered for each bitrate because APN-Ts have various bitrates.

Multi-vendor Operation	It is easy to implement even in the early stages of the Open APN.	It is difficult to implement in the early stages of the Open APN. At the ultimate, final stage of the Open APN (fully opened network), it is no longer an issue.
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6.1.3. Design Criteria for the Geography-oriented Grouping

For the short-term and mid-term deployment of the Open APN, it is recommended to assume the geography-oriented grouping when designing GOIPs because of its simplicity. A GOIP can be designed with the following criteria, for example.

1. Define the standard bitrate (e.g., 100 Gbps).
2. Create a GOIP as a physical network (i.e., a set of nodes and links) to establish a direct optical connection with the standard bitrate for the longest path.
 - To check if the direct optical connection can be established for the longest path, a signal-to-noise ratio (SNR) design must be done in advance.
 - It is necessary to consider the secondary path (i.e., detour path) at least. Tertiary and quaternary paths are also considered depending on the required availability and reliability. "The longest path" should be determined, including those detour paths.

Assigning different bitrate wavelength paths from the standard bitrate is permitted in the geography-oriented grouping. When applying geography-oriented grouping, inter-GOIP connections can be realized using the methods described in Section 6.1.5.

6.1.4. Design Criteria for the APN-T-oriented Grouping

APN-T-oriented grouping enables longer GOIP as it is not limited to a geographical region and only considers APN-T characteristics. Therefore, it minimizes path fragmentation in the broader network. On the other hand, it requires central control of the wider network and very complex management. Hence, the design criteria of APN-T-oriented grouping are for further study.

6.1.5. Inter-GOIP Connections

In the case of using high bitrate APN-T (e.g., 400 Gbps and more) with geography-oriented GOIPs, inter-GOIP connections become more necessary because of the limited transmission distance. An Inter-GOIP connection is defined as the connection between multiple GOIPs. It may be optical or electronic, involving OEO conversion. Figure 6.1.5-1 illustrates the structure of inter-GOIP connections for such cases. Here, we assume there are three GOIPs whose standard bitrate is 400 Gbps in the Open APN, and consider 100 Gbps and 400 Gbps end-to-end wavelength paths. The 400 Gbps end-to-end wavelength path must be divided into three wavelength paths because the standard bitrate of the GOIPs is set to be 400 Gbps. On the other hand, the 100 Gbps end-to-end wavelength path can be set up without any relay APN-Ts because its transmission distance is longer than 400 Gbps. Thus, the point of introducing inter-GOIP connections is that it is possible to set up direct wavelength paths across the multiple GOIPs as long as the transmission performance can be guaranteed and the wavelength resource can be allocated in every GOIP. This minimizes cost and power consumption by eliminating unneeded APN-T at the border of GOIPs.

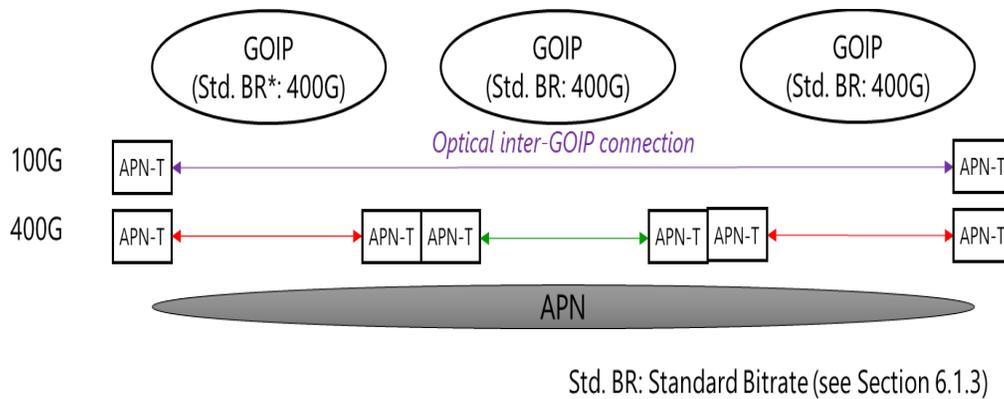


Figure 6.1.5-1: Inter-GOIP Connections

Another advantage of inter-GOIP is that it enables the direct accommodation of user data across multiple GOIPs. Figure 6.1.5-2 illustrates four cases: the first case has a repeater at the border of two GOIPs, as shown in Figure 6.1.5-2(a). We assume that the user data from source APN-T at left(right) GOIP is transmitted to destination APN-T at right(left) GOIP. When user data crosses the GOIPs, optical signals are once received at the APN-T of the repeater, and again optical signals are transmitted from another APN-T at the repeater to the GOIP on the right(left) side. Note that there are several repeater options, including a traditional OEO repeater. If the OEO repeater is used, an optical path is terminated within the repeater. An end-to-end connection can be established through the inter-GOIP connection of two wavelength paths in the two GOIPs. As a repeater has two APN-Ts, different wavelengths can be used in such different GOIPs, i.e., the wavelength may be converted within a repeater. Also note that such repeaters can be deployed at the edge of each GOIP, as shown in Figure 6.1.5-2(b). The third case shown in Figure 6.1.5-2(c) is that the two GOIPs are connected via a dark fiber, Ethernet, or OTN connection. When using dark fiber, the two GOIPs may be housed in different buildings or on different floors. The last case shown in Figure 6.1.5-2(d) is that a single end-to-end direct path accommodates user data from multiple users. In this case, user data from multiple users is accommodated in a single Ethernet or OTN by Flexible Bridging Services.

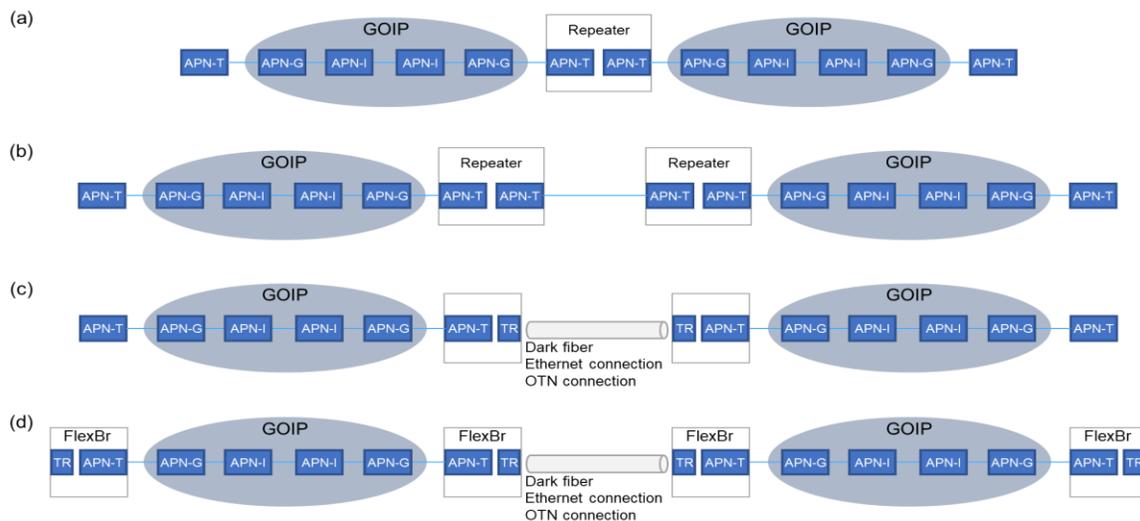


Figure 6.1.5-2: Direct Accommodation of User Data across Multiple GOIPs

Moreover, inter-GOIP connections can also be realized by APN-I. Note that a wavelength conversion function optionally provided by APN-I can relax or avoid several factors limiting reachability across multiple GOIPs. Such factors include differences in physical-layer attributes. For example, when G.652 and G.653 fibers coexist, the C-band is generally used on G.652 fiber while the L-band is used on G.653 fiber in conventional network operation. This forces GOIPs to be separated into each fiber type or each wavelength band. In such cases, a wavelength conversion is essential for eliminating unnecessary path terminations, enabling lower latency and lower power consumption. For more details on wavelength conversion technologies, please see Annex B.3.6.

Figure 6.1.5-3 shows typical cases where APN-I enables providing end-to-end direct connections across multiple GOIPs. In particular, Figure 6.1.5-3(a) depicts the example where multiple fiber types coexist as mentioned above. Figure 6.1.5-3(b) illustrates the case where APN-Is connects multiple GOIPs with different wavelength-band operations. In this case, wavelength-band conversion (also referred to as inter-band wavelength conversion) allows activating bands of each GOIP to be determined independently in accordance with traffic density while providing end-to-end direct connections. Figure 6.1.5-3(c) presents the case where an APN-I interconnects one GOIP with dual-fiber unidirectional transmission and another with single-fiber bi-directional transmission. Although bi-directional transmission requires further study, it can potentially suppress the required fiber resources.

Furthermore, a wavelength conversion function can also achieve wavelength arbitration across multiple GOIPs with different wavelength allocation policies. As a result, as shown in Figure 6.1.5-3(d), APN-I can provide end-to-end direct connections even across multiple GOIPs that are managed by different operators. This can contribute to a multi-operator environment, one of the design goals of the Open APN, described in Section 1.3 (in Part-I). Note that two APN-Is located at the edge of GOIPs may be housed in different buildings or on different floors in the same building.

To ensure end-to-end transmission quality, APN-C should be aware of the accumulated transmission penalty or transmission quality achieved in each GOIP, as described in Section 6.1. Specifically, APN-C should consider the transmission penalty accumulated in each GOIP and that induced by the wavelength conversion function when path provisioning. Note that transmission quality may be expressed by GSNR (described in Annex B.3.3). APN-C should be aware of wavelength conversion functions in path setup and management. In addition, root cause analysis must be executed across multiple GOIPs when defects occur.

Also note that, as the GOIP port is defined as the interface between APN-T and the access link (see Section 6.1.1), the ports of the APN-I in the middle of the two GOIPs in the figure are not GOIP ports.

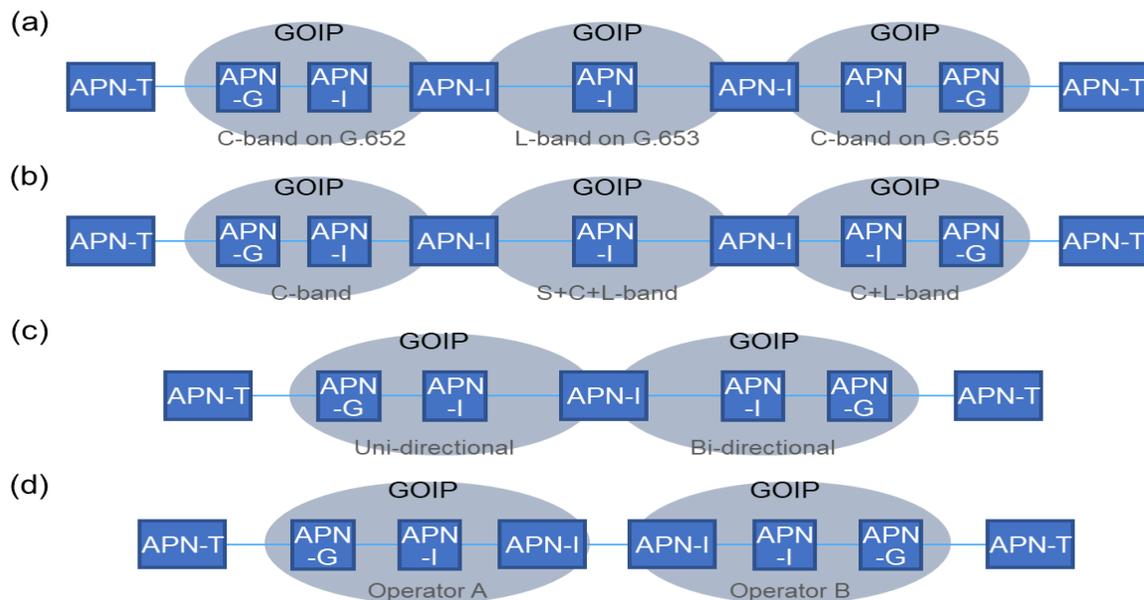


Figure 6.1.5-3: End-to-end Direct Connection across Multiple GOIPs Realized by Wavelength Conversion Function of APN-I

6.2. User Plane Reference Architecture within a GOIP for Open APN.WX

This section describes a single-GOIP network. Figure 6.2-1 shows the architectural diagram of Open APN.WX within a GOIP.

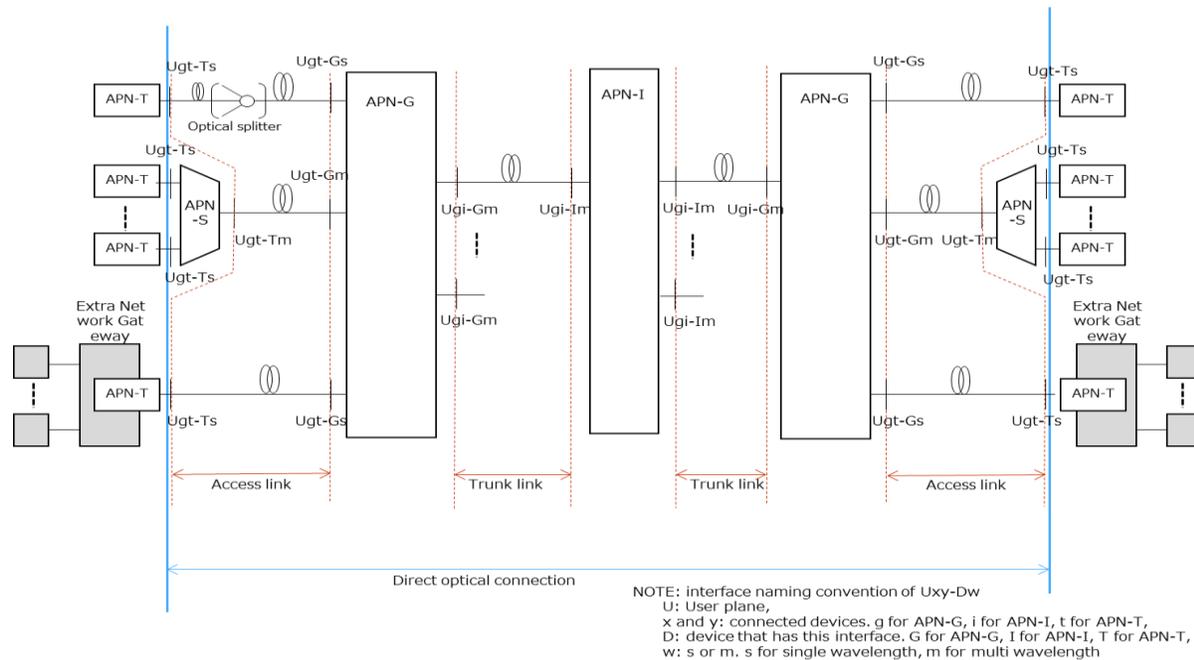


Figure 6.2-1: Architectural Diagram of Open APN.WX within a GOIP

GOIP consists of APN-T, APN-G, APN-I, APN-S, 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 the wavelength path. APN-S multiplexes wavelength paths from multiple APN-Ts between APN-Ts and APN-G. There is a possibility to use multi-core optical fibers as optical fibers that connect those Open APN functions.

Regarding sending and receiving, bi-directional transmission is implemented with a single fiber (through 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, using single-core fibers or MCFs, the fiber core number of Ugt-Ts, Ugt-Tm, Ugt-Gs, and Ugt-Gm shown in Figure 6.2-1 is one or two.

Two cases transmit a single wavelength by a single core (Ugt-Ts) and multiple wavelengths by a single core (Ugt-Tm). In the case of using multi-wavelengths, the WDM function, which enables multiplexing of Ugt-Ts of multiple APN-Ts, is needed between Ugt-Ts and Ugt-Tm. APN-S provides this WDM function. APN-S branches GOIP between APN-Ts and APN-G, which allows multiple wavelength paths to share the same access fiber. For branching, both passive and active configurations can be employed. APN-S may include in-line optical amplification to compensate for the loss through branching. A WDM filter, e.g., AWG and WSS, functions as the branch for APN-S. An optical splitter also functions as the branch for APN-S, while an additional wavelength-selective filter in the APN-T is needed to support IM-DD-based APN-T. When an optical splitter is used, it provides the branching function in the Open FX layer for PtMP fiber path service.

When using APN-S, the APN-G add/drop function needs to be enhanced to allow multiple wavelengths to be added/dropped through an add/drop port. The number of wavelengths of Ugt-Gm might be small compared to that of Ugi-Gm and Ugg-Gm. APN-G implementation-dependent features and constraints are described in Annex C. The primary constraint on provisionable wavelength-path configurations is that wavelength paths from multiple trunk links cannot be dropped onto the same access fiber when a contentionless-type M×N add/drop configuration (e.g., multicast switch-based add/drop) is employed due to per-port rather than per-wavelength forwarding at the add/drop. This constraint does not matter when wavelength paths from APN-Ts under the same APN-S are terminated at the same location (e.g., cloud data center).

Regarding low bitrate transmissions of 10 Gbps or less, one must select the higher efficiency method for wavelength resources to use the Open APN's transmission capacity 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 flexible grid [G.694.1]. If two or more APN-Ts exist on the user premises, one wavelength 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 (in Part-I), 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.

Single-fiber bi-directional transmission in the fiber path may also be used for a cost-effective network for both PtP and PtMP topologies. In this case, the wavelength paths for the single-fiber bi-directional transmission may be assigned so as not to conflict with its uplink and downlink wavelength paths, while the wavelengths for the two directions in the two-fiber system could be the same. Suppose an optical connection consists of two-fiber unidirectional fiber paths and single-fiber bidirectional fiber paths in a GOIP. In that case, some converters are needed at the connection points. Further study is required on building such converters.

Annex C shows implementation examples in APN-T, APN-G, and APN-I, focusing on the wavelength path services.

Continuing to focus on Open APN.WX, Figure 6.2-2 illustrates the relationship between the traditional ROADM, which comprises Wavelength CrossConnect (WXC), Add/Drop, and Transponders (TPDs), which include optical transceivers, and the Open APN.WX function blocks.

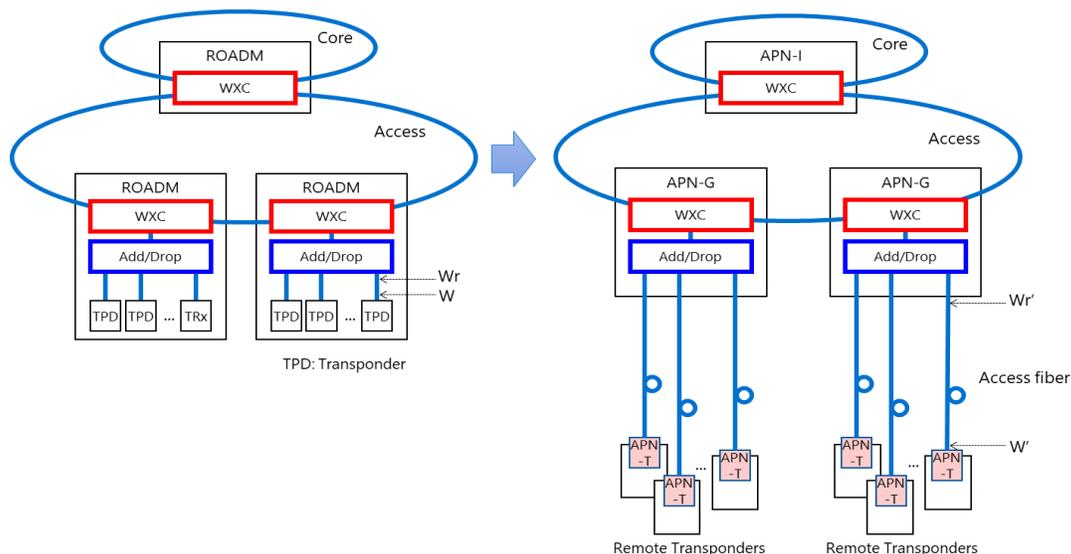


Figure 6.2-2: Relationship between ROADM and Open APN.WX Function Blocks

APN-I and APN-G are evolved ROADM nodes in the core and access, respectively. Their functions are described in detail in Section 3.1 (in Part-I). The following gaps stated in Section 1.5 (in Part-I) are now filled by updates of the OpenROADM MSA yang model and optical specification due to collaboration between IOWN GF and OpenROADM MSA.

1. Optical paths (i.e., direct optical connections) cannot be set between transceivers under the same ROADM in the conventional ROADM-based network.
2. A control/management channel is not supported for the remotely located transceivers 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.

More specifically, OpenROADM yang model release 13.0 supports turnback links, thus addressing 1 in the above. Besides, OpenROADM optical specification 7.0 defines new optical interfaces W' and Wr' for the remote transponder and the add/drop port of the ROADM node to support the remote transponder, respectively; see Figure. 6-7. These interfaces support the loss budget of up to 18 dB and the use of Optical Supervisory Channel (OSC) between the

ROADM node and the remote transponder, thus addressing 2 and 3 above. Note that traditional optical interfaces between the (non-remote) transponder and the add/drop port of the ROADM node are defined as W_r and W , respectively.

Accordingly, APN-C shall comply with OpenROADM yang model version 13.0 (or a later version) in the Open APN. Also, APN-G and APN-T shall comply with W_r' and W' of OpenROADM optical specification 7.0 (or a later version) in the Open APN.

6.3. Optical Interfaces

Ugt-Ts in Figure 6.2-1 correspond to the optical transmission/reception interfaces listed in Section 2.2 (in Part-I) (User plane services). Specifications of other optical interfaces in Figure 6.2-1 are for further study.

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

6.4.1. Wavelength Paths Connecting Optical Interfaces

This section describes the required information on wavelength paths connecting optical interfaces, the physical information needed for such paths in the GOIP context, and how the connection is established between APN-T.

From the controller perspective, the maximum number of available wavelength paths between two determined endpoints shall be accessible for a given path capacity and reachability. On the physical layer, information on the path allocation is managed according to the reference architecture.

Considering a GOIP as defined in Section 6.1, the ability to interconnect optical ports shall be managed according to the network management system, based on physical layer information and network requirements. Therefore, interconnecting ports in the GOIP context will depend on the required bandwidth, the bandwidth offered by the connected APN-T, the required reachability between the connected APN-T, and the characteristics of the wavelength path between the APN-T. If one or several wavelength paths are used to connect the APN-T, the physical references of these paths 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 paths in the GOIP
 - Information relative to the compatibility of APN-T for connection through wavelength path (e.g., modulation format, symbol rate, used FEC, etc.)
 - A bitrate of the APN-T connection
 - Specification for the error-free transmission of APN-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 path
 - Physical information of the wavelength path (e.g., used fibers, wavelengths, used bandwidth)
 - Factors limiting the reachability over the path, 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 so that the bitrate of the connected APN-T satisfies the bandwidth requirement. 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 5.5.

6.4.2. Wavelength Paths for Ultra-Wideband Optical Transmission

Ultra-wideband optical transmission technologies include possible approaches to expand the wavelength resource of the 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 add 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 the multiplexing of narrower grid channels

Similarly, SDM technologies add more channels by parallelizing the same wavelengths on the spatial dimension. Considering the time frame for the realization of 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 path of Section 6.4.1, the specificities of ultra-wideband technologies apply as follows:

- The physical reference of the wavelength paths using ultra-wideband technologies
 - The wavelength dimension of the path:
 - The optical band used for transmission.
 - The central wavelength of the carrier and the bandwidth inside the band.
 - The space dimension of the path:
 - The fiber used inside a cable for transmission.
 - The core inside the fiber.
 - The direction of the path
- Factors limiting the reachability over the path considering the specificities of ultra-wideband technologies.
 - Noise may depend on the transmission characteristics of ultra-wideband signals or through components.
 - The transmission of ultra-wideband signals may cause impairment.

Details on the characteristics of ultra-wideband optical transmission and an example of QoT based on the Generalized Signal to Noise Ratio (GSNR) are given in Annex B.3.3.

Inside a single GOIP, primary optical paths shall be allocated without physical conversion as described in Section 6.1.1. However, different GOIPs may have different implementations and, therefore, different characteristics in the above dimensions. As a result, regeneration or conversion is possible between different GOIPs. This difference in possible implementations is illustrated in Table 6-2 for several use cases. The characteristics given in Table 6-2 are examples of implementation. Specifications are to be delivered in future versions of the Open APN. Furthermore, it is to be noted that the wavelength paths created in these examples are purely illustrative and that wavelength paths need to be established to meet the requirement of bandwidth and reachability described in Section 6.4.1.

Table 6-2: Examples of Architectures of Ultra-wide Bandwidth for Open APN

PATH ALLOCATION POSSIBILITIES (PHYSICAL DIMENSION)	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	Dual-band (C+L)	more than three bands (C, L, and more)
Carrier wavelength and bandwidth	~100 wavelengths on C and L bands	More than 100 wavelengths on C, L, and extended bands

Number of spatial channels (number of fibers in a cable, fiber type, and number of cores)	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 paths	~10,000 to ~30,000	More than 30,000
Note 1: “Standard single-mode fiber” intends to be optically compatible with existing international standards (e.g., ITU-T Recommendation G.65x).		
Note 2: Ultra-high fiber count cable, which accommodates 1000-7000 fibers, has been developed for the inter-connection of hyper-scale data centers.		

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 path. The first option is the minimum version for implementing the Open APN; it relies on using standard APN-T, APN-G, and APN-I elements described in Section 3.1.1 (in Part-I) and interfacing these elements to match the physical characteristics of the wavelength path. Concretely, this interface can be realized with physical conversion elements like wavelength conversion repeaters for extension of wavelength resource on WDM dimension or fan-in fan-out elements for extension of the wavelength resource on SDM dimension. The second option is for future versions of the Open APN, and it requires the development of new APN-T, APN-I, and APN-G optimized for the characteristics of the wavelength path, i.e., optical transmission band, grid width, number of cores, density, and direction.

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

Moreover, wavelength resources must be efficiently utilized even when ultra-wideband transmission technologies are applied. In such ultra-wideband cases, huge wavelength resources must be efficiently handled, especially in APN-I. For example, band-switchable WXC can be helpful when multiple bands are activated. Note that the wavelength conversion is a viable technology option for band-switching operation, which can lead to efficient wavelength utilization across multiple wavelength bands. It should be emphasized that the band-switchable WXC is a typical case of APN-I enabling inter-GOIP connections (described in Section 6.1.5). In addition, spatial-lane changeable WXC can be useful when SDM fibers (e.g., multi-core fibers) are used. Although the spatial-lane change itself requires further study, efficient wavelength utilization can be achieved across multiple spatial lanes (i.e., cores in multi-core fibers).

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

6.5. Support of One-span PtP Wavelength Path Service

To support one-span PtP wavelength path service, the add/drop function (e.g., circulator, coupler, filter, WDM coupler) shall be inserted immediately after the outgoing interface of the APN node (i.e., APN-T/APN-G/APN-I) and before the incoming interface of its peer APN node, as shown in Figure 6.5-1. This add/drop function should be implemented with as little impact on the quality of DWDM signals as possible. Unidirectional and bidirectional transmission of optical signals in a single fiber is provided.

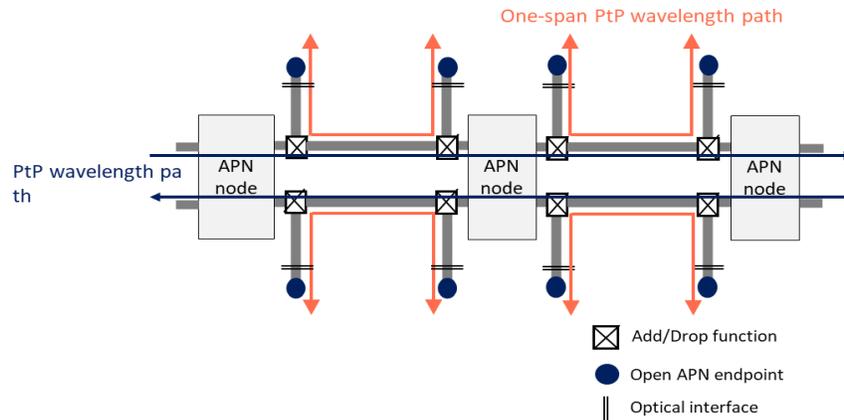


Figure 6.5-1: System configuration view of one-span PtP wavelength path

Various optical signal types, including non-DWDM ones with a specified set of wavelengths, can be transmitted without passing through functional elements of Open APN nodes (i.e., optical amplification, wavelength cross-connect, etc.). A layered structure view of the Open APN service paths is shown in Figure 6.5-2, which includes a one-span PtP wavelength path (the left-most U shape arrow) as well as service paths being provided in release 3.

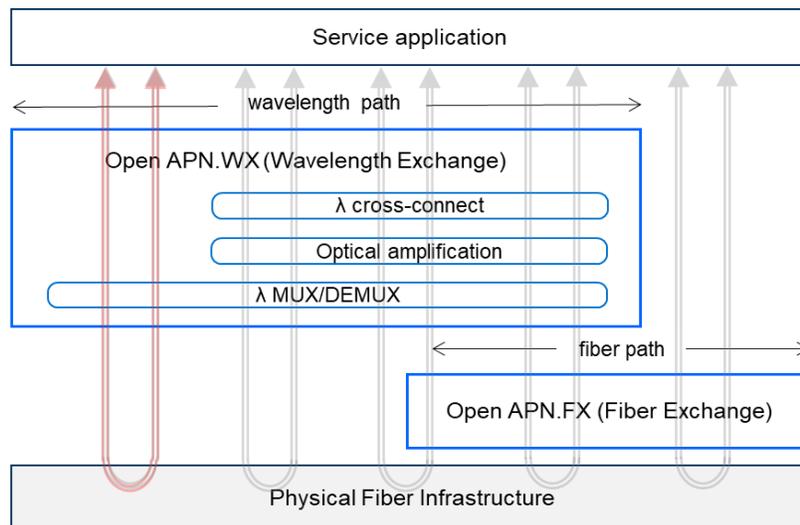


Figure 6.5-2: Layered structure view of Open APN service paths

Physical characteristics of the optical signal transmission (e.g., wavelengths, used bandwidth, and optical power) for this service should be communicated with APN-C before provisioning of this service is executed. The exact parameters and parameter values of this communication are left to be studied further. The provisioning algorithm for one-span PtP wavelength path service should be executed so as not to affect the signal quality of PtP/PtMP wavelength path services when they share a fiber section with each other.

7. Conclusion

Based on the high-level reference architecture described in Open APN Functional Architecture Part-I, this document (Open APN Functional Architecture Part-II) describes the Control and Management plane reference architecture, as well as the User plane reference architecture.

Control and Management functions of Open APN are provided by APN Controller (APN-C). In addition to general functions needed in a controller for conventional optical transport systems, APN-C has some unique functions for supporting endpoints at user premises and their registration. APN-C also has some advanced functions for supporting dynamic provisioning of end-to-end optical paths as well as lifecycle management to cover network designing, optical-path provisioning, monitoring, and device management.

As the aim of the Open APN is to provide end-to-end optical paths (i.e., wavelength paths and fiber paths), its User plane must be carefully designed considering various constraints in the physical layer (maximum transmission distance of each optical transceiver, maximum number of available wavelengths in each node and each fiber, etc). Group of Optically Interconnectable Ports (GOIP) is defined in the Open APN Wavelength Exchange (Open APN.WX), which is the wavelength-path layer of Open APN, to help the careful design through clarifying where direct optical connections are available under the limitation of transmission distance and number of available wavelengths.

Ultra-wideband optical transmission technologies are essential to overcome/alleviate the limitations of the number of available wavelengths.

[Part-III] Annexes

Annexes

A. IOWN Flexible Bridging Services

A.1. Introduction

An Open APN provides optical paths at the Ugt interface. A user device or an Extra Network FDN Gateway (defined in [IOWN GF DCI]) 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. The data rate would be lower for a narrower bandwidth service of with a high-layer functional split. 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 Annex 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, requiring some mechanism to close the granularity gap. 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 between the Ugt interface and multiple DCI gateways in a data center may also exist. 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., 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 (i.e., networking with FlexBr and without FlexBr) 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 500 kB/Frame and 15 frames per second.

A.2. Flexible Bridging Services (FlexBr)

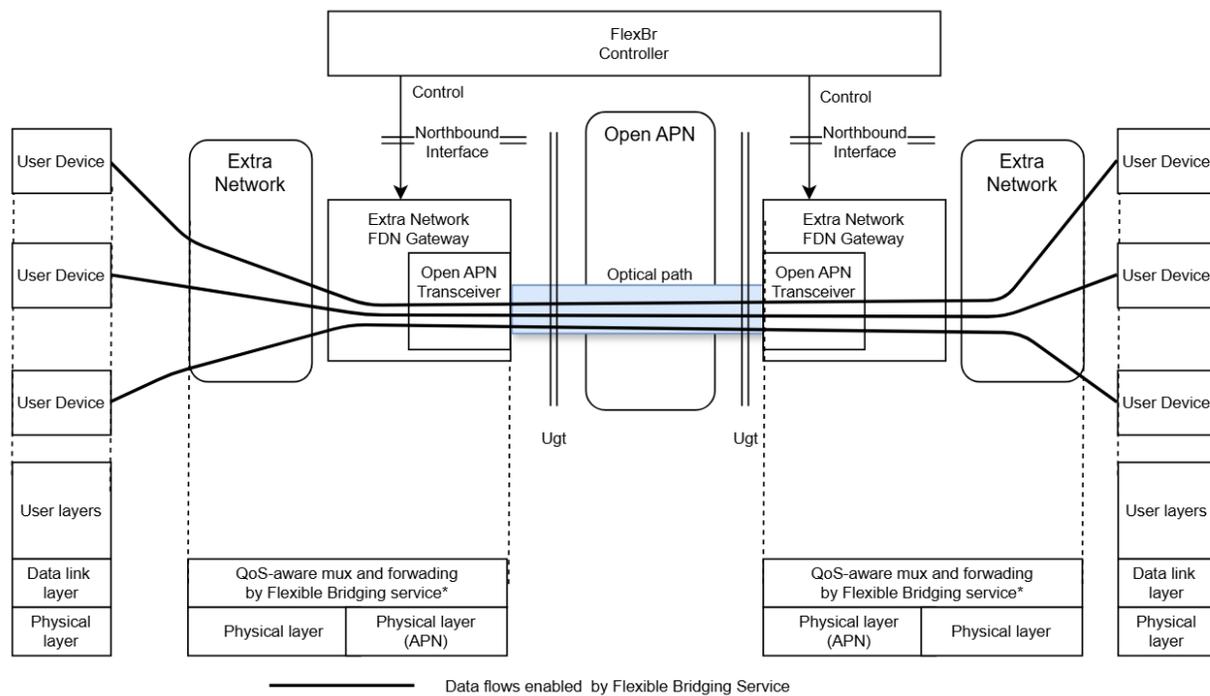
A.2.1. Definition

A Flexible Bridging Service (FlexBr) is a forwarding service aggregating multiple data flows and sending them over an Open APN optical path. It is provided by extra network infrastructure connected with the Open APN Ugt interface. As defined in Annex 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. 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 in 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.



*The implementation technologies should be studied during activities that follow this deliverable. Several multiplexing methods, including packet-based at L3/L2 and non-packet-based at L1, are being considered

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 limited 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 Figure A.2-2 illustrates. Examples of such flow control mechanisms are Peak Rate Limit and Priority-Based Flow Control. 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 stringent latency requirements, e.g., mobile front haul and SDI video distribution.
- The latency values, i.e., L1-L6, should indicate the forwarding latency by one bridge. The IOWN GF should discuss whether it needs to specify these values as requirements narrowly. If the IOWN GF decides to do so, they should be described separately from the functional architecture documents in the implementation guidelines.

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

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

(PtP: Point-to-Point, PtMP: Point-to-Multipoint)

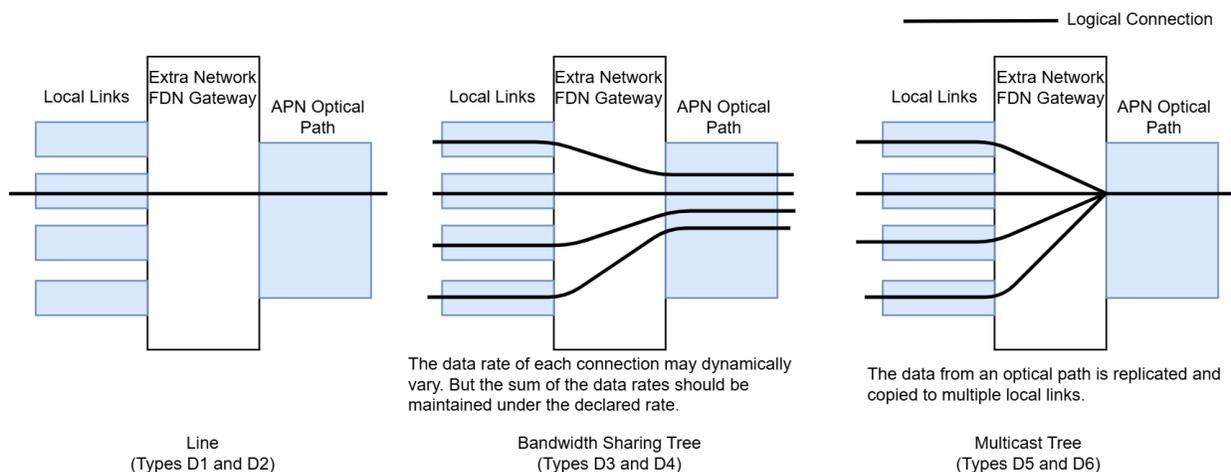


Figure A.2-2: Line, Bandwidth Sharing Tree, and Multicast Tree

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 strategies to achieve the required QoS, e.g., deterministic latency/jitter and ultra-high energy efficiency. These strategies may vary with FlexBr forwarding service types.

A.3. Examples of IOWN 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. The Open APN would be an ideal transport network for such converged network services (See Figure A.3-1).

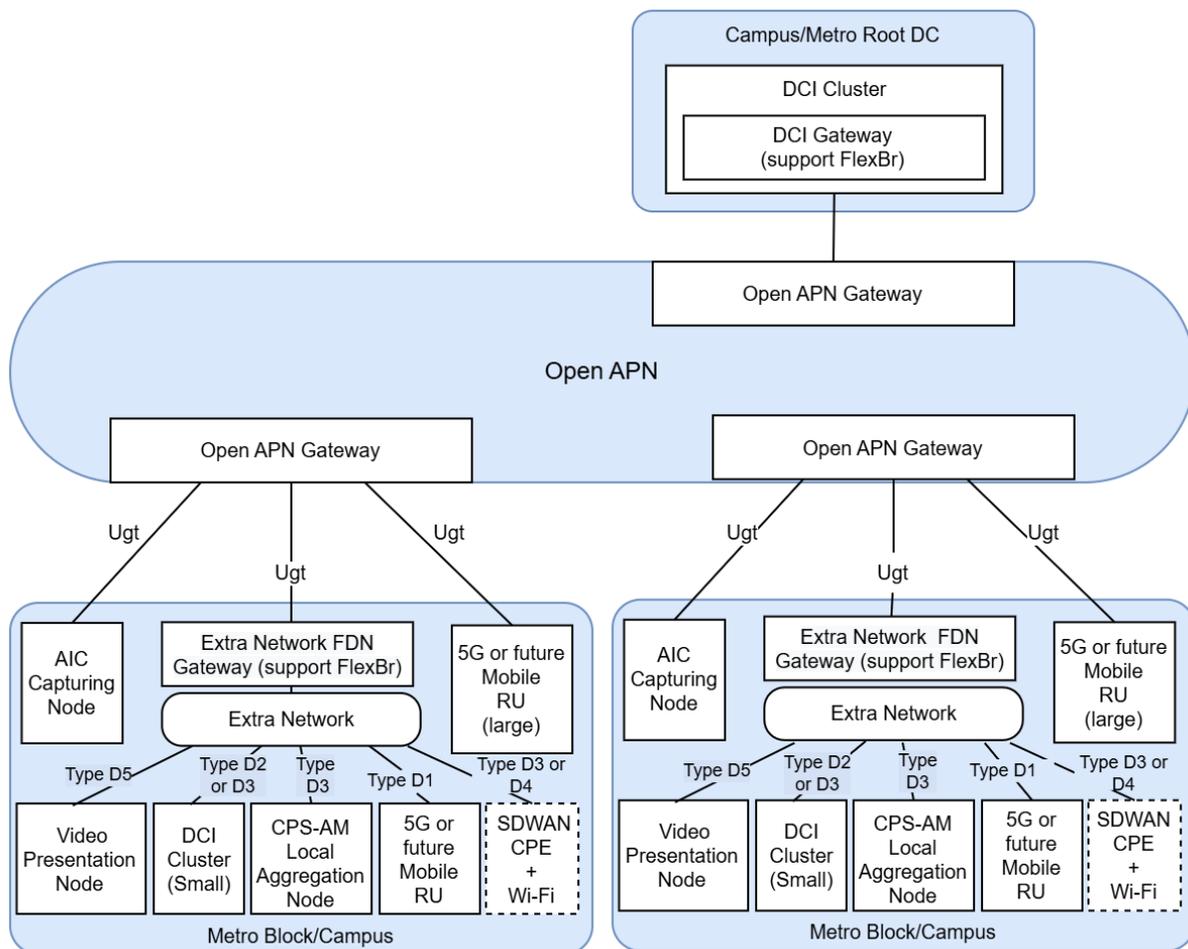


Figure A.3-1: Converged Network Service for Campus/Town/Metro

A.3.2. Data Center Interconnect Service

Many service providers and customers have multiple data centers 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 the sharing of computing resources across data centers and thus reduce the size of computing infrastructures and energy consumption. The Open APN would be an ideal network for such data center interconnects (See Figure A.3-2).

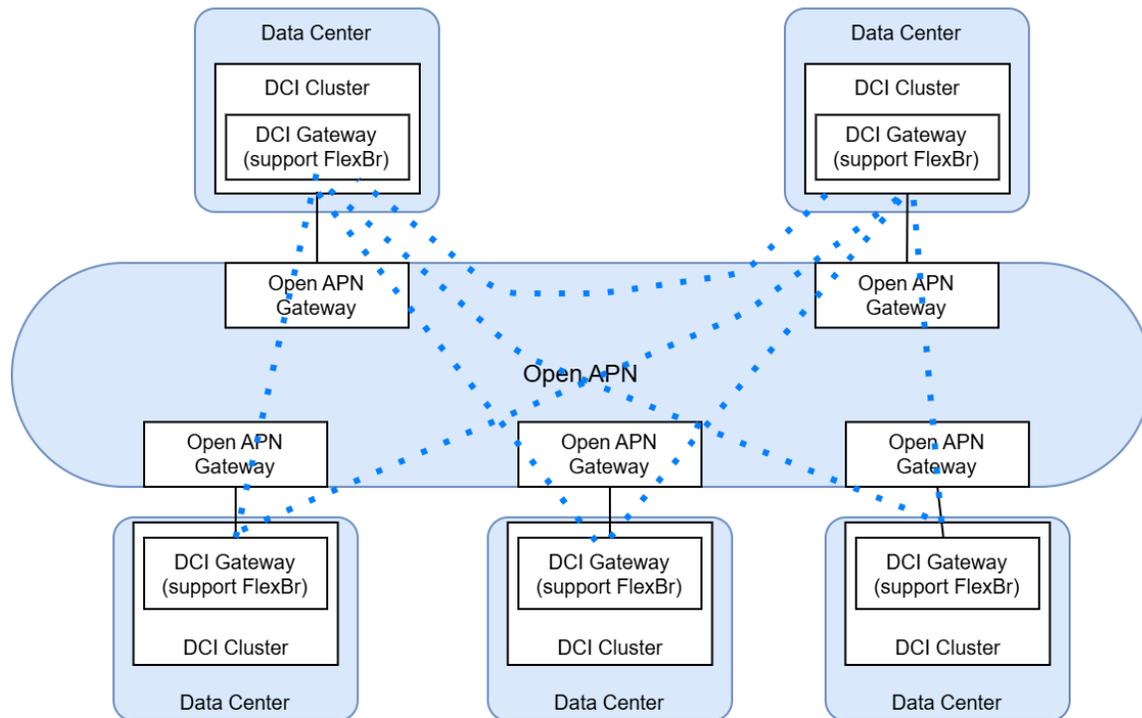


Figure A.3-2: Data Center Interconnect Service

B. Scenario to Expand Wavelength Resource

B.1. Introduction

Two approaches can be taken in the context of expanding the wavelength resources to enable numerous end-to-end optical connections for the Open APN. The first approach is to improve the utilization of existing wavelength resources through improvement in wavelength utilization. Network topologies such as the one described in Annex 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 Annex 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 (randomly occurring) between two access nodes in the different access rings are assumed. The wavelength assignment tends to be more severe regarding 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 easing 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 optical paths that can be established with a call loss probability of 1% or less in each topology are 1,416, 1,614, and 1,881, respectively, which shows the effect of adding a link for accommodating the optical path.

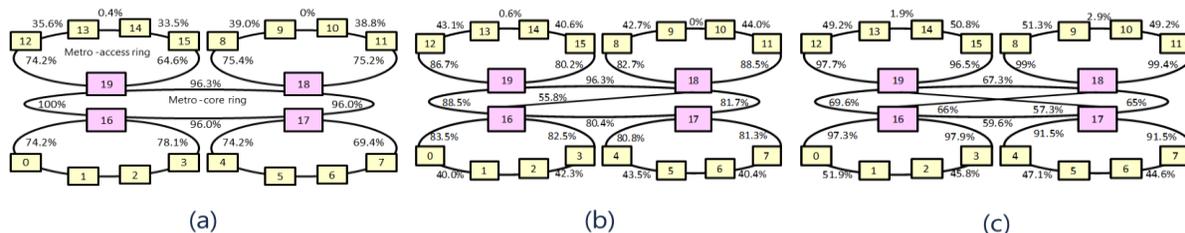


Figure B.2-1: Simulation Results of Wavelength Utilization in Two-tiered Ring Model; The Number of Wavelengths: 480, Routing and Wavelength Assignment (RWA): Shortest Path First (SPF) / FirstFit, No Wavelength Conversion

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, all path requests for connecting the eastern and western sides in this model are assumed to lead to call losses.

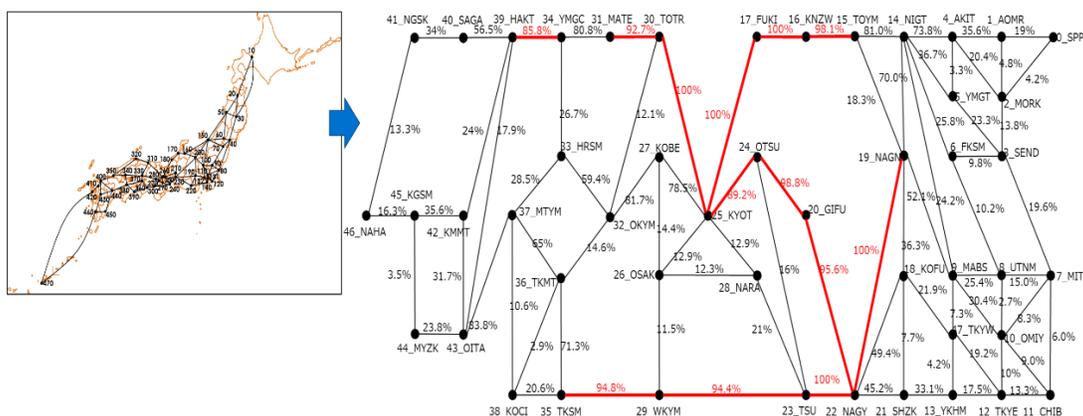


Figure B.2-2: Simulation Results of Wavelength Utilization in Japanese Network Model; The Number of Wavelengths: 480, RWA : SPF / FirstFit, No Wavelength Conversions, 3,000 Path Request

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 become more difficult.

In addition, unlike conventional static networks, the 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 considering 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.

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 Section 1.5. 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 Section 3.3.4.2, the technological options considered in ultrawideband 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, 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 how they expand wavelength resources compared to current transmission technologies are described in Figure B.3-1.

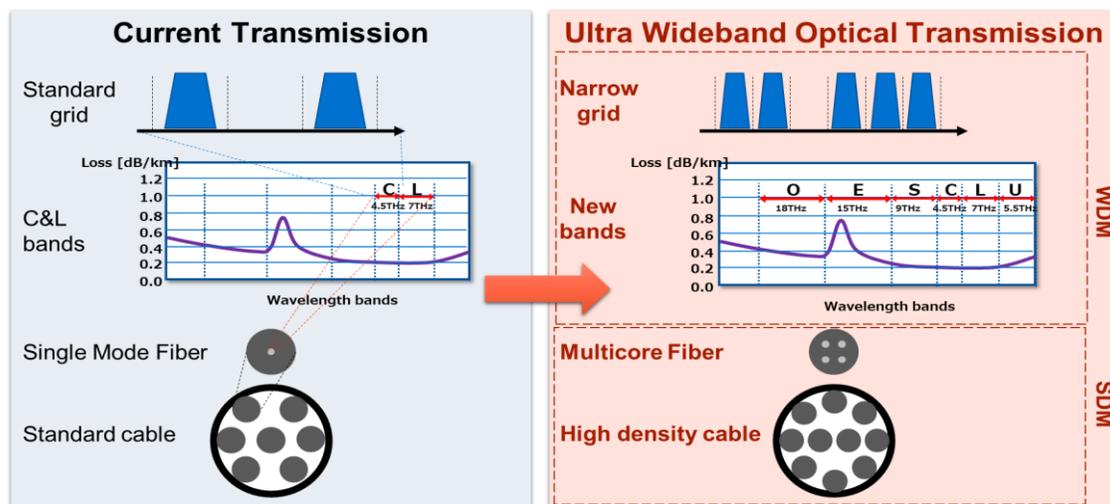


Figure B.3-1: Illustration of the Technological Options for Ultra-Wideband Optical Transmission

The four technologies illustrated in Figure B.3-1 in the UWOT section are not mandatory for the minimum implementation of the Open APN. However, demand for a high number of wavelength paths will serve as a strong 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 by creating newly available wavelengths using ultra-wideband optical transmission, it is necessary to build models that account for the technologies in this scope. Therefore, GOIP would use 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 to add 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 discuss the technology gaps that must 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 (Ss) and Rx (Rs) 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 the defined bitrate supports the required bandwidth, the characteristics of the wavelength path 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 (GSR) as developed in Annex 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 fiber 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 an end-to-end path.

3. Examine the wavelength resource to characterize the reachability (QoT) of the following technologies in scopes according to the GSR described in Annex B.3.3.

While ultra-wideband optical transmission technologies enable expanding 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. APN-I should handle optical signals efficiently to provide an end-to-end optical path, even when several fibers and/or wavelength band configurations coexist. These challenges are detailed below among other technical gaps.

a) Additional bands

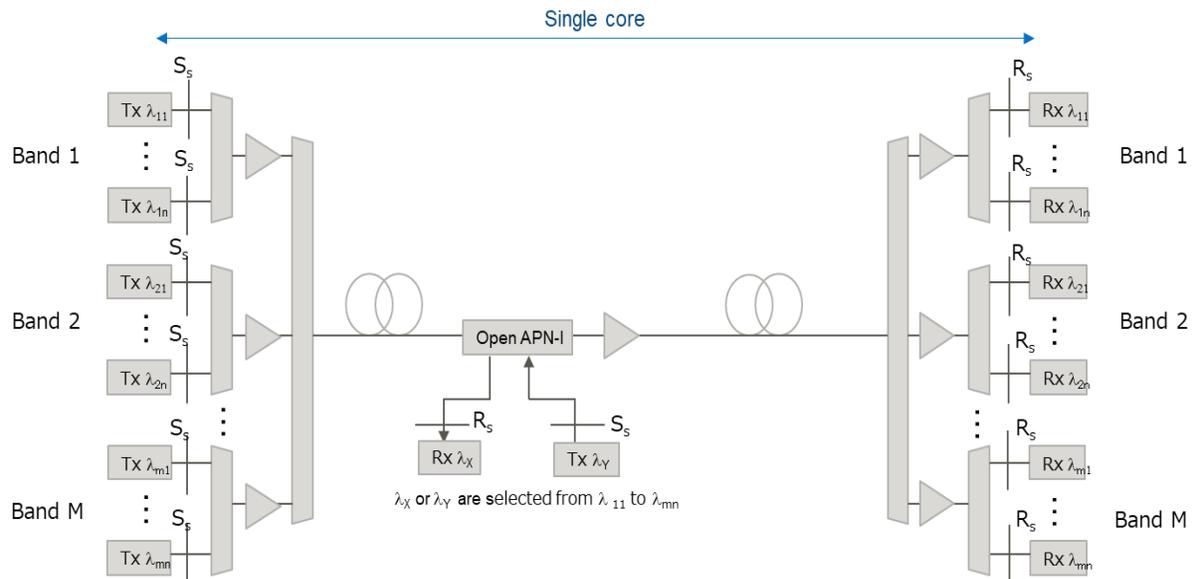


Figure B.3-2: The Additional Bands' Reference Mode

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 bands, such as L-, S-, U-, E-, and O-bands. On the other hand, there are issues to overcome when 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 via GSNR should be examined, and 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.

- Transceiver (TRx) used in the ultra-wideband range including tunable lasers and photodetectors
- 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 the interfaces of U_{ii} and U_{gi} . Specifically, the difference in band operation will limit the interconnection pattern. For efficient end-to-end optical connectivity, 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

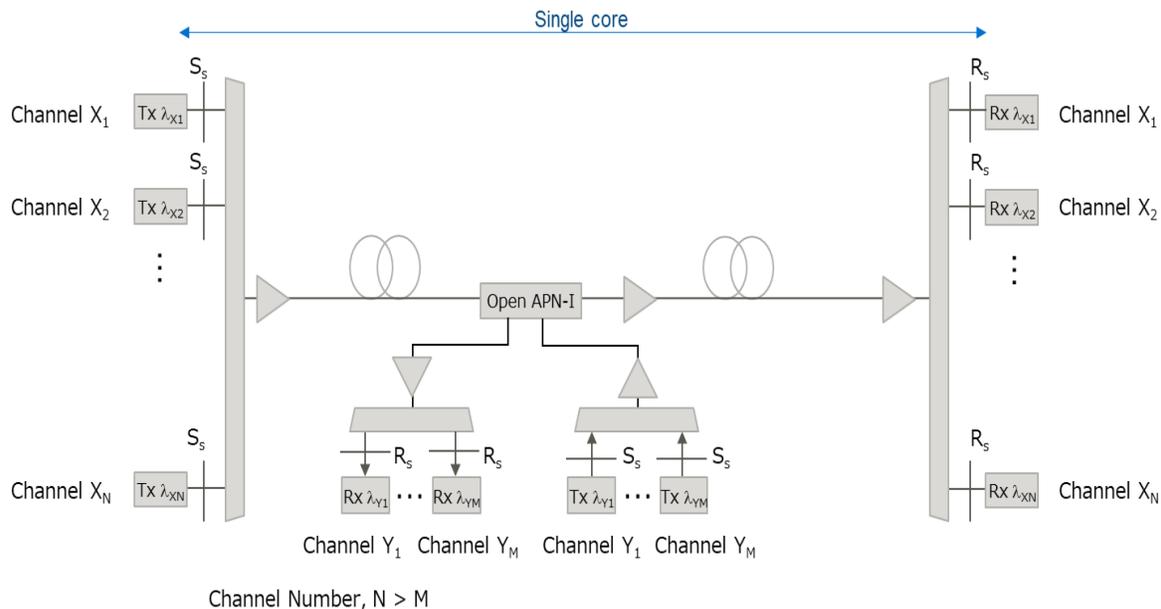


Figure B.3-3: The Narrow Grid Reference Model

The second way to expand wavelength resources is to narrow the wavelength grid. Hereafter, this method is referred to as the narrow grid. The transmission capacity could be drastically increased by reducing the channel grid 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 grid optics
- Node configuration to maintain a moderate interface with the current network system

c) Multicore fiber transmission

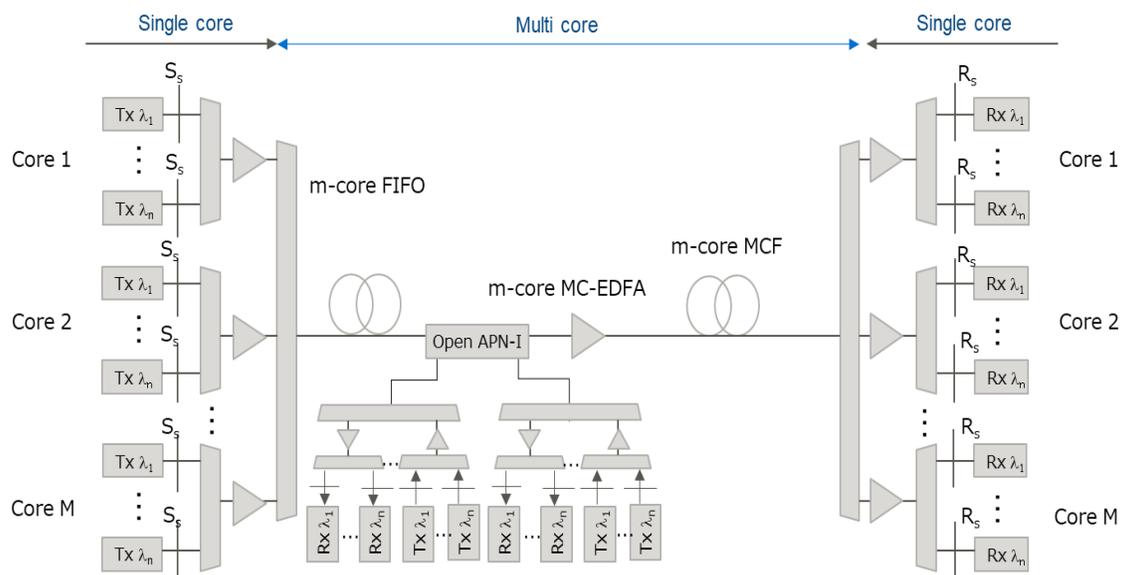


Figure B.3-4: The Multicore Fiber Transmission Reference Model

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. However, there are significant technical issues to overcome before such technology can be implemented. The influence of deployed multicore fibers on QoT, which involves transmission loss and crosstalk among cores, should be considered. 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 must be filled.

- Fan-in-Fan-Out (FIFO) devices are used to connect MCF to single-mode fiber. There exist several technologies for realizing such devices, as listed in Annex B.3.4. In particular, one must consider the additional loss and crosstalk of such devices, which may impact QoT.
- MCF characteristics. The MCF still needs to be standardized. Furthermore, one must consider crosstalk inside the fibers, which may impact QoT.
- Multicore fiber erbium-doped fiber amplifier (MC-EDFA). Several technologies have been reported to realize MCEDFA. One must consider the crosstalk and noise figure of such amplifiers, which may impact 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 impact 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 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

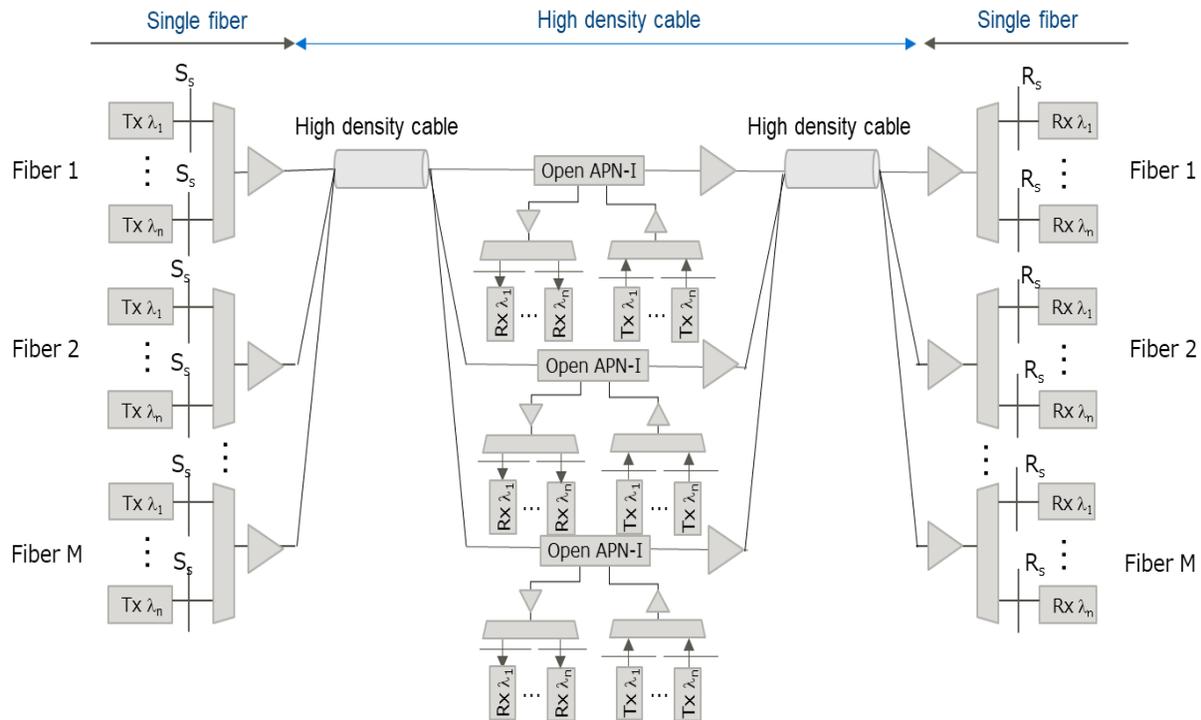


Figure B.3-5: The High-density Cable Reference Model

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:

1. Diameter of the cable. Some cables with high core counts may have large diameter filling ducts making them more challenging 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 for understanding 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 levels of the disturbances in the channel bandwidth for ASE noise and NLI (Non-Linear Interference).

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

Notably, to consider 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

Multiple considerations and discussions regarding components will be required to expand the capacity and wavelength resources using technologies described in Annex B.2.

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 the 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.

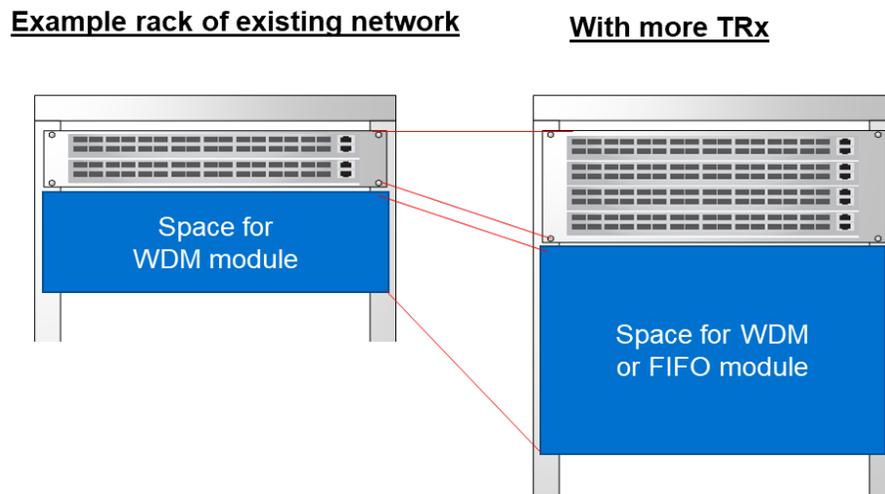


Figure B.3-6: Illustration of Rack Space Required for TRx Ports and WDM/FIFO Module Using Existing Components

New high-density optical connectors can be a viable solution to 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 a multi-fiber ferrule connector type, the 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.

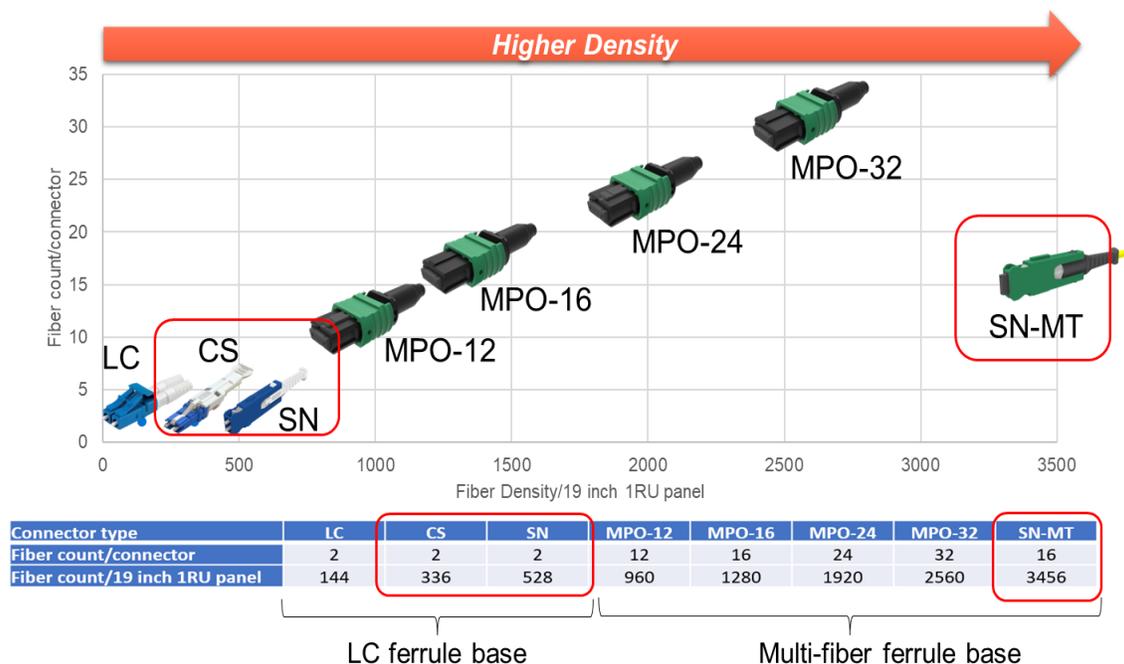


Figure B.3-7: Graph of Fiber Optic Connector Density Comparisons among LC, CS, SN, MPO, and SN-MT Connectors

The 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 their size. SN connectors of a reduced size can fit two duplex connectors in SFP-DD and four in QSFP-DD. Compared with duplex LC in SFP+, SN can increase density by two to four times more (See Figure B.3-8).

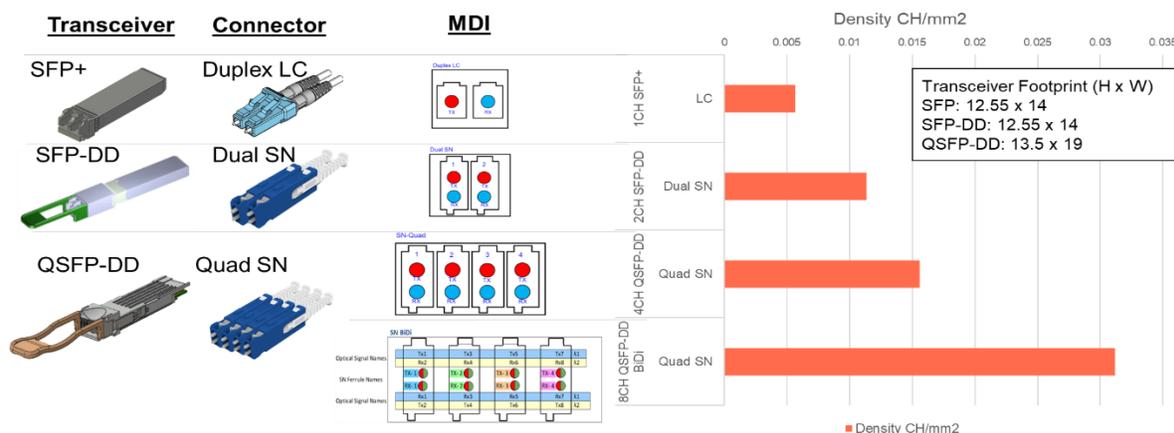


Figure B.3-8: Comparison Chart of Transceiver Density among Different Transceiver and Connector Types

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 if new solutions apply 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 should be considered because it may be compatible with the conventional MPO connector and could overcome the space issue of UWOT equipment. Both would accelerate the dissemination of UWOT.

This section discusses adopting a new high-density optical connector 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. However, there have been some reports of a few hundred of kilometers-long, low-loss 4-core links formed using MCF provided by three manufacturers.
- Optimized devices like transceivers for ultra-wideband optical transmission. Two options for APN-T are discussed in Section 3.3.4.2, one based on legacy APN-T devices with interfaces and the other 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 reduce energy consumption.

Regarding the use cases of MCF in fields, FIFO devices for MCF may be required, especially as one multi-core fiber should connect to each single-core fiber.

In this case, their roles are twofold:

1. Enabling compatibility of the Open APN with legacy networks by connecting parts of the Open APN featuring multicore fiber transmission technology to legacy networks or parts of the Open APN using single-core fiber. Therefore, GOIP may be defined on single-core fibers, multicore fibers, or a mix of both types connected with FIFO.
2. Enabling earlier adoption of multicore transmission technology, in the scope of UWOT, by offering the possibility to connect multicore fiber components with legacy components.

For example, multicore fiber and components can be used without multicore APN-T or multicore amplifiers but with currently deployed transceivers and optical amplifiers connected with FIFO.

Indeed, some FIFO devices are available for deployment, such as devices realized using free space connection with lenses, waveguides drawn by laser, fusing fibers, or bundling fibers. Table B.3-1 shows FIFO devices currently available in the market.

Table B.3-1: Types of FIFO devices

	TYPE OF DEVICES	FREE SPACE OPTICS	FUSED TAPER FIBERS	FIBER BUNDLE	3D WAVEGUIDE	LAMINATED PLC	OTHERS
Features	Description	<ul style="list-style-type: none"> •Lens system supports arbitrary core arrangement with low loss and low crosstalk •Device size tends to be large (*5) 	<ul style="list-style-type: none"> •Multiple SMFs are bundled and tapered to match with the MCF cross section •Fusion splice is available, and achieves high-power resistance •MFD mismatch should be cared (*6, *7) 	<ul style="list-style-type: none"> •Thin cladding SMFs are bundled to match with the MCF cross section •Applicable to pluggable connector, and realizes low loss •Precise fiber alignment is needed, and much suitable for hexagonal core arrangement (*8) 	<ul style="list-style-type: none"> •Laser inscription realizes arbitrary core arrangement and small device insertion loss (*9) •Polymer waveguides using the Mosquito Method (*17) 	<ul style="list-style-type: none"> •Enables mass-production with low loss •Laminated structure requires precise positioning, and hard to realize three layers or more (*10) 	
	Compatibility with	Shown on some paper *14, 15, 16.					

	bidirectional technology	No discussion on the FIFO type. No fundamental reason for incompatibility as no type reports use of isolator.					
Geometry	Size & shape	φ8 x 40 mm (*2)	The device length might be about 50 mm (*3,4)	70x22x9 mm	20 mm long – 45 mm long (*18), width and height; TBD	W60 x D15 mm Example of 4-MCF to 16-SMF type.	
	Number of cores	7	2 ~7 (*3,4)	4 (*11), 7 (*12) and 19 (*13)	4 cores (*18), and 7 cores (*17)	4 Scalable to horizontal direction, and applicable to MCF array	
Properties	Insertion loss	<1.0 dB (*2)	0.15~0.8 dB (*3,4) Note – the value 0.15 dB is measured at C-band (*4), and 0.8 dB is measured at 1625 nm in wavelength (*3)	<0.6 dB (*1)	1.4 dB for 4 core waveguides on 1.31 μm, and 4.0 dB for 7 core waveguides (*18)	<2.5 dB at 1550 nm	
	Crosstalk	<-49 dB (*2)	<-53 dB (*3) Note – this value is measured at 1625 nm in wavelength.	<-50 dB (*1)	TBD for Polymer waveguides using the Mosquito Method		
Application	Expected application		Submarine application (*4)		Optical interconnecting in Co-packaged optics (*18)		
Readiness	Availability	R&D		R&D	R&D	R&D	

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B.3.5. Requirements for Installed Optical Fibers

It is very important to examine what kind of fiber is available in present core, metro, and DCI networks, particularly when the UWOT technologies are advanced.

The candidates of the fiber for the metro/core/DCI region and the characteristics are summarized in the following table. To examine the UWOT adaptation to the current region, the following issues could be addressed.

- Clarify the following issues:
 - Can we consider G.652 as a base fiber for UWOT?
 - Should we consider a low loss fiber which supports S-L band?
 - Does it meaningful considering U-band as alternative for S-band?
 - Others
- Contribute to the update of the Open APN architecture according to the above information.
- Optical bands among S, C, L and U.
- Optical fibers and optical components (amplifiers, ROADMs, transceivers)

Solutions may differ depending on the considered application (Table B.3-2). According to the previous discussions, a few cases have appeared:

1. Short reach transmission (without amplifier), like DCI
2. Longer reach transmission (with amplifier)
 - (a) Using components (amplifier, etc.) covering the considered new band (S or U)
 - (b) Using components (amplifiers, etc.) in the C or L band with wavelength conversion scheme.

Table B.3-2: Solutions for each application

APPLICATION AREA	CORE		METRO	DCI	MOBILE	
					XH	FH
Distance	>500 km		120~500 km	<120km	>~30 km	~30 km
Number of wavelengths						
Number of fiber/ch pairs						
1R amplifier	Needed		Almost needed	Not needed	Not needed	Not needed
Topology	PtP or Mesh		Mesh/Ring	PtP	Mesh/Ring	PtP
Wavelength conversion	Needed		Needed	Not Always		
Uni-/Bi-directional	Uni		Uni	Uni?	Bi?	Bi
Candidate fiber	G.652	G.654	G.652	G.652	G.652	G.652
Bandwidth	O, S, C, L	C, L	O, S, C, L	O, S, C, L	O, S, C, L	O, S, C, L
Attenuation (dB/km)	≤ 0.40 (O, S, L) ^(*1) ≤ 0.30 (C) ^(*1) 0.5 (1260-1360 nm) ^(*2) 0.275 (1530-1565 nm) ^(*2) 0.35 (1565-1625 nm) ^(*2)	≤ 0.23 (1550 nm) ^(*1) ≤ 0.25 (1530-1612 nm) ^(*1) TBD (1550 nm) ^(*2) TBD (1625 nm) ^(*2)	≤ 0.40 (O, S, L) ^(*1) ≤ 0.30 (C) ^(*1) 0.5 (1260-1360 nm) ^(*2) 0.275 (1530-1565 nm) ^(*2) 0.35 (1565-1625 nm) ^(*2)	≤ 0.40 (O, S, L) ^(*1) ≤ 0.30 (C) ^(*1) 0.5 (1260-1360nm) ^(*2) 0.275 (1530-1565nm) ^(*2) 0.35 (1565-1625nm) ^(*2)	≤ 0.40 (O, S, L) ^(*1) ≤ 0.30 (C) ^(*1) 0.5 (1260-1360 nm) ^(*2) 0.275 (1530-1565 nm) ^(*2) 0.35 (1565-1625 nm) ^(*2)	≤ 0.40 (O, S, L) ^(*1) ≤ 0.30 (C) ^(*1) 0.5 (1260-1360 nm) ^(*2) 0.275 (1530-1565 nm) ^(*2) 0.35 (1565-1625 nm) ^(*2)
Bending loss (dB)	≤ 0.1 (R30 mm, 100t, 1625 nm) ^(*1)	≤ 0.1 (R30 mm, 100t, 1625 nm) ^(*1)	≤ 0.1 (R30 mm, 100t, 1625 nm) ^(*1)	≤ 0.1 (R30 mm, 100t, 1625 nm) ^(*1)	≤ 0.1 (R30 mm, 100t, 1625 nm) ^(*1)	≤ 0.1 (R30 mm, 100t, 1625 nm) ^(*1)
Nonlinearity (1/W)	$\sim 3.8 \times 10^{-10}$ (1550 nm) ^(*3)	$\sim 2.3 \times 10^{-10}$ (1550 nm) ^(*3)	$\sim 3.8 \times 10^{-10}$ (1550 nm) ^(*3)	$\sim 3.8 \times 10^{-10}$ (1550 nm) ^(*3)	$\sim 3.8 \times 10^{-10}$ (1550 nm) ^(*3)	$\sim 3.8 \times 10^{-10}$ (1550 nm) ^(*3)
Issues						
Note	(*1) Specification in ITU-T Recommendation G.652 category D or ITU-T Recommendation G.654 category E. For G.652.D fiber, maximum attenuation in wavelength from 1260 nm to 1310 nm is 0.07 dB/km larger than the attenuation at 1310 nm. (*2) Typical link value described in Appendix of ITU-T Recommendation G.652 or G.654. "TBD" means "To Be Discuss". (*3) Typical n_2/A_{eff} value when assuming $n_2 = 3.0 \times 10^{-20}$ (m ² /W) and $A_{eff} = 80 \times 10^{-12}$ (m ²) for G.652 and $n_2 = 2.3 \times 10^{-20}$ (m ² /W) and $A_{eff} = 113 \times 10^{-12}$ (m ²) for G.654.					

B.3.6. Wavelength Conversion to Efficiently Expand Wavelength Resources

Wavelength conversion is a unique technology that efficiently expands wavelength resources without installing new transceivers (i.e., APN-Ts). Wavelength conversion is classified into four groups according to the number of channels to be converted and wavelength mapping tunability.

- Number of channels
 - Single channel only
 - Several channels
 - Whole band simultaneous
- Tunability
 - Fixed mapping between input λ to output λ
 - Tunable mapping
 - Full arbitrary mapping

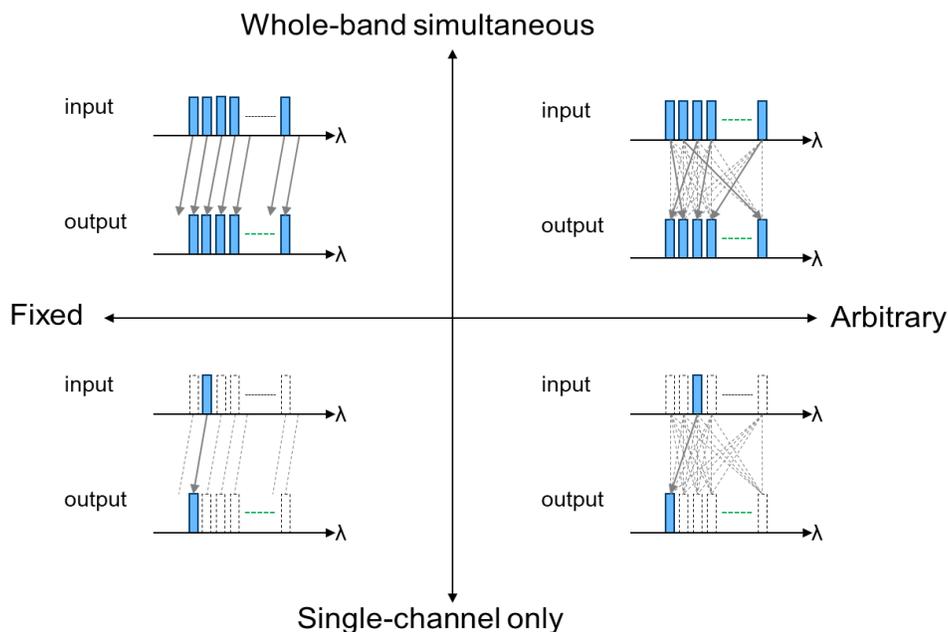


Figure B.3-9: Classification of wavelength conversion techniques

In the Optical-Analog-Optical (OAO) conversion which is mapped on the lower-right region, the single- λ signal goes through the OA and AO converters. The wavelength conversion can be performed from one wavelength to an arbitrary wavelength. This conversion performs without signal processing, different from the OEO conversion.

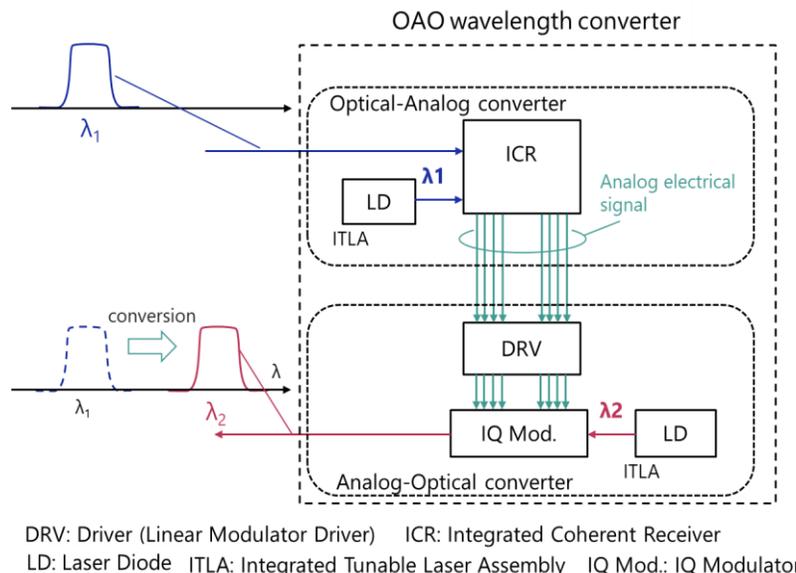
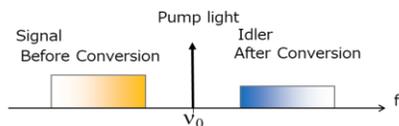


Figure B.3-10: Conversion principle of the OAO conversion

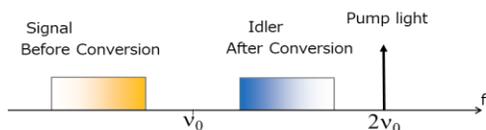
Regarding the OO (all optical) conversion is mapped on the upper-left region in Figure B. 3-9. There are several approaches to OO wavelength conversion, depending on system requirements and device type characteristics, which are shown in Figure B. 3-11.

• Single- λ excitation

- Optical parametric amplification by 3rd order nonlinearity



- Differential frequency generation by 2nd order nonlinearity



• Double- λ excitation

- Orthogonal configuration



- Parallel configuration

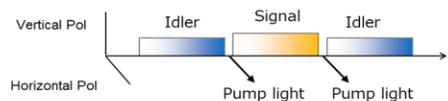


Figure B.3-11: Conversion principle of the OO (all optical) conversion

The characteristics of wavelength conversion may be summarized in *table B.3-3*.

Table B.3-3: Characteristics of wavelength conversion

	3R Transponder (OEO)	Optical-Analog-Optical (OAO)	Optical-Optical (OO)
Modulation independent	No	Yes	Yes
Baud-rate independent	No	Yes*	Yes
Multi-wavelength conversion	Single λ	Single λ	Multiple λ / whole band
Termination of OTU/ODU	Yes	No	No
Flexibility of conversion	Tunable	Tunable	Fixed
Cabling	Per- λ cabling	Per- λ cabling	Less cable required
Performance Monitoring	Supported	Partially supported	Not supported
Cost/bit @ WDM	High	Med	Low
Watt/bit @ WDM	High	Med	Low
Size @ WDM	High	Med	Low
Cost @ 1λ	Med	Low	(to be confirmed)
Watt @ 1λ	Med	Low	(to be confirmed)
Size @ 1λ	Med	Low	(to be confirmed)
Process latency	Large	< μ s [†]	< μ s [†]
Transmission penalty	No	(to be confirmed)	(to be confirmed)

*maximum baud-rate is limited by electronic bandwidth

†Latency is determined by transmission distance within the device

C. Implementation Examples of APN-I, APN-G, and APN-T

This Annex describes examples of implementation in APN-I, APN-G, and APN-T to ensure that Open APN hardware is implementable based on current technologies. Note that it does not intend to exclude other implementations that may be possible, especially other long-term solutions to realize more scalable, cost-effective, and energy efficient Open APNs in the future. Also note that this annex is focusing on the implementations for the wavelength path services while those for the fiber path services will be considered for further study.

C.1. APN-I

Figure C.1-1 shows an implementation example of APN-I with 4 Multi-Wavelength (MW) interfaces connected to other APN-Is or APN-Gs. Each Degree in the figure is identical to the direction/degree defined in the OpenROADM MSA [OpenROADM Network White Paper].

Each Degree typically comprises a pair of 1x4 Wavelength Selective Switches (WSSs) where one WSS demultiplex the incoming wavelength set into 3 wavelength groups while the other WSS multiplex 3 wavelength groups into the outgoing wavelength set. The grouping is reconfigured by the Open APN controller. The incoming/outgoing optical interface for each direction (MW interface, (U_{ii} or U_{gi}) in the figure) corresponds to (i.e., shall comply to) Multi-wave interface (MW interface) defined in the OpenROADM MSA [OpenROADM Device White Paper]. Optical Amplifiers are not shown but put between the MW interface and Degree to boost the optical power of outgoing wavelengths as well as to recover the optical power of incoming wavelengths. These four degrees in this figure correspond to a WXC of APN-I in Figure 3.3-7.

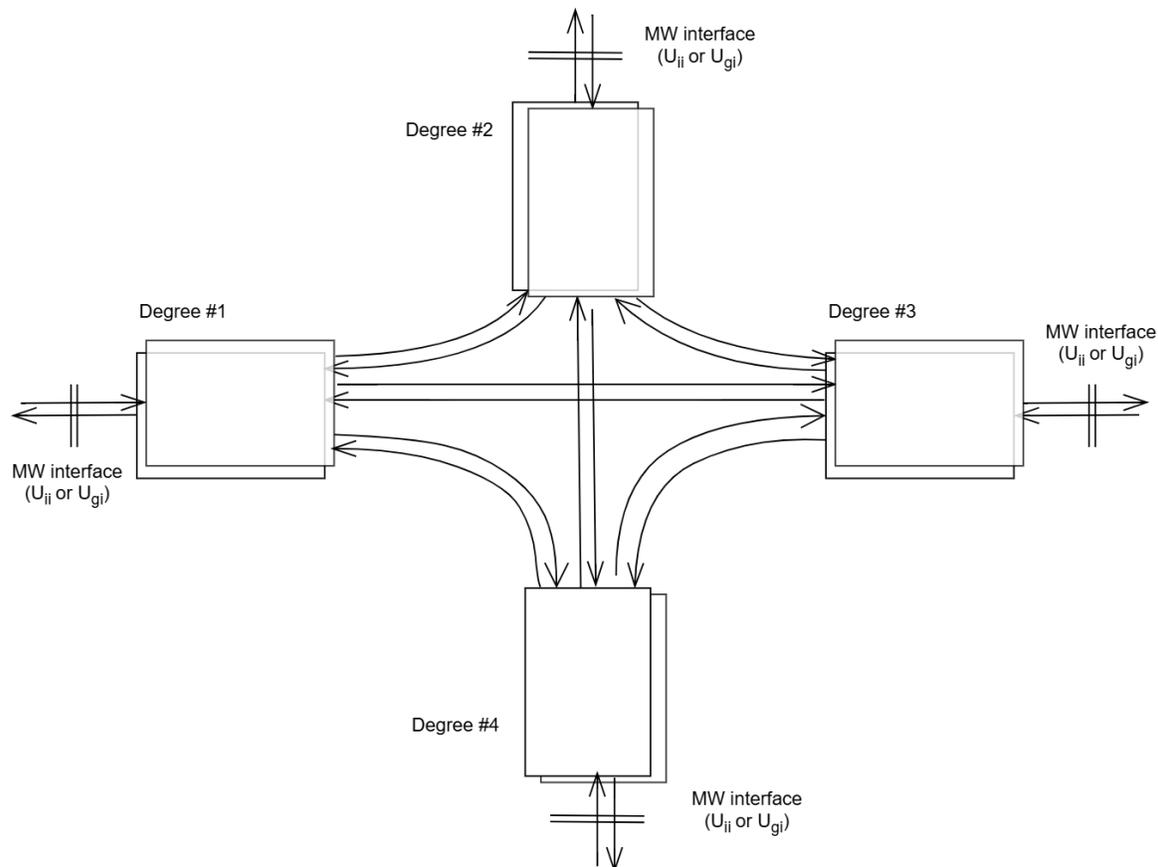


Figure C.1-1: Implementation Example of APN-I

C.2. APN-G

Figure C.2-1 shows an implementation example of APN-G that has two Shared Risk Groups (SRGs) and two Degrees [OpenROADM Network White Paper][OpenROADM Device White Paper]. Each SRG has eight interfaces connected to/from APN-Ts and two internal interfaces connected to/from Degrees.

Each SRG is a pair of $M \times N$ WSSs [G.672][WSS], a pair of Multi-Cast Switches (MCSs) [G.672][MCS ROADM], or a pair of Optical Cross Connects (OXC)s with wavelength multi/demultiplexers [G.672][OXC ROADM], typically. The SRG is identical to the one defined in the OpenROADM MSA [OpenROADM Device White Paper]. The components of the Degree can be the same as that of APN-I. The SRG in Figure C.2-1 corresponds to an add/drop of APN-G in Figure 3.3-7 and two degrees in the figure correspond to a WXC of APN-G in Figure 3.3-7.

Two uplink ports of each SRG are connected back to back; this is to realize a turn-back connection between two APN-Ts under the same SRG. Note that we need to spend two uplink ports for the turn back under the same SRG to allow the use of the same wavelength for the transmitter and the receiver of each of the two APN-Ts under the turn-back connection.

Another uplink port of the two SRGs are connected to each other; this is to realize a turn-back connection between an APN-T under SRG #1 and an APN-T under SRG #2. When the number of SRGs is 3 or higher, this is extended to mesh connections among all the SRGs so that the turn-back connections become available between any two APN-Ts under any SRGs.

Downlink ports of the SRGs are connected to WDM filters by which control signals are multiplexed onto main signals; this is to realize the remote control of APN-Ts located at user premises where external access to APN-C is not available. The control signals can be a long-reach version of a Gigabit Ethernet (GbE) interface having a wavelength

different from the main signals, e.g., 1000BASE-ZX at 1310 nm. Control signals are fed to/from APN-C via an Ethernet switch.

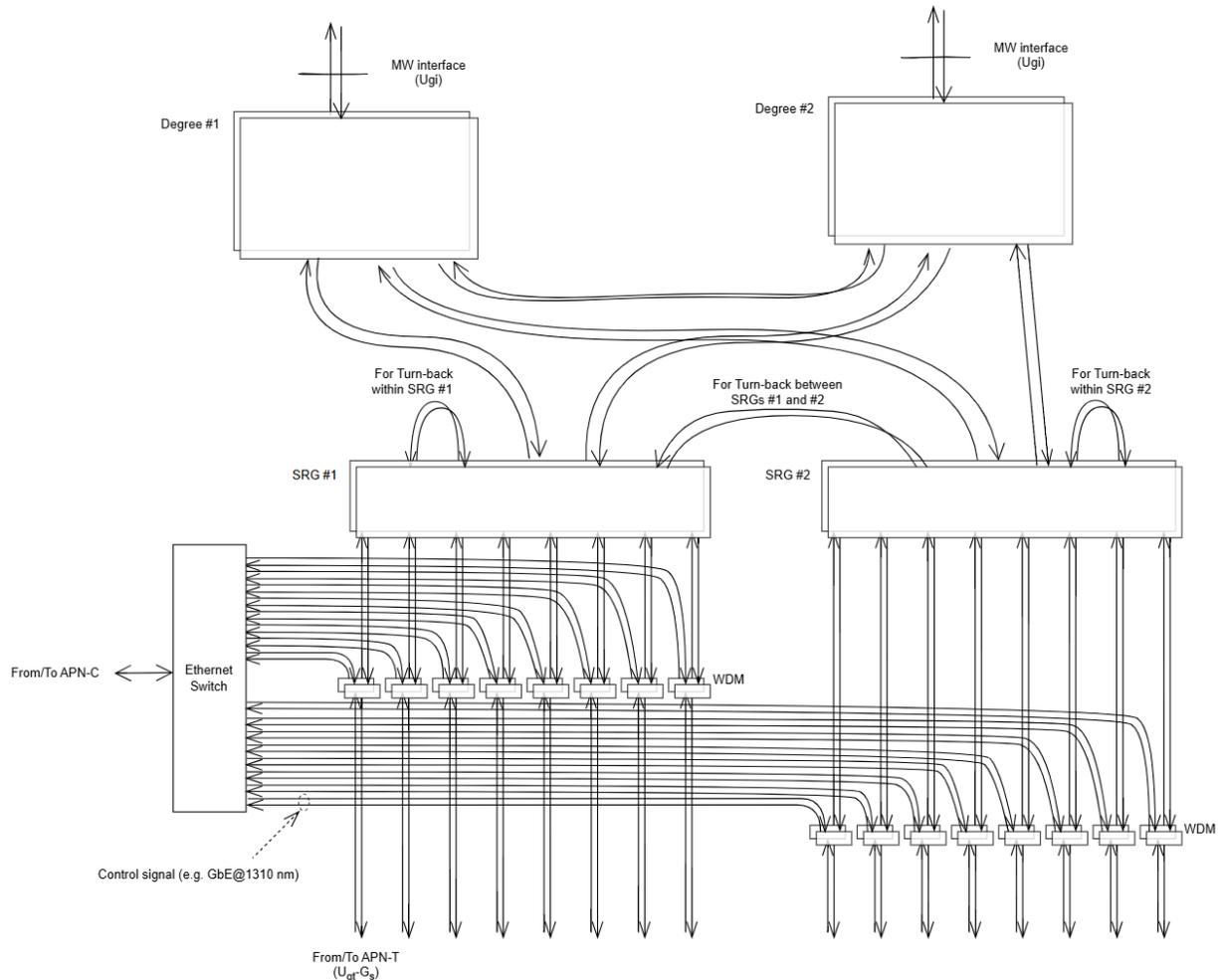


Figure C.2-1: Implementation Example of APN-G (1)

Figure C.2-2 shows another implementation example of APN-G with a turn-back module. Instead turn-back between uplink ports of SRGs directory, a turn-back module is added for turn-back connection between different SRGs. The turn-back module can be a compromise with NxN WSS, and that can be composed with a group of back-to-back connection of two Degrees (i.e., a connection of a Nx1 WSS and a 1xN WSS.)

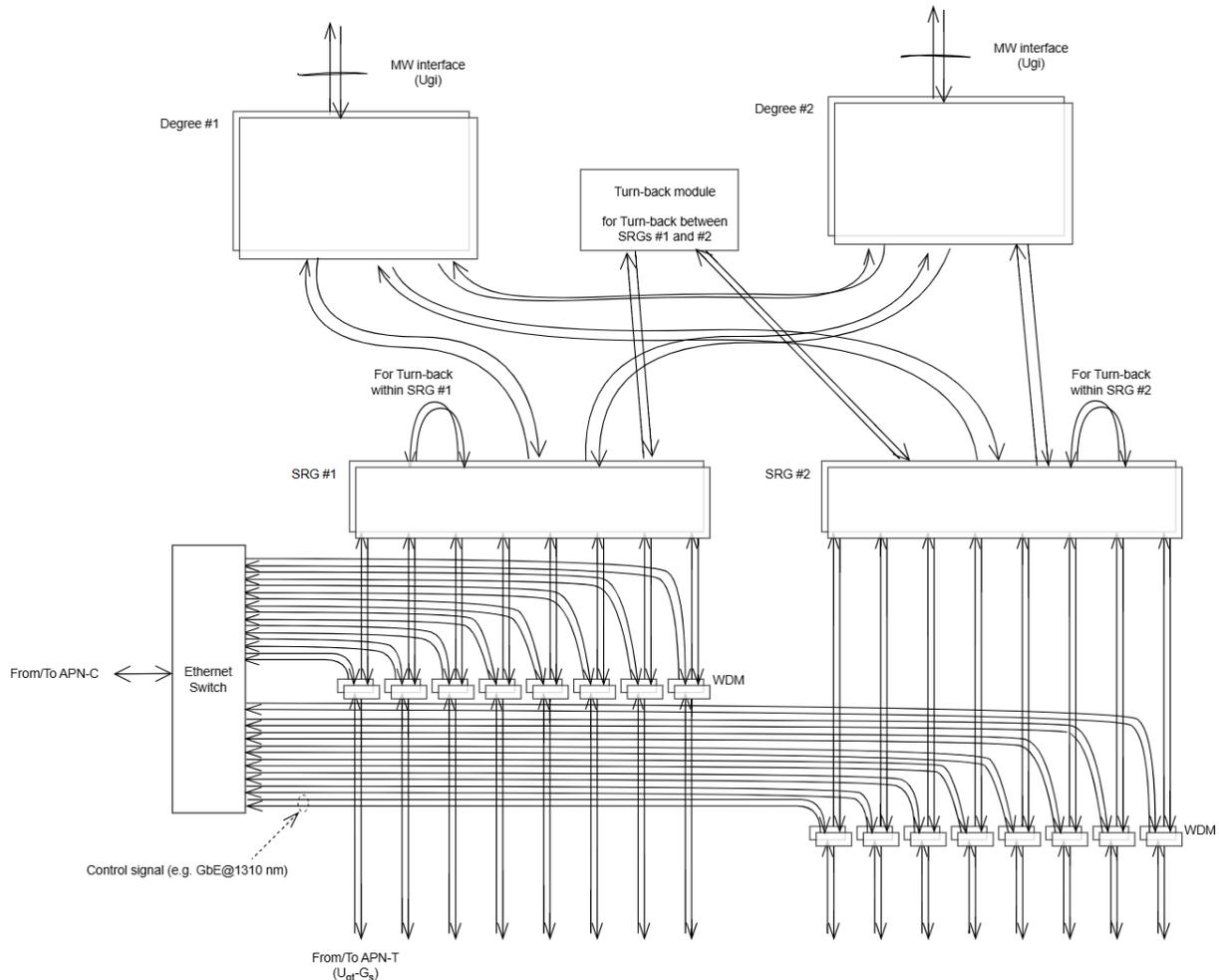


Figure C.2-2: Implementation Example of APN-G (2)

C.3. APN-T

Figure C.3-1 shows an implementation example of APN-T for the digital-coherent optical interfaces. The optical transceiver for transmitting/receiving the main signals (TRx1) is a digital coherent optics (DCO) that complies with the Optical Specification defined by the OpenROADM MSA [G.972]; “W interface” in the figure corresponds to (i.e., shall comply with) the Single-wave (W) interface defined in the OpenROADM MSA [OpenROADM Device White Paper][OpenROADM spec].

In addition to TRx1, the APN-T employs an optical transceiver for the control signals (TRx2). The control signals (upstream and downstream) are allocated in a different wavelength band from the main signal (e.g., in the 1310-nm band). The main signal and the control signal are multiplexed/demultiplexed via a pair of WDM filters (WDM). TRx2 can be a long-reach GbE optics, e.g., 1000BASE-ZX at 1310 nm.

A white-box transponder hosts the two transceivers. A remote-control agent is installed in the CPU in the white-box transponder, so that the DCO can be remotely controlled from the APN-C via the APN-G as described in the previous subsection.

To compensate for the optical loss of optical fibers for the main signals between APN-T and APN-G, it will be necessary to add optical amplifier(s) at the side(s) of APN-T and/or APN-G.

Namely, the APN-T function is realized by several distributed components inside the box with dashed border in Figure C.3-1. In this example, the APN-T function is expected to be integrated into a single module in the future.

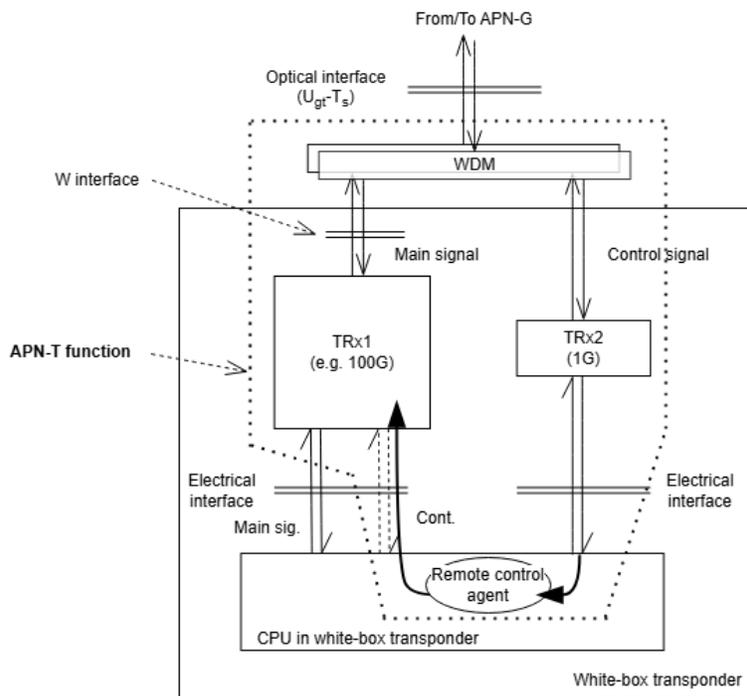


Figure C.3-1: Implementation Example of APN-T

Figure C.3-2 shows an implementation example of an integrated APN-T into a single module. The remote control agent may be installed into the CPU in the APN-T. If the control path can be established from APN-C to the CPU in the Host, the remote control agent may be installed into the CPU in the Host. Here, the two main roles of the remote control agent are to authenticate the APN-T and to set the parameters of the main signal. If the APN-T can be remotely controlled via the CPU of the Host, the implementation of the APN-T can be simplified by separating the functions of the remote control agents into the APN-T and the Host. How to use the CPUs and remote control agents depends on the use case, the amount of remote control processing, the processing ability of the CPUs, and the implementability (form factor, power consumption, and so on).

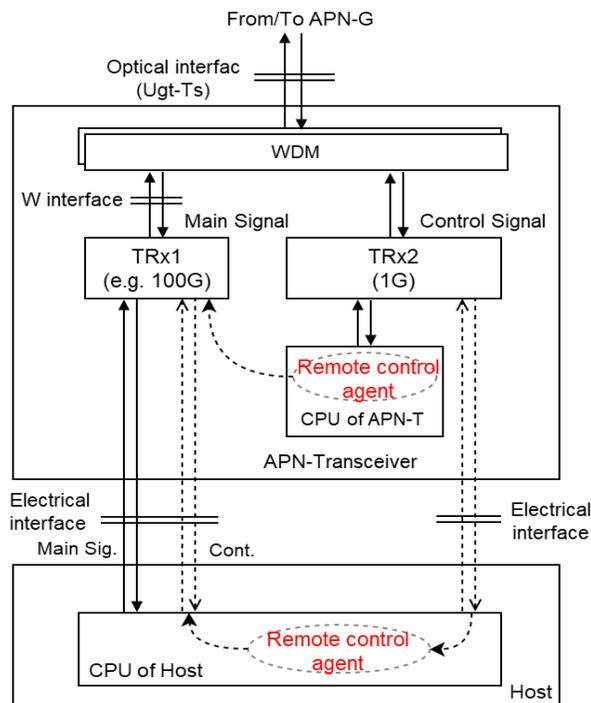


Figure C.3-2: Implementation Example of Integrated APN-T into Single Module

While these examples show the configuration that the main and the control signals are on the same access fiber, it is also possible to configure the control-signal channel on another physical route. For example, if there is an IP network to control and manage the white-box transponder, APN-T can also be controlled via the network.

When multiple APN-Ts are in one site, the number of fibers between the APN-G and the APN-Ts can be reduced using WDM. In this configuration, multiple APN-Ts can be controlled through one control-signal channel. This configuration is for further study and beyond the scope of this document.

The Open APN Functional Architecture also defines optical interfaces based on Intensity Modulation - Direct Detection (IM-DD). In this case, TRx1 will be an optical transceiver based on IM-DD, e.g., DWDM SFP+ that complies with ITU-T G.698.2 for the 10G optical interface.

C.4. Multi-lambda access between APN-T and APN-G

To achieve multi-lambda access via APN-S, APN-G must add/drop multiple wavelengths through one add/drop port. Figure C.4-1 shows implementation examples of APN-G that enable multi-lambda access. From the perspective of operational efficiency and durability, it is desirable to install APN-S in a location that is easy to operate and maintain, e.g., customer premises.

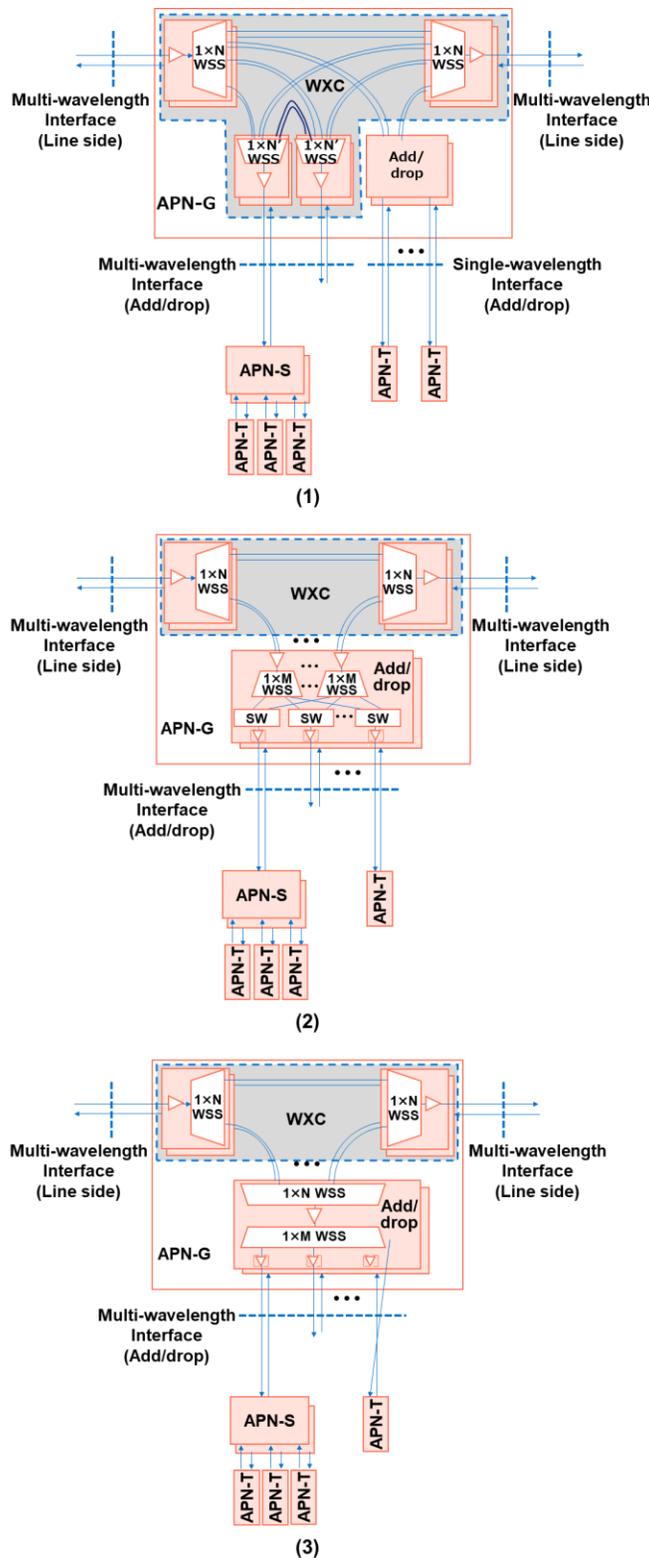


Figure C.4-1: Implementation Examples of APN-G Enabling Multi-Lambda Access.

In Fig. C.4-1(1), some multi-wavelength ports comprising the wavelength cross-connect (WXC) in APN-G are used as add/drop ports rather than line-side ports. Each multi-wavelength add/drop port accommodates multiple wavelength paths from APN-Ts within the same remote site. This configuration uses OpenROADM degree ports with MW

interface as multi-wavelength add/drop ports. Therefore, the existing OpenROADM YANG models can be applied. Since each multi-wavelength add/drop port is connected to APN-S, APN-S has functions equivalent to the degree port. In general, the number of wavelengths between APN-G and APN-S is smaller than that at the line-side degree port. Additional optical specifications for the multi-wavelength interface to OpenROADM MSA are for further study. Conventional add/drop in APN-G can still support wavelength paths from APN-Ts through a single-wavelength interface.

In Fig. C.4-1(1), among the four multi-wavelength ports comprising the WXC in APN-G, two ports are used as line-side ports while the other two ports are used as add/drop ports. Line-side ports mainly consist of $1 \times N$ WSSs and booster/pre-optical amplifiers for main-signal transmission. Add/drop ports mainly consist of $1 \times N'$ WSSs and booster/pre-optical amplifiers for main-signal transmission. When turn-back wavelength paths between remote sites are not required, N' can be smaller than N . To increase the number of accommodable remote sites, multi-wavelength ports with a larger number of WSS ports are needed. This configuration can drop wavelength paths from multiple line-side ports onto the same access fiber. In addition, wavelength overlap between remote sites can be allowed, allowing the same wavelength to be assigned to APN-Ts located at different remote sites. APN-G in Fig. C.4-1(1) can add/drop any combination of wavelengths to/from one add/drop port.

In Fig. C.4-1(2) and Fig. C.4-1(3), add/drop in APN-G is enhanced to enable to add/drop multiple wavelength paths through an add/drop port while the optical interface of the add/drop port (SRG port) is defined as a single-lambda interface W_r in OpenROADM MSA. The update of OpenROADM YANG models is for further study. When one APN-T is directly connected to APN-G, the add/drop port is configured to add/drop a single wavelength path.

APN-Gs in Fig. C.4-1(2) and Fig. C.4-1(3) include contentionless and contention-type add/drop unit, respectively. As the contentionless-type add/drop unit, a contentionless $M \times N$ WSS can be used as shown in Fig. C.4-1(2). The contentionless $M \times N$ WSS mainly consists of, for example, M sets of $1 \times N$ optical switches and N sets of $1 \times M$ WSSs. A $M \times N$ MCS can also be used as a contentionless-type add/drop unit. The $M \times N$ MCS mainly consists of, for example, M sets of $1 \times N$ optical switches and N sets of $1 \times M$ optical couplers/splitters. As the contention type add/drop unit, a contention-type $M \times N$ WSS is used as shown in Fig. C.4-1(3). In the contention-type $M \times N$ WSS, a $1 \times M$ WSS and a $1 \times N$ WSS are connected back-to-back. For both contentionless and contention types, there is no need to increase the number of WSS ports comprising the line-side multi-wavelength port every time the number of remote sites increases, unlike APN-G in Fig. C.4-1(1). For contentionless type shown in Fig. C.4-1(2), a constraint exists on provisionable wavelength-path configurations. Specifically, wavelength paths from multiple line-side ports cannot be dropped onto the same access fiber. In other words, wavelengths from multiple APN-Ts within the same remote site are forwarded to the same line-side port. This is due to the per-port rather than per-wavelength forwarding at the optical switches in the contentionless $M \times N$ WSS or the $M \times N$ MCS. Meanwhile, the contention type does not allow overlapping wavelengths between remote sites. APN-Gs in Fig. C.4-1(2) and Fig. C.4-1(3) can add/drop any combination of wavelengths to/from one add/drop port.

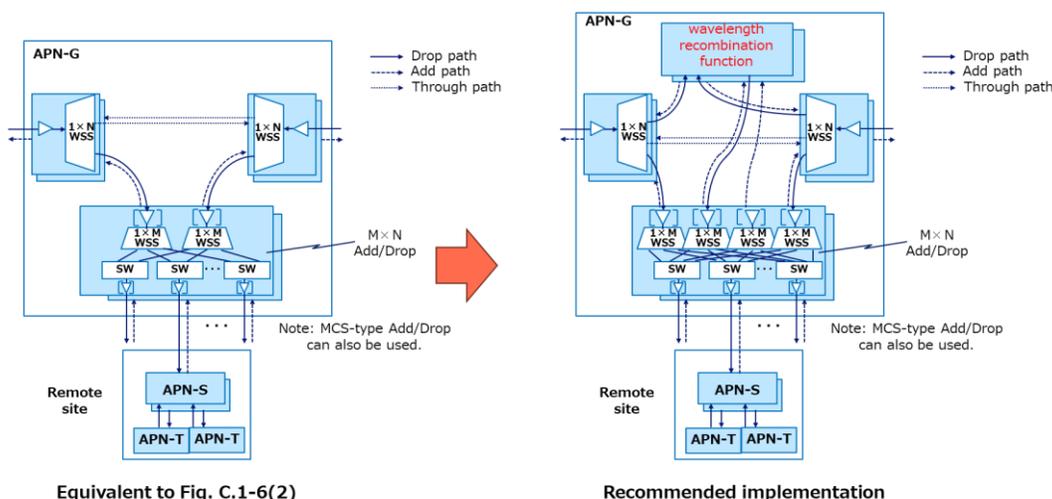
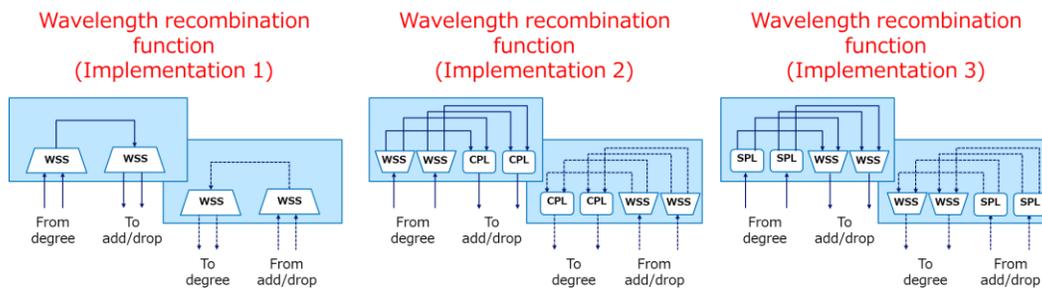


Figure C.4-2: Recommended Implementation of APN-G for the Multi-Lambda Access based on Contentionless-Type Add/Drop.

Figure C.4-2 shows a recommended implementation of APN-G for the multi-lambda access based on contentionless-type add/drop, in which the constraint for APN-G configuration shown in Fig. C.4-1(2) is eliminated. The figure on the right shows a solution that adds a wavelength recombination function, as shown in red. When drop paths with destination APN-Ts in the same remote site are input from multiple line-side ports, these drop paths are once forwarded to the wavelength recombination function section. The wavelength recombination function section outputs these drop paths to the same upper-side port of the contentionless-type M×N add/drop unit. In this way, APN-G can drop wavelength paths from multiple line-side ports onto the same access fiber. Note that when all wavelengths with destination APN-Ts in the same remote site are input from the same line-side port, these paths do not need to be recombined or pass through the wavelength recombination function. They are directly forwarded from one of the line-side ports to the contentionless-type M×N add/drop unit, as with regular APN-G. As for the add path, wavelengths from the same remote site are once forwarded from the contentionless-type M×N add/drop unit to the wavelength recombination function section when necessary. The wavelength recombination function section separates these add paths according to the wavelength path route.



WSS: Wavelength Selective Switch, CPL: Optical Coupler, SPL: Optical Splitter.

Figure C.4-3: Implementation Examples of Wavelength Recombination Function.

Figure C.4-3 shows some implementation examples of the wavelength recombination function. In Implementation 1, two WSSs are connected in a back-to-back configuration. As for the drop path, the first WSS combines drop paths from multiple line-side ports, or degrees. The second WSS separates them for each remote site. As for the add path, the first WSS combines add paths from multiple remote sites. The second WSS separates them for each degree. In Implementations 2 and 3, a combination of WSSs and optical couplers (COLs) and a combination of optical splitters (SPLs) and WSSs work for the wavelength recombination function, respectively. It is possible to use different implementations for add and drop paths. For example, WSSs + CPLs for drop paths in implementation 2 and WSSs + SPLs for add paths in implementation 3 can be combined.

C.5. Single-fiber bidirectional access

Single-fiber bidirectional transmission is widely utilized in the access network. At the same time, dual-fiber transmission is general used in carrier metro/core networks. To support end-to-end optical transmission through the access and carrier network in APN, the conversion between single-fiber and dual-fiber transmission is necessary. Figure C.4-4 shows some implementation examples of single-fiber/dual-fiber conversion. Blue lines between APN-T and APN-G/APN-FX are APN access network and single-fiber bidirectional transmission is used. Generally, different wavelengths (or sub carriers) are assigned for upstream (APN-T to APN-G/APN-FX) and downstream (APN-G/APN-FX to APN-T) transmission to avoid signal degradation due to reflection. For simplicity, a pair of upstream and downstream signals of λ_{up} and λ_{dn} is depicted here, but multi-lambda can also be supported.

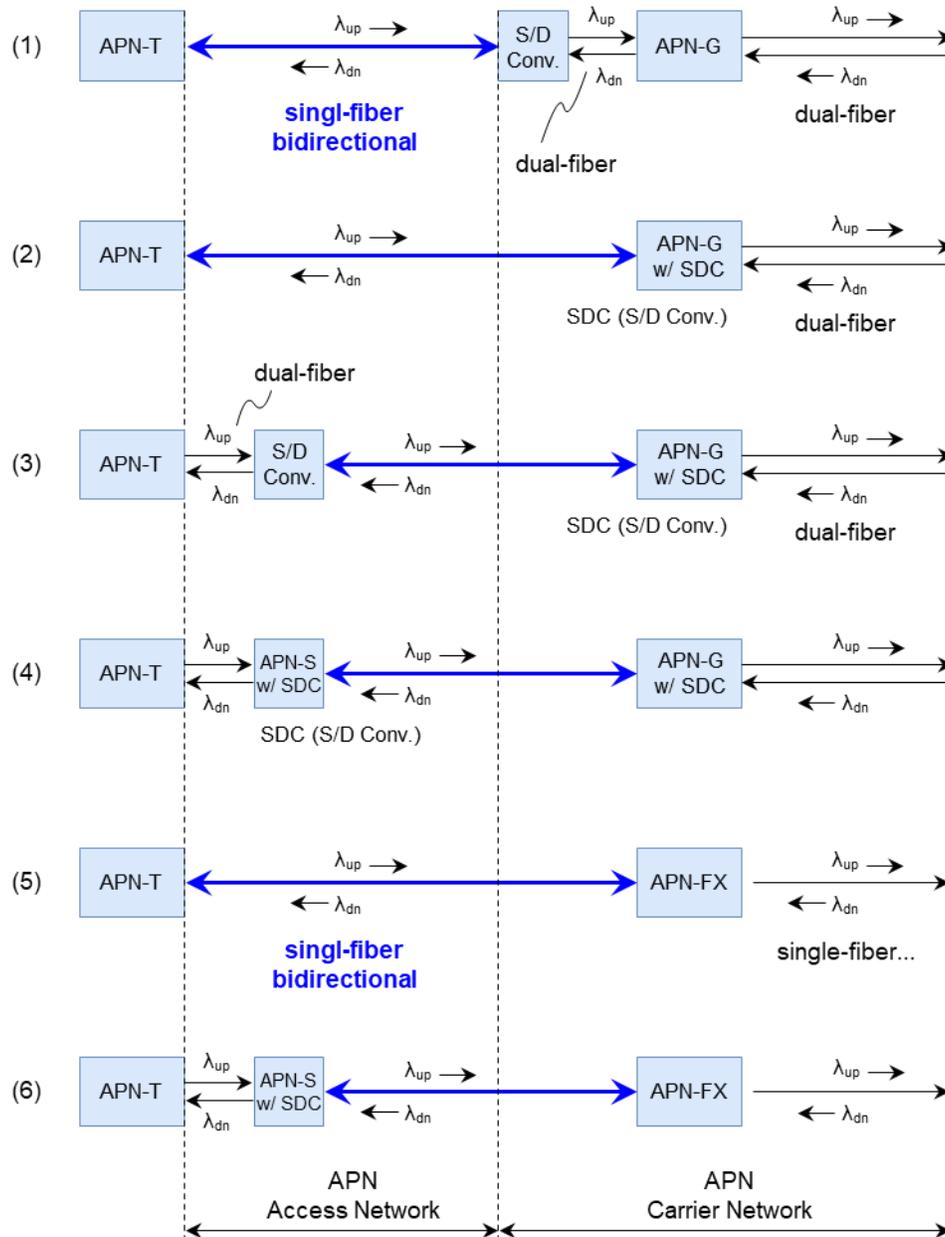


Figure C.4-4: Implementation Examples of Single-fiber Bidirectional Access

(1) Use of Single/Dual Converter on APN-G side

Single/Dual conversion is executed by a Single/Dual Converter (SDC) on the access side of APN-G. SDC can consist of optical circulators, WDM couplers, WSS and so on, and upstream and downstream signals of λ_{up} and λ_{dn} are transferred between single-fiber and dual-fiber. Note that when passive WDM couplers are used, the wavelengths of λ_{up} and λ_{dn} are fixed. Here, APN-T is a bidirectional transceiver. This implementation has the advantage of using the current dual-fiber APN-G to support single-fiber bidirectional access.

(2) Use of APN-G with Single/Dual Converter

If APN-G typically connects with single-fiber bidirectional access, it is cost effective that APN-G has the function of Single/Dual conversion in APN-G. APN-G can include Single/Dual Converter described in the example (1). It

is also possible to be configured to perform Single/Dual conversion using WSSs that comprise the add/drop blocks in APN-G.

(3) Use of Single/Dual Convertor on APN-T side

In case that APN-T is a dual port transceiver with Tx and Rx ports, Single/Dual Convertor (SDC) is necessary on the APN-T side. SDC can consist of optical circulators, WDM couplers, WSS and so on.

(4) Use of APN-S with Single/Dual Convertor

APN-S may have the function of Single/Dual conversion. This implementation can support multi-lambda and single-fiber bidirectional access.

(5) Use of APN-FX supporting single-fiber bidirectional metro

APN-FX can connect with single-fiber in the metro carrier network. Therefore, APN-FX can support single-fiber bidirectional access without the conversion. If optical amplification is necessary, dual-fiber carrier network can also be supported in APN-FX configuration. In this case, Single/Dual convertor (SDC) is needed like the example (1) of APN-G case. Here, APN-T is a bidirectional transceiver.

(6) Use of APN-S and APN-FX

In case that APN-T is a dual port transceiver, APN-S can be used in APN-FX configuration. This implementation can support multi-lambda and single-fiber bidirectional access.

D. Open APN Use Cases

D.1. Plug and Play Data Center

As a current issue with optical network infrastructure, the amount of data between data centers continues to increase each year, while the energy and resources consumed by data centers are becoming enormous, making it impractical to build large data centers in one centralized location. As a solution, one possible approach is to decentralize data centers and distribute them outside urban areas, leveraging renewable energy sources. One example is the concept of micro data centers. Micro data centers are smaller-scale data centers designed with a distributed processing architecture, unlike traditional centralized data centers. By interconnecting data centers through Open APN, it is expected to shorten the deployment time for high-speed, high-capacity networks.

With current technology, Linux-based network OS can be applied to transmission devices such as transponders. This allows for automatic optical path optimization technology using an infrastructure orchestrator to open optical transmission devices, enabling control of the entire data center by using open architecture software. It involves centralized implementation for building, configuring, and managing ICT resources such as network and computing resources, as well as optimizing their operations and configurations.

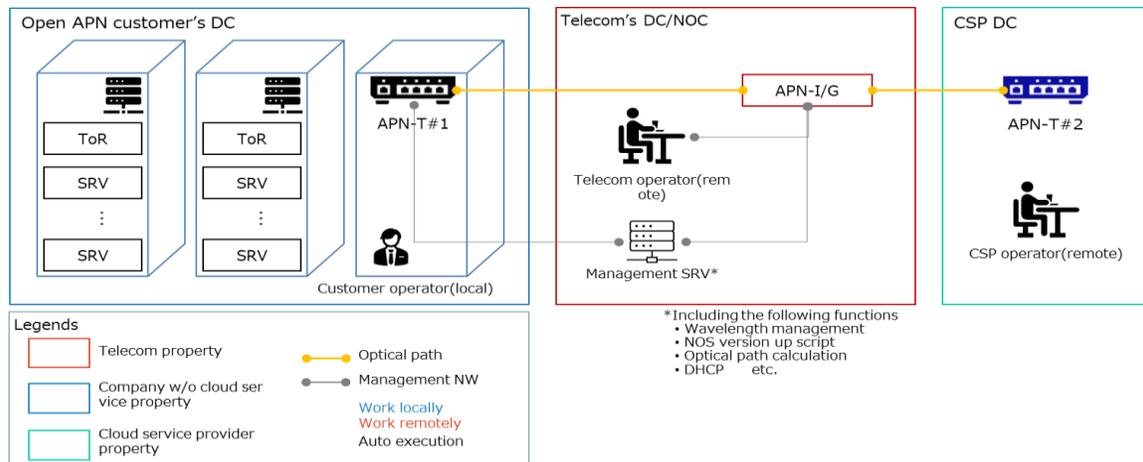
“Plug-and-Play” refers to the technology where devices are automatically recognized and configured without the need for additional manual setup or configuration by the user, simply by connecting the device. The purpose of Plug-and-Play is to simplify device usage and reduce the time required to start using them.

Operations to be automated:

- Automatic detection and setup of connections between optical transmission devices and servers.
- Remote troubleshooting of communication failures to identify the faulty component.

Potential use cases (Figure D.1-1):

- Copying large VM data between data centers with ultra-low latency service. Copying begins automatically and immediately when a new device is connected. For instance, in cases where it is necessary to set up temporary data centers in multiple locations, automating the process can be an effective use case for reducing the time to deployment.
- Rapid backup between data centers during disasters or power supply limits. Automating the process of data center optical path provisioning, which was traditionally done manually, can significantly reduce the time involved. For example, it is expected to eliminate the need for skill in tasks specific to optical equipment, such as "optical settings configurations." This makes it a suitable use case for situations where quick backups are required.



Objective

- Connecting APN-T#1 and APN-T#2

Prerequisite

- The wavelength is assigned management SRV in Telecom's DC

Point

- ALL optical path configurations are set remotely or automatically
- Customer operator does not need transponder skills

Figure D.1-1: Plug and Play Data Center Use Case

Provisioning workflow

1. Power on the APN-T
2. Cabling APN-T to management network
3. Establish IP reachability to management network of APN-T
4. APN-T version check and version up if need
5. Establish L1 reachability to Other DC of APN-T
6. Power on the ToRs and SRVs
7. Cabling ToRs and SRVs to APN-T
8. Setting-up Applications

D.2. Resilient Network Connectivity

Networks may be disconnected unexpectedly for multiple reasons (e.g., due to natural disaster). The Open APN would provide a highly resilient network with an automatic recovery mechanism, which is composed by streaming telemetry and path computation functions.

The target time for the network connectivity restoration needs further discussion (e.g., less than 50 ms [G.873.1][G.984.1]).

The following requirements are derived as an example from this use case (Figure D.2-1):

- real-time monitoring and streaming telemetry of network state and interface where disconnection happens,
- topology management of optical path,
- real-time analysis functions for making decisions regarding the allocation of path switching based on network state and the redundant resources of optical path.

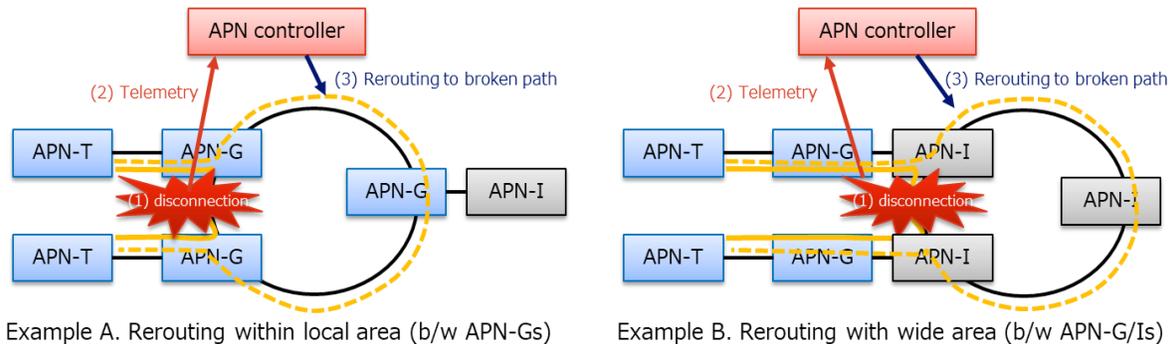


Figure D.2-1: Real-time Control for Resilient Network

D.3. Dynamic Optical Path Switch according to User Mobility

Traffic variation in optical networks occurs due to the movement of UEs. These variations become more dynamic with the increase of mobile traffic in a future mobile system such as 5G and 6G. In such situations, a central unit (CU) demands excessive computing resources because it is designed with the maximum resource size that can accommodate network traffic in a worst case scenario (i.e., it does not consider traffic variation).

The Open APN realizes load balancing of computing resources for mobile equipment (such as CUs) by providing a dynamic optical switch function according to the traffic variation by real-time estimation of mobile traffic using information through extended CTI (eCTI). On the other hand, if traffic exceeding the dynamically allocated computing resources arrives, the delay will continue to increase as long as the optical path remains unchanged, and frames are lost in the worst case. Therefore, realtime control of optical path switching is important in this application. Further discussion will be required in future releases regarding the detail of eCTI.

The following requirements are derived as an example from this use case (Figure D.3-1):

- realtime analysis functions for making decisions of path switching based on mobile traffic volume,
- redundant resources of optical path and wavelength,
- redundant mobile system resources (i.e., CUs) at different locations,
- topology management of combination of optical path and mobile system,
- cooperation method between Open APN and mobile network systems to monitor variation of mobile traffic volume, and
- dynamic path switching with cooperation of "change of gNB-CU-UP" [TS38.401]

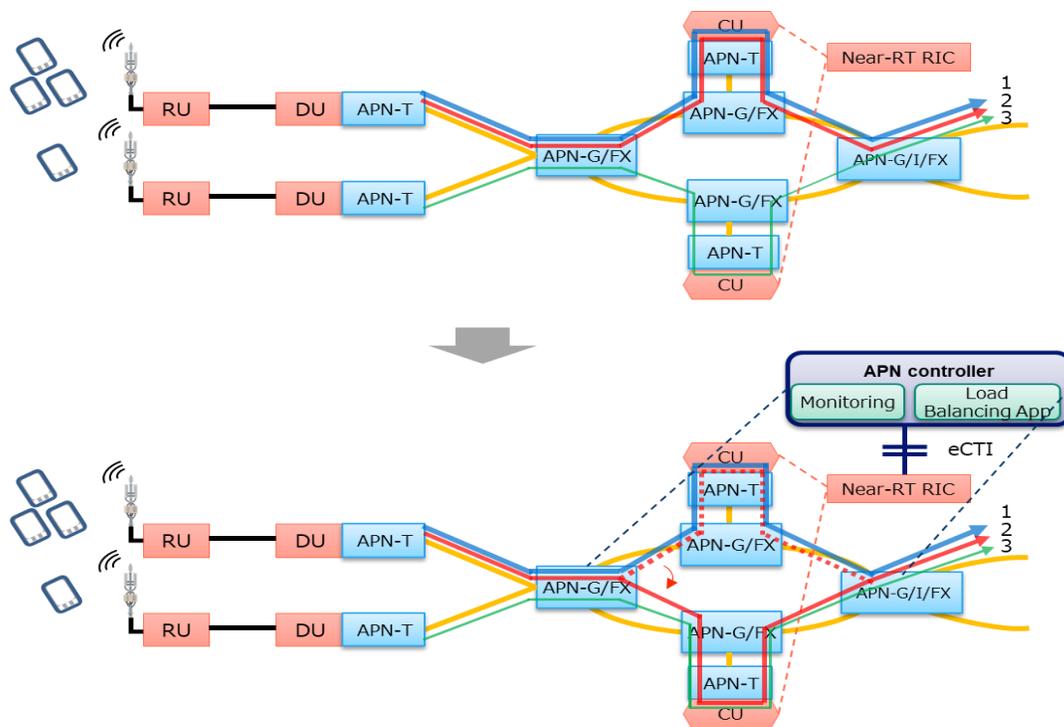


Figure D.3-1: Dynamic Optical Path Switch according to User Mobility

For APN-C, actual equipment to connect to via eCTI depends on the requirements of real-time control. Figure D.3-2 and Figure D.3-3 illustrate more concrete configurations in the case of aligning with O-RAN architecture. When the requirements are in the order of seconds or minutes, APN-C may receive information from non-realtime RIC as shown in Figure D.3-2. When the requirements are less than one second, APN-C will have to coordinate with near-realtime RIC which targets control between 10 milliseconds to one second, as shown in Figure D.3-3.

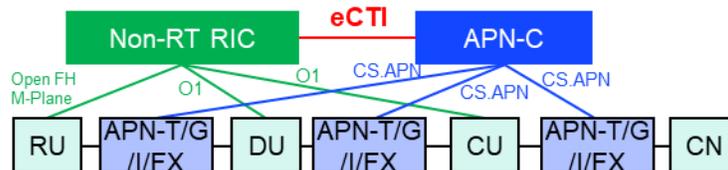


Figure D.3-2: eCTI between non-realtime RIC and APN-C

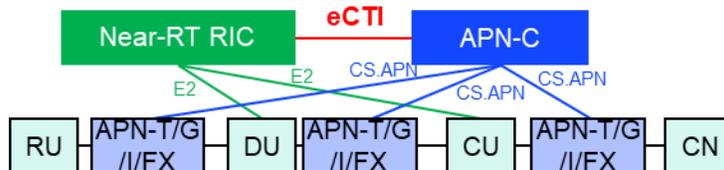


Figure D.3-3: eCTI between near-realtime RIC and APN-C

D.4. Real-time Optical Path Control for Stringent SLA

The Open APN will be an ideal platform for services that require a stringent SLA.

One of these assumed services is a remote failure detection service for infrastructure to factories by using remotely controlled drones with a control application on the edge of the network, which is shown in Figure D.4-1. If drones

move to other cells, an Open APN controller switches an APN-T for handover as well as an optical path from A to B for the effective utilization of wavelength resources. To sustainably keep to the SLA (e.g., E2E latency), the controller dynamically assigns optical path B (rather than path C) by analyzing the target SLA of the service and collected realtime latency information on each optical path and wireless network.

The following requirements are derived as an example from this use case:

- real-time monitoring and streaming telemetry of QoS (e.g., E2E latency), where QoS includes quality in mobile system and edge compute in addition to optical path,
- real-time analysis functions for making decisions of allocation of path switching based on QoS (e.g., E2E latency),
- topology management of a combination of optical path, mobile system, and edge computing resources,
- redundant resources including a combination of optical path, mobile system, and edge computing resources, and,
- stable user communications during dynamic path switching

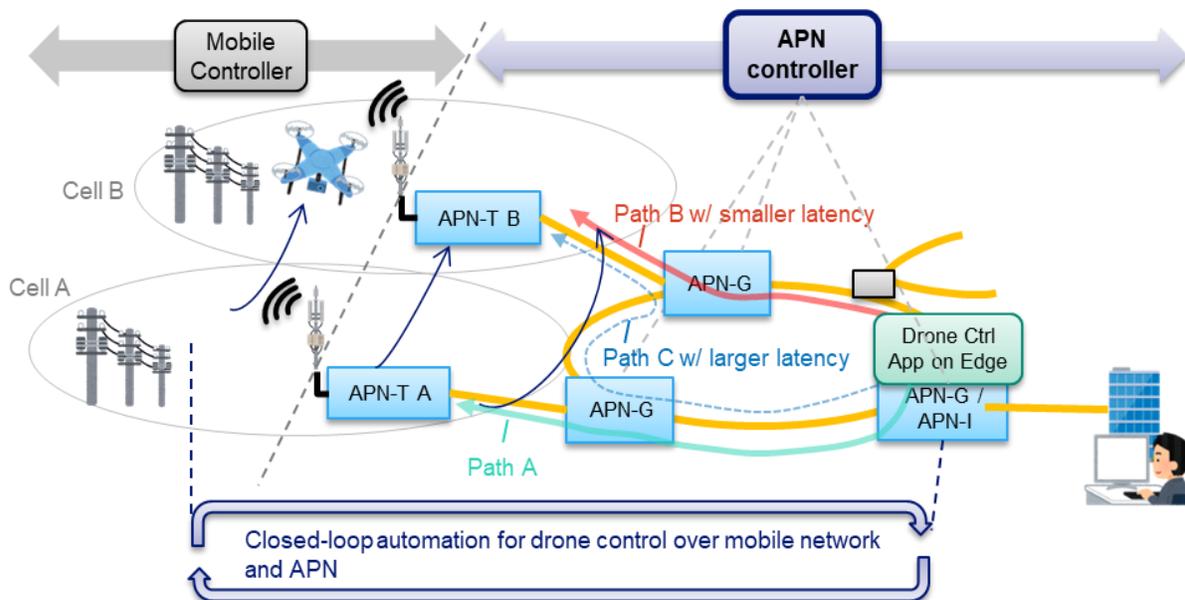


Figure D.4-1: Real-time Optical Path Control for Stringent SLA

D.5. Data Center Interconnect and Cloud Access Services

The Open APN will be an ideal platform for data-center interconnect (Annex A.3.2), as well as multi-cloud access services (Figure D.5-1).

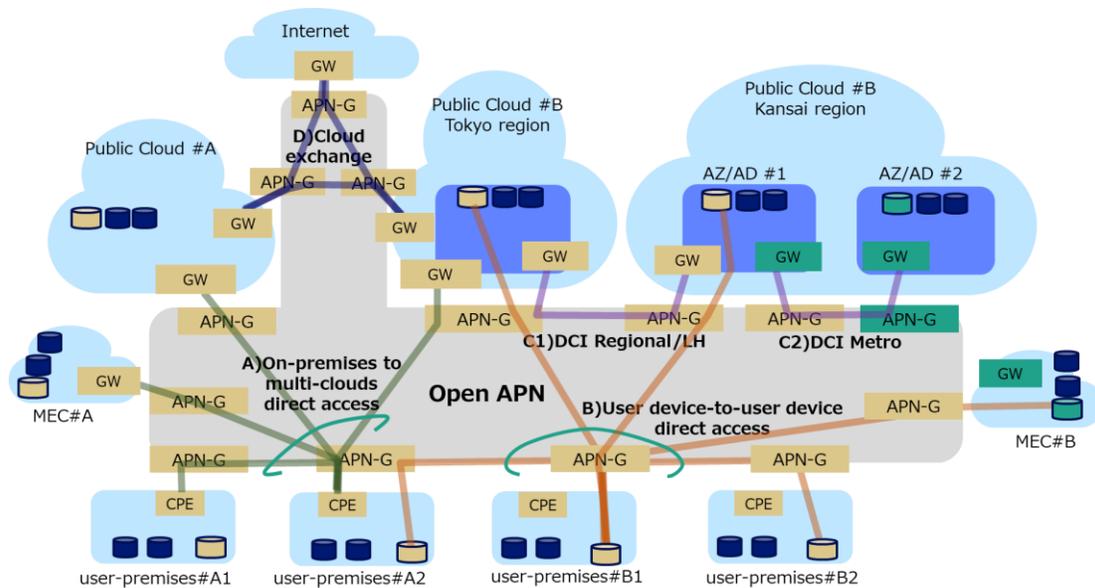


Figure D.5-1: Data Center Interconnect and Cloud Access Services

A) On-premise to multi-cloud direct access

- User-premises can access multiple cloud services or different user-premises with direct optical connection via an Open APN service provider.
- The Open APN service provider interconnects user-premises site#A and targeted cloud site or user-premises site#A and user-premises site#B with optical connection and transfer data to target sites according to data destination.

B) User device-to-user device direct access

- A user device can access targeted user devices within multiple cloud sites and other user-premise sites via an Open APN service provider. This is to provide ultra-low latency data transfer for user applications.
- An Open APN service provider interconnects user device#a and user device#b or user device#a and targeted user device#b within a cloud and transfers data to target user devices according to the data destination.

C) Data center interconnect for regional/long haul & metro connection

- Data centers forming a cloud service can interconnect with each other for data transfer. It is common that such data centers are organized by region (geographical location) or by availability zone/domain (fault isolation purpose).
- An Open APN service provider interconnects data centers for Regional/Long Haul (e.g., over 100km) (such as inter-region) and for Metro (e.g., within 100km) (such as inter-AZ/AD and intra-AZ/AD).

D) Cloud exchange

- User applications/data within a cloud can access other cloud services or Internet connectivity.
- An Open APN service provider interconnects multiple clouds and Internet.

E. Open APN Control Plane Details

E.1. Open APN Service Model Details

This section describes service model details utilizing the Open APN with a specific focus on where the Open APN provides PtP wavelength paths. Figure E.1-1 summarizes service model details when APN-Ts are located at user sites. Such APN-Ts may be user-owned. The vertical blue line in Figure E.1-1 is the boundary between the user network (including user-owned access fiber) and the Open APN service provider network.

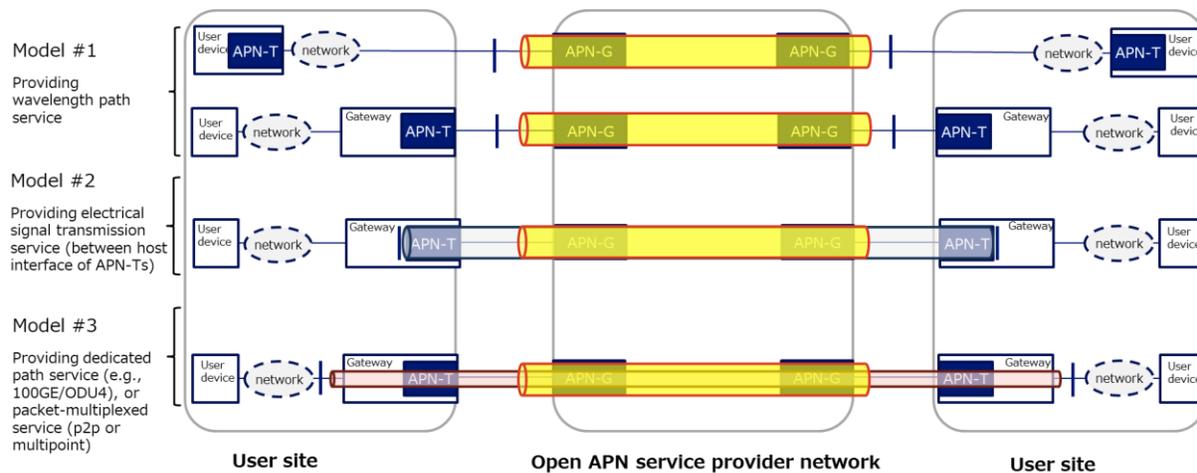


Figure E.1-1: Summary of Service Model Details Utilizing Open APN

Model#1 corresponds to the direct connect service described in Section 2.1. Model#2 provides electrical signal transmission between the host interface of APN-Ts. Model#3 corresponds to Flexible Bridging Services described in Annex A. Model#1 and Model#2 provide full capacity of a single wavelength path for use device while Model#3 typically provides mux/demux capability in the capacity of a single wavelength path.

- Model#1: An Open APN service provider offers wavelength path service to a user. Specifically, an Open APN service provider offers OTSi Wavelength Connectivity service provisioning.

NOTE: OTSi Wavelength Connectivity service provisioning is described in [TAPI547]. This corresponds to the connectivity service provided by the wavelength path.

- Model#2: An Open APN service provider offers electrical signal transmission service (NOTE) to a user. Examples of a gateway in Model#2 are a transponder, a muxponder, and a switchponder with a pluggable transceiver (APN-T); the electrical interface of the APN-T works as the service interface.

NOTE: The service interface specification depends on the type of APN-T. In the case of CFP2-DCO as an example, the electrical interface specified by OIF IA [OIF-CFP2-DCO] can be used as the service interface.

- Model#3: There could be various services via this model. One is where an Open APN service provider offers dedicated (not packet-multiplexed) path service to a user. Specifically, the Open APN service provider offers Digital Signal Rate (DSR) connectivity service (NOTE 1) to a user, supported over wavelength path(s). An example of a gateway is a muxponder. The other is where an Open APN service provider offers a user packet-multiplexed service (NOTE 2). The packet-multiplexed service is supported over optical wavelength path(s), with packet optical integration/cooperation. An example of the gateway is switchponder [OpenROADM Device White Paper].

NOTE 1: This is TAPI terminology, meaning a digital signal of an unspecified format. An example is 100GE/ODU4 for connectivity service.

NOTE 2: Example services are P2P (E-Line) or multipoint (E-LAN or L3VPN) services over optical wavelength paths. Example technologies are MPLS/VXLAN over optical wavelength paths.

E.2. Control and Management Scope of the APN-C

The scope of control and management of the APN-C depends on the service model details described in Annex E.1. Figure E.2-1 shows a summary of the control and management scope of the APN-C.

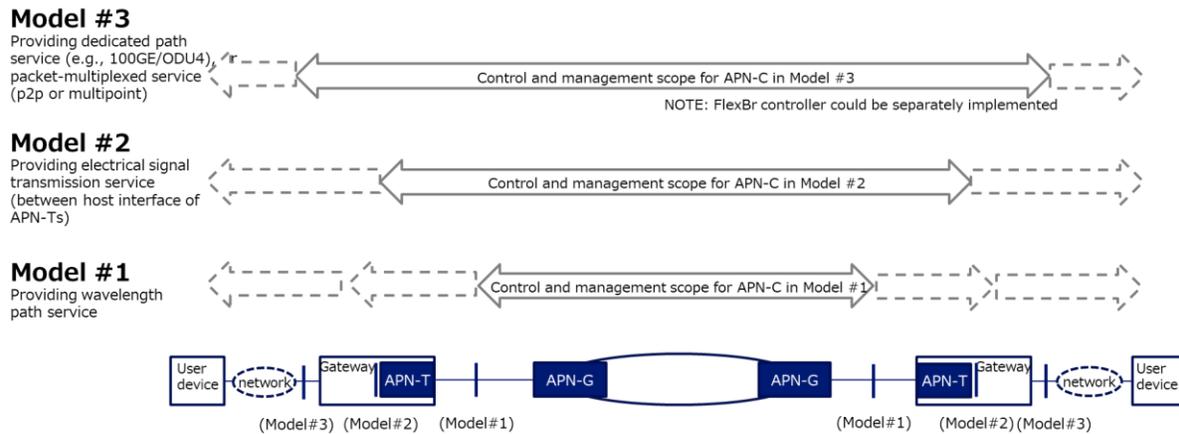


Figure E.2-1: Summary of Control and Management Scope of APN-C

In Model#1, the APN-C not only controls and manages the APN-G/I but also maintains some elements of user network information, as described in Section 5.1. At a minimum, the APN-C needs to maintain the APN-T capabilities/parameters and access fiber parameters (if access fiber is part of the user facility) as part of the user network information. For such purposes, the APN-C may be privileged to directly control and manage APN-Ts after network attachment and authentication. Unless there is a clear demarcation between APN-T and other parts of the gateway, the APN-C may be privileged to directly control and manage the gateway as a whole.

The semantics of endpoint addresses for wavelength path services may differ depending on the scope of control and management of the APN-C. When the APN-C is privileged to control and manage an APN-T, endpoint addresses are assigned to gateway line interfaces.

When the APN-C is privileged to control and manage the gateway, endpoint addresses are assigned to the gateway client interfaces.

Furthermore, the APN-C may maintain or be privileged to control and manage the user network at a granular level, down to user devices, to assure QoT of end-to-end communications.

In Model#2, the APN-C controls and manages the APN-T and APN-G/I. Furthermore, the APN-C may maintain or may be privileged to control and manage the gateway as a whole and the entire user network down to the network's user devices to ensure QoT of end-to-end communications.

In Model#3, the APN-C controls and manages gateways (including APN-T) and APN-G/I. Furthermore, the APN-C may maintain or may be privileged to control and manage the user network, including user devices, to assure QoT of end-to-end communications. In this model, single APN-C controller or multiple controllers including those other than APN-C may be used. For example, FlexBr controller is a logical entity controlling the gateways.

E.3. Detailed Sequences

This subsection describes detailed sequences for the registration of a user network device (APN-T or a gateway) and the wavelength path setup involving the user network device. These sequences are applied to all the models described in the previous subsection. In the case of Model#1, the APN-C needs to be privileged to control and

manage the APN-T or the gateway directly or via the user network controller. In the case of Model#2, the APN-C controls and manages the APN-T or the gateway via the in-band or communication channel described in Section 5.2 and Annex C.3, or via the out-band communication channel.

Figure E.3-1 shows detailed sequences of (1) the registration of a user network device, described in Section 5.4. In this example, the APN-C receives requests from the orchestrator or other external management system through its Northbound Interface (NBI). In addition, it is assumed that the APN-C is privileged to directly control and manage APN-Ts/gateways. There is also an alternative model where a user network controller or application exists. In this case, the APN-C does not directly communicate with APN-Ts/gateways, but communicates through this user network controller or application. Note that the use of in-band and out-band control channels in regard to NBI/SBI requires further study.

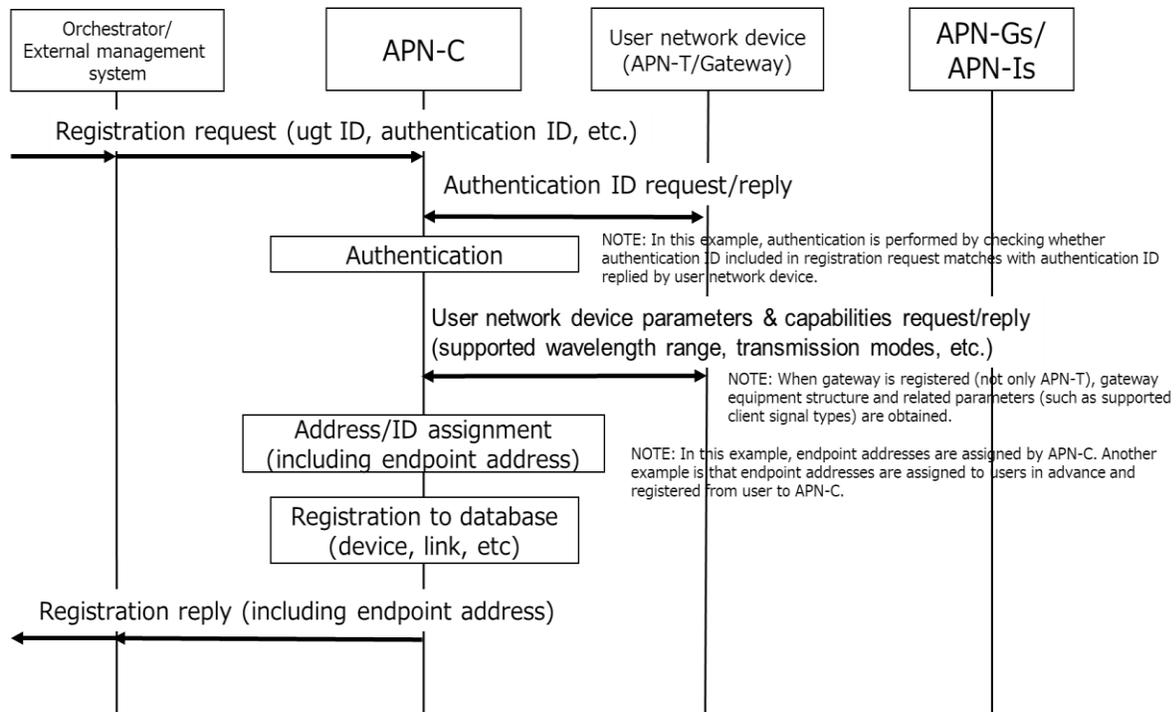


Figure E.3-1: Detailed Sequences for Registration of User Network Device

In Figure E.3-1, authentication of a user network device is performed by checking whether the authentication ID included in the registration request matches with the authentication ID provided by the user network device. There could be other methods, but further study is needed for authentication mechanisms, considering trust models, available technologies, etc.

Furthermore, in Figure E.3-1, endpoint addresses are assigned by the APN-C and sent to users. Users can request path setup by specifying endpoint addresses. Alternatively, endpoint addresses may be assigned to users in advance and registered to the APN-C. Further study is needed for endpoint address assignment mechanisms, considering usability, manageability, etc.

Figure E.3-2 shows detailed sequences of (2) wavelength path setup, described in Section 5.4.

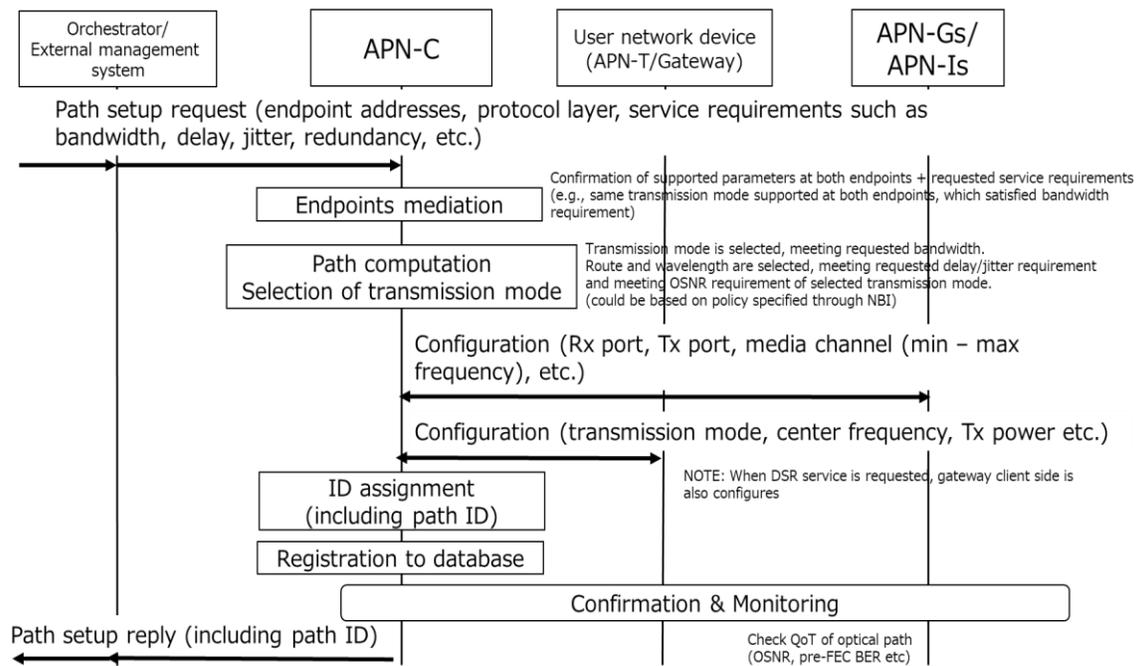


Figure E.3-2: Detailed Sequences for Optical Wavelength Path Setup

TAPI [TAPI] is a good candidate for APN-C NBI. OpenROADM [OpenROADM] and OpenConfig [OpenConfig] are good candidates for APN-C SBI (OpenROADM for APN-G/I/T and OpenConfig for APN-T). Further study is needed for the applicability of TAPI and OpenROADM/OpenConfig to sequences of (1) registration for user network devices.

When APN-C controls user network device with in-band control channel described in Sections Annex C.2 and C.3, wavelength-path and fiber-path endpoints can be flexibly set beyond the reach of the control and management network. In this case, it would be ideal that user network device registration and wavelength path setup are performed based on control-signal exchange between APN-C and user network device, without any requests from an orchestrator or external management system. This capability, as known as plug-and-play feature, enables wavelength paths to be established simply by connecting user network device to APN, shortening the lead time for establishing wavelength paths.

Figure E.3-3 shows an example sequence of the registration of a user network device based on the plug-and-play concept.

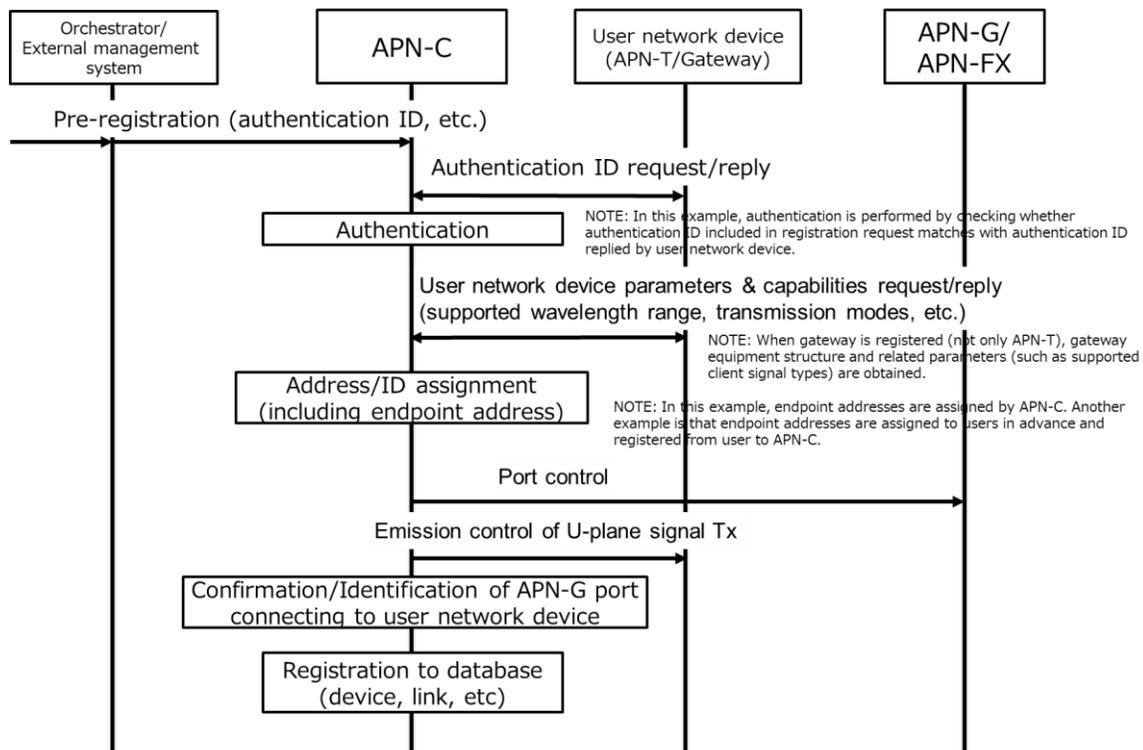


Figure E.3-3: Detailed Sequences for Registration of User Network Device based on Plug-and-Play Concept

The authentication IDs of user network devices that can be allowed to connect to APN are registered in advance in APN-C as a whitelist. This is a difference compared to the sequence in Figure E.3-1, where the authentication ID of user network device is notified to APN-C in the registration request only when registration is required. Authentication ID request and reply starts when a user network device is connected to the APN. Authentication of the user network device is performed by checking whether the authentication ID contained in the authentication ID reply is included in the pre-registered authentication IDs.

The assignment of addresses/IDs, including endpoint address, is performed in the same manner as the sequence in Figure E.3-1.

Before proceeding to the step of the registration to the database, APN-C executes port control to APN-G/APN-FX as well as emission control of the transmitter (Tx) for user-plane (U-plane) signal to the user network device (APN-T/Gateway), thus confirming or identifying the APN-G/APN-FX port that is connected to the authenticated user network device. When APN-C already recognizes the APN-G/APN-FX port connected to the authenticated user network device during the authentication process, APN-C validates the authenticated user network device and confirms the physical connection between APN-G/APN-FX port and user network device to allow it to connect Open APN through APN-G/APN-FX. The physical connection between APN-G/APN-FX port and the user network device can be confirmed by checking whether the optical power of the U-plane signal from the user network device reaches the appropriate APN-G/APN-FX port. The emission control of Tx for the U-plane signal in the user network device enables a plug-and-play option where APN-C autonomously identifies the APN-G/APN-FX port that is connected to the authenticated user network device. In this case, APN-C identifies the APN-G/APN-FX port that detects optical power according to the emission control as the port connected to the authenticated user network device.

Figure E.3-4 shows an example sequence of wavelength path setup based on the plug-and-play concept.

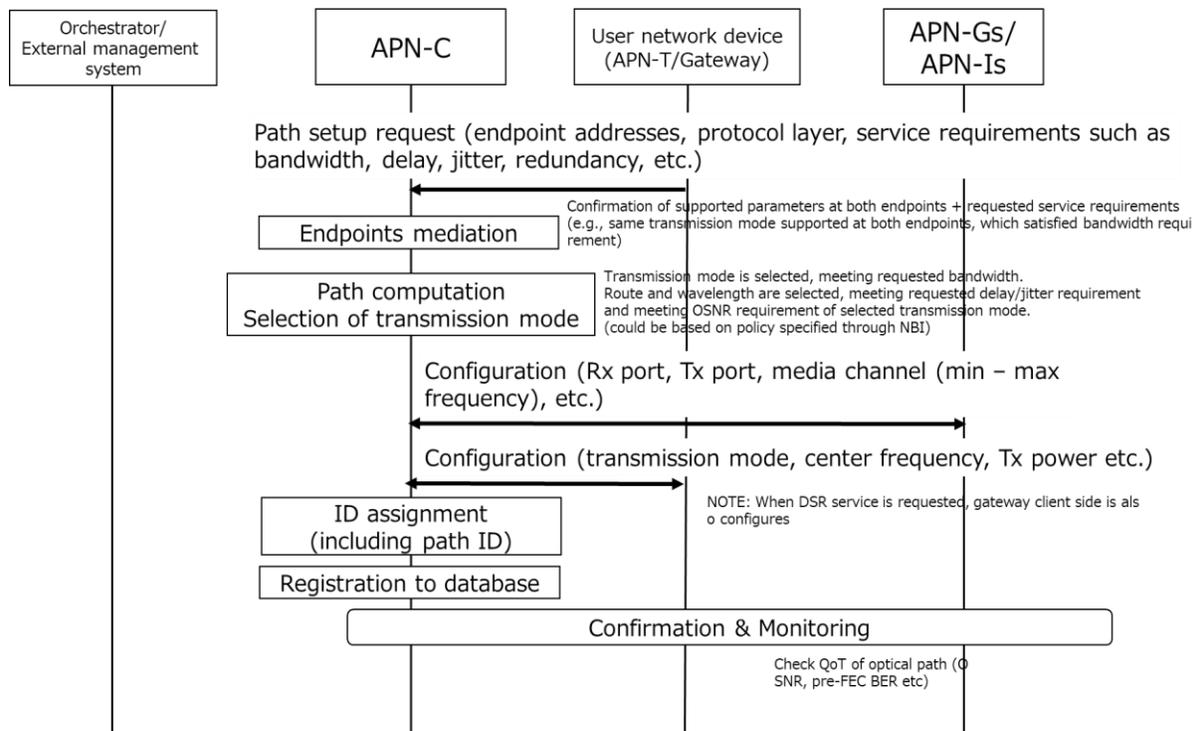


Figure E.3-4: Detailed Sequences for Optical Wavelength Path Setup based on Plug-and-Play Concept

Path setup request is notified to APN-C from user network device via APN-G rather than from orchestrator or external management system.

The protocol, e.g., NETCONF or a lightweight protocol, used to exchange control signals between APN-C and user network device needs to be determined according to the processing capabilities of the user network device.

E.4. Controller and Orchestrator

The Infrastructure Orchestrator automates and manages infrastructure such as Open APN and DCI (Figure E.4-1). It can handle complex infrastructure resources, including multiple Open APN optical paths and DCI computer resources, in an integrated manner, enabling efficient resource utilization, high availability, and scalability. It streamlines and automates the service and operation lifecycle. For Open APNs, it creates/updates optical paths and maintains the Open APN architecture. It also dynamically optimizes Open APN resources. Policies for these functions are determined and directed by the administrator.

Specifically, The Infrastructure Orchestrator has the following features:

- Automated assignment of infrastructure resources: It can automatically assign and manage infrastructure resources required for service delivery. It also optimizes resource allocation to efficiently utilize resources.
- Scaling: It can automatically scale infrastructure resources up or down based on service demand.
- Load balancing: It can distribute loads across multiple infrastructure resources automatically if the load is concentrated on a particular resource.
- Monitoring and restoration: It can monitor the state and operation of the infrastructure and perform troubleshooting and recovery actions in case of problems.

The Infrastructure Orchestrator automates and manages multiple infrastructures, such as computers, networks, and storage. Specifically, they perform the following roles:

- Resource allocation: The orchestrator automatically allocates infrastructure resources, such as the Open APN, as needed. This ensures system scalability and flexibility and enables more efficient resource provisioning. The Infrastructure Orchestrator allocates resources through the provisioning interface by communicating with the APN-C connection service function.
- Monitoring: The Infrastructure Orchestrator monitors resources through the notification interface by communicating with the APN-C monitoring function. This enables the early detection and quick resolution of system issues. Examples of the targets being monitored include the status of equipment or optical paths.
- Automation and Integration: The Infrastructure Orchestrator automates workflows by combining processes for multiple operations. This automates tasks such as assigning or updating infrastructure resources, monitoring, and error handling. The orchestrator manages the services and states of multiple Open APNs and coordinates communication and data exchange between them. This enables the efficient management of complex infrastructure resources and increases the availability and reliability of the provided infrastructure.
- Administration: The administrator feature determines and instructs how The Infrastructure Orchestrator, connectivity service, and monitoring collaborate and operate based on what policies. Through these policies, it assists in the smooth provision of infrastructure resources. It also collects and analyzes information on resource status for more granular control. The role also includes maintaining the controller, such as performing system updates and improving resource management.

By performing these roles, Infrastructure Orchestrators play a crucial role in automating, scaling, and improving the availability and reliability of systems.

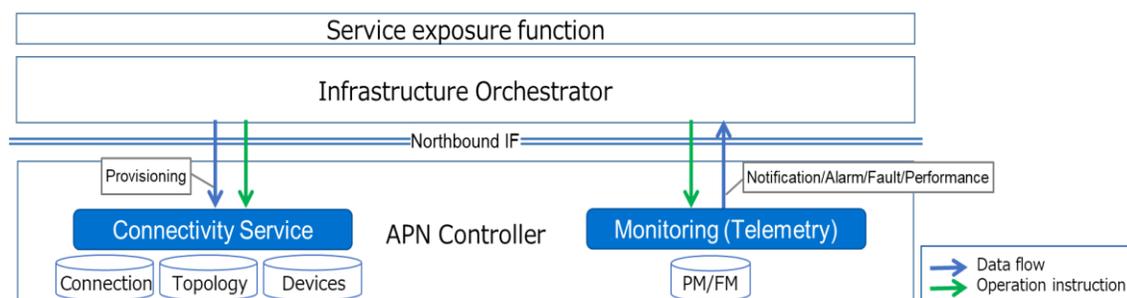


Figure E.4-1: Infrastructure Orchestrator Functional Diagram

The Infrastructure Orchestrator centrally manages multiple resources of Open APNs, automates resource assignment, and performs resource optimization. In addition, the service exposure provides a mechanism to expose infrastructure externally, such as through an API gateway. This allows for the provision of high-speed and high-capacity infrastructure services of Open APNs. These roles are closely related to building ecosystems such as microservices architectures. The Infrastructure Orchestrator can provision infrastructure resources such as Open APNs and schedule resource assignments automatically. This allows for quick and easy provisioning of dynamic and temporary resource assignments.

There are still unresolved issues that should be discussed regarding the functional composition between the Infrastructure Orchestrator and other resource controllers. Additionally, the coordination among multiple controllers will be further elaborated and specified during future discussions.

E.5 Accurate QoT estimation

To maximize the benefits of APN, it is essential to optimize network resources by selecting suitable routing, wavelength allocation, and modulation format through APN-C. At the same time, APN-C must also control the transport equipment, such as optical transceivers, amplifiers, and so on, to ensure enough quality of transmission (QoT) to connect the paths assigned. Therefore, it is necessary to set a suitable margin considering uncertainties caused by individual differences in the transport equipment, such as the receiving sensitivity of the transceiver, ASE noise of amplifiers, and so on, when determining reachability. Since open and multi-vendor networks such as the OpenROADM project allow various implementations of optical transport equipment, uncertainties in the characteristics of the used equipment increase. It is critical to reduce the margin for these uncertainties to realize both increasing the transmission capacity and provide enough quality of transmission. There are methods to use the QoT based on the obtained monitoring data concerning actual equipment and path properties to overcome this issue as

shown in ref. (*1~3). The accurate QoT estimation is realized because their real performance, which eliminates the uncertainties of individual differences and vendor-dependent differences in the transport equipment, can be used. Therefore, the function to estimate the QoT from the actual network should be implemented in APN-C to use the maximum amount of network resources.

Figure E.5-1 shows a summary of QoT estimator implemented to APN-C. The QoT estimator monitors the actual network path and equipment of APN and estimates QoT based on the monitored data. Because the quality of transmission (QoT) can be verified using the Gaussian Noise (GN) model-based simulation tool, e.g. GNPY, the function to create and update the model is necessary for APN-C.

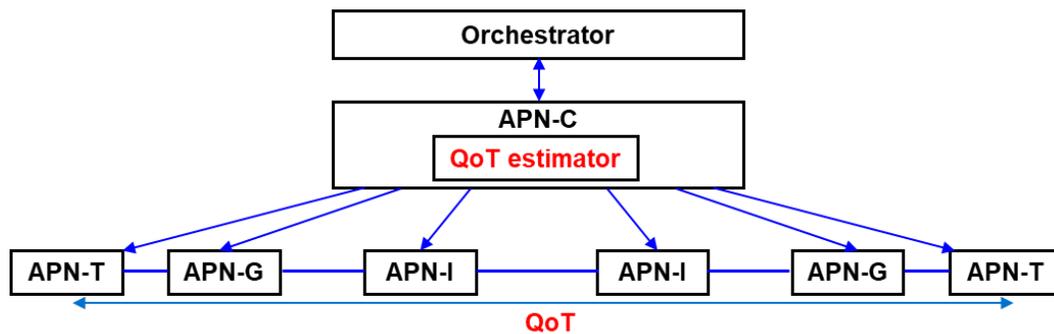


Figure E.5-1: Summary of QoT estimator implemented into APN-C

Figure E.5-2 shows an example of the procedure to obtain the accurate QoT and use it to find the highest-order modulation format. The BERs and OSNRs monitored from the equipment provisioned to the network are sent to the QoT estimator. Based on the monitored data, model parameters for QoT of the concerning equipment are updated. QoT of potential modulation formats for new service requests is estimated using the updated model and the highest-order modulation format is assigned. The following methods have been proposed to improve the accuracy of QoT estimation and to optimize network resources.

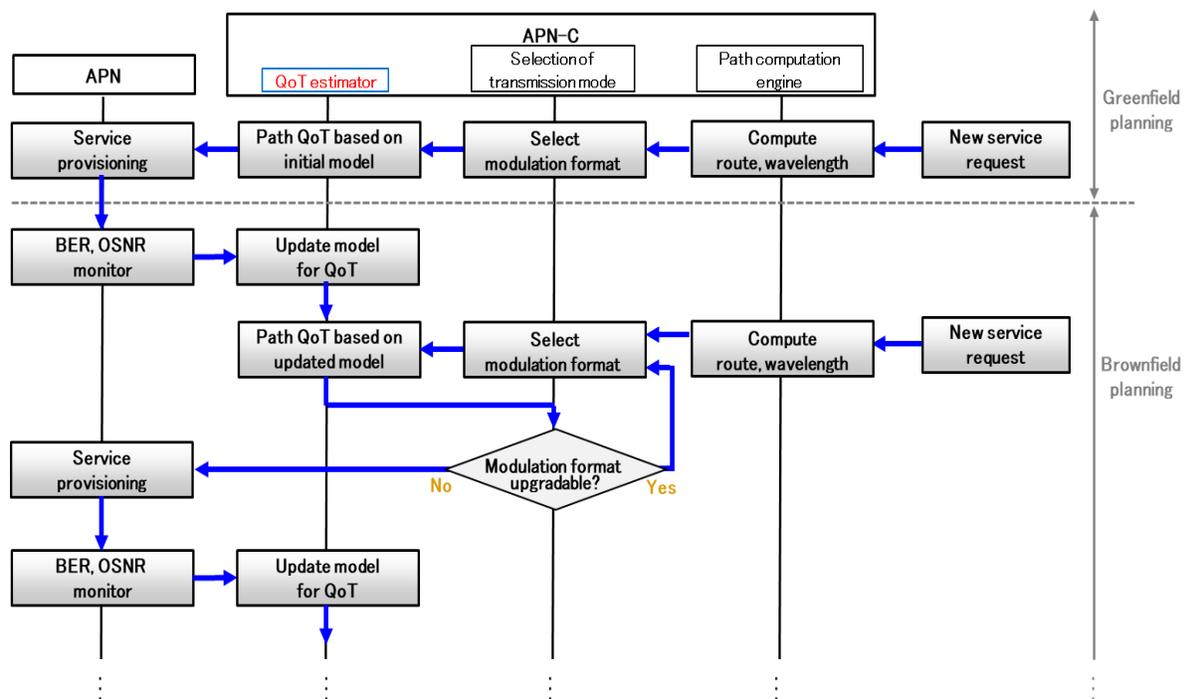


Figure E.5-2: Procedure to obtain the accurate QoT and use it to find the highest-order modulation format

Methods to improve the accuracy of QoT estimation:

- By measuring the back-to-back (B2B) BER-OSNR values, individual transceivers can be modeled as Gaussian noise like ASE and NLI noises. In addition to the characteristics of a conventional transmission path such as ILA, a model corresponding to the transceiver can be used. Therefore, the transmission quality (QoT) can be estimated with high accuracy.
- By monitoring the characteristics related to the received signal, such as Pre-FEC BER, in the network currently in use, the QoT of the relevant path can be measured. A function to update the parameters of the transmission model based on Gaussian noise model using the measured QoT is implemented in the APN controller. With this function, the accuracy of the model can be improved, which can be helpful to operate networks close to actual performance. In ref. (*2), it was demonstrated that the reachable highest-order modulation format based on the QoT estimation with increasing accuracy can be selected when a new connection service is requested. The total capacity improvement by approximately 15% was successfully confirmed in the network test bed.

*1 H. Nishizawa et al., "Dynamic Optical Path Provisioning for Alien Access Links: Architecture, Demonstration, and Challenges" in IEEE Communications Magazine, Vol. 61, No. 4, p136-142, April 2023.

*2 S. Oda et al., "Network Capacity Improvement by Quality of Transmission Estimator with Learning Process" in Proc. ECOC2017, Th.2.C.4.

*3 P.Yvan, "Design of Low-Margin Optical Networks" in Journal of Optical Communications and Networking, Vol. 9, No.1, pp. A9-A17, 2017.

E.6 Network lifecycle management

Network Lifecycle Management is performed by the interaction of the following actors. It is executed in four phases. Network Digital Twin (NDT) has the potential to streamline Network Lifecycle Management operations.

- Actors
 - User/Application Layer: Requests the use of the APN services
 - Infra Orchestrator: Allocates network resources (incl. APN) according to the user requests
 - Network Operator: Controls/manages the APN path
 - APN-C: Creates/Controls the optimal APN path
- Phases
 - Service Request
 - The User/Application Layer requests the Infra Orchestrator to use the service. The Infra Orchestrator sets network requirements according to the service request.
 - Network Design/Implement
 - The APN-C and Network Operator design the APN based on the network requirements. Once the path design results are approved by the User/Application Layer, the APN path is created. After that, the user starts using the service.
 - Operation/Monitoring
 - After the service has been started, the network should be monitored. The Network Operator detects any degradation of service quality or failure. When the service degradation or failure occurred, the Network Operator reconstructs the path to deal with the failure.
 - Service end
 - When the service is terminated, the APN paths that have been established are deleted.

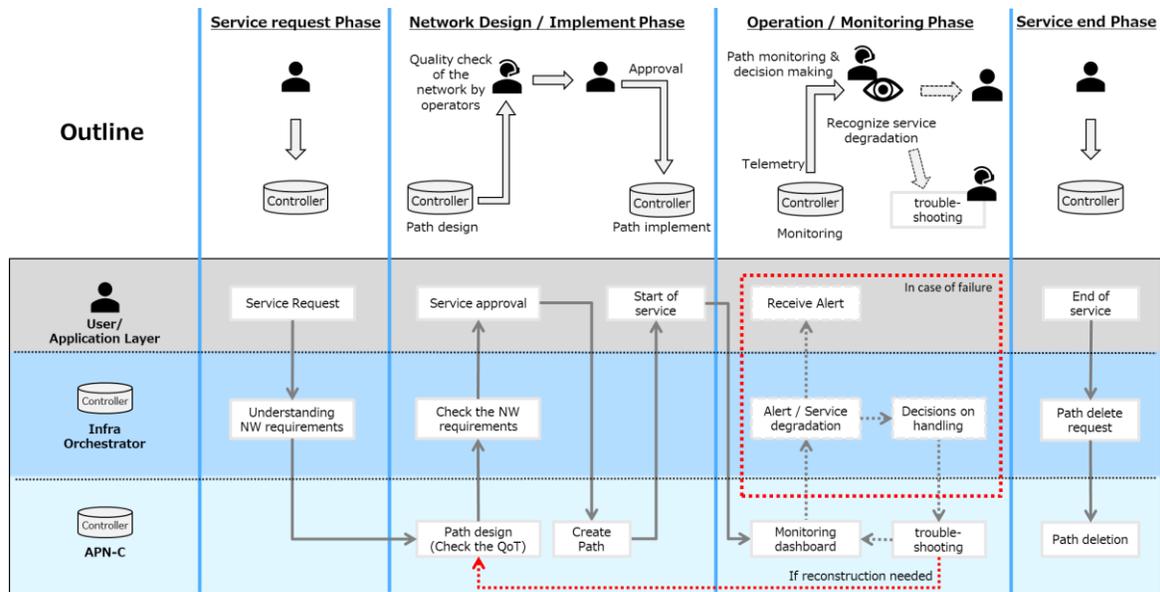


Figure E.6-1: Network lifecycle management (w/o NDT)

Network Digital Twin can be applied step by step in the Network Design/Implement and operation/monitoring phases of operation. For example, QoT information obtained during the monitoring process is fed back to the NDT. This information could be used to construct new paths or to optimize the whole APN.

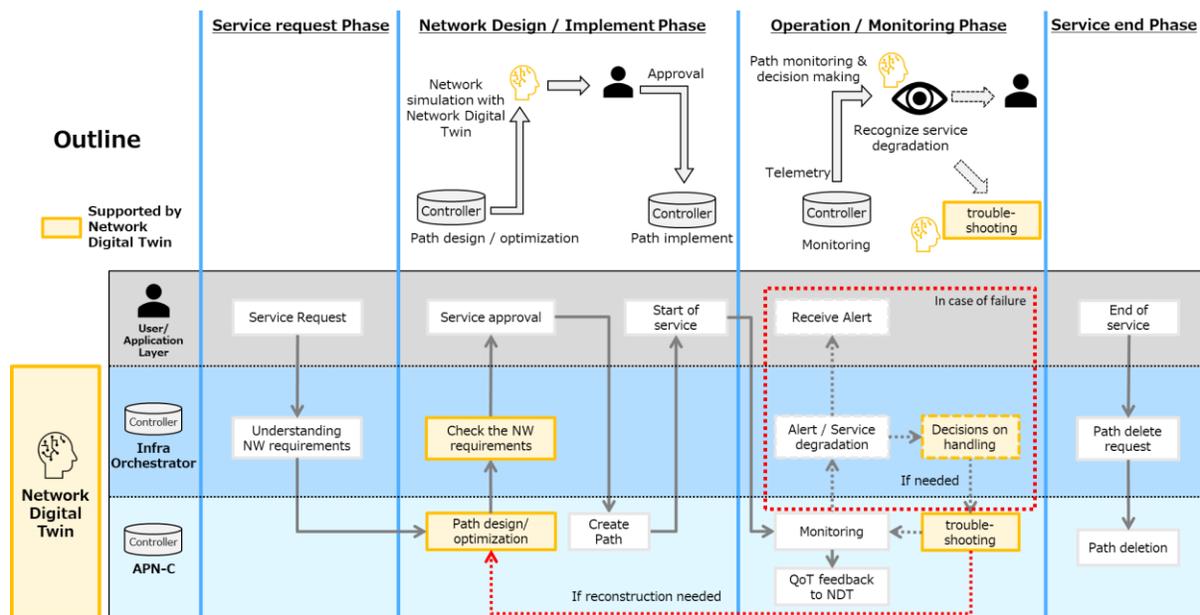


Figure E.6-2: Network lifecycle management (w/ NDT)

F. Point-to-multipoint Technique

This Annex describes characteristics of general point-to-multipoint (PtMP) optical access techniques as well as some frameworks to leverage them in Open APN.

For realize the PtMP wavelength path service in Open APN, further studies are needed on detailed requirements (e.g., acceptable latency), how to accommodate the PtMP optical signals in Open APN.WX (especially in APN-G and APN-I), etc.

On the other hand, the PtMP fiber path service just offers optical paths equivalent to a PtMP fiber infrastructure (i.e., splitter(s) plus fibers). In that regard, many existing PtMP optical access systems are expected to be implemented on the top of it.

F.1. Multiplexing Methods

Passive Optical Networks (PONs) are a traditional PtMP optical access technique that covers a range of access technologies to deliver FTTx connectivity over a shared and passive point-to-multipoint optical distribution network. The system consists of an Optical Line Termination (OLT) node serving one or multiple Optical Distribution Networks (ODNs), each ODN connecting multiple user-facing Optical Network Units (ONUs) to the OLT. The OLT is the controller of the ONUs.

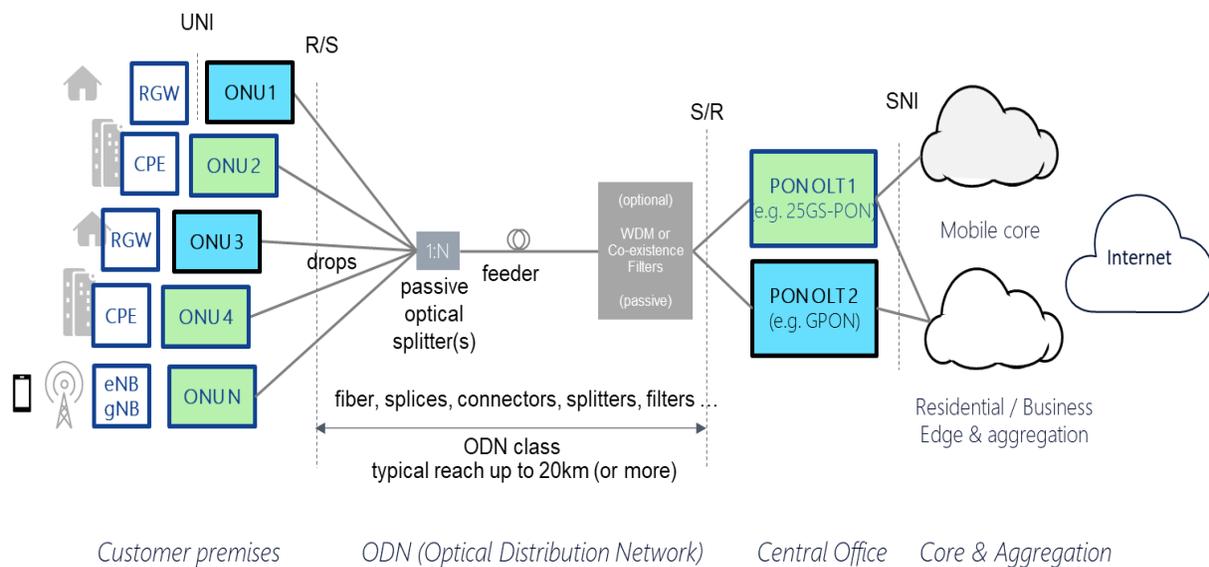


Figure F.1-1: A Passive Optical Network System Composed of OLT, ONUs, and Point-multipoint Fiber Infrastructure

Two-way communication between the OLT and the ONUs is full-duplex by using different wavelength bands on the fiber for the upstream and downstream directions.

There are basically four types of PON technologies.

The first is TDM PON, where the bandwidth on the common upstream and downstream wavelengths is shared between the ONUs in a Time Division Multiplexing (TDM) fashion. TDM PON reaches point-to-multipoint connectivity over a point-to-multipoint fiber infrastructure (See Figure F.1-2).

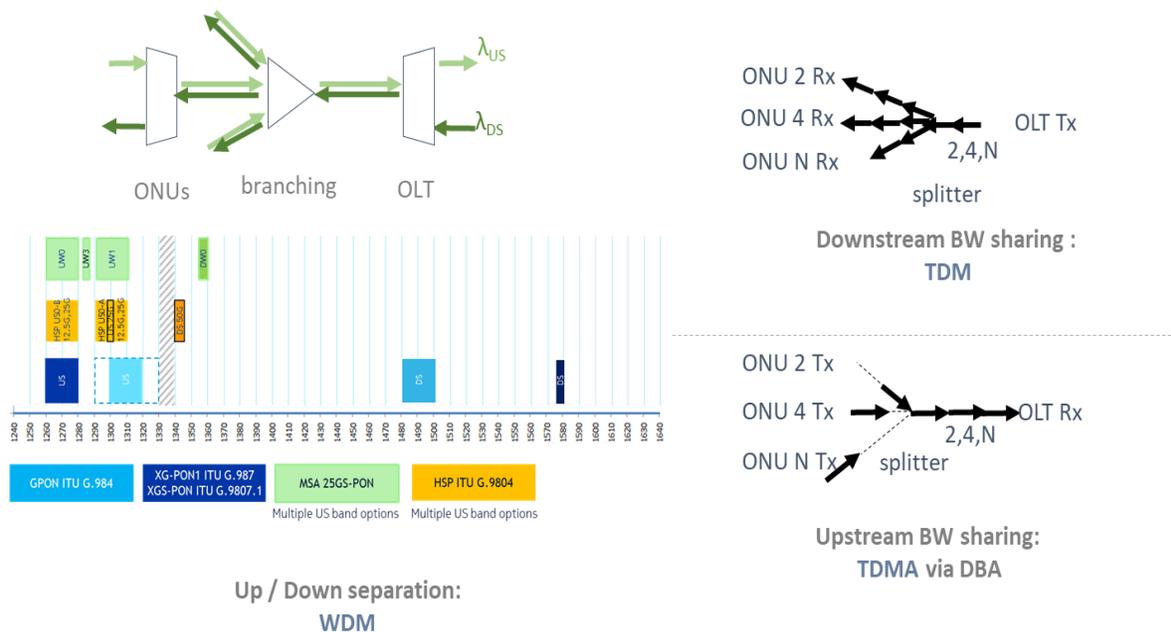


Figure F.1-2: TDM PON: Up- and Downstream Separation by WDM, Up- and Downstream Bandwidth Sharing by TDM(A)

The second is WDM PON, using a dedicated wavelength pair (upstream + downstream) per ONU (See Figure F.1-3). There is no sharing of capacity, as WDM PON gives point-to-point connectivity over a point-to-multipoint fiber infrastructure. A further distinction can be made based on the type of passive branching stage in the fiber network. With a passive power splitter all wavelengths are equally shared overall drop fibers (Wavelength Selective WDM-PON). In contrast, with a WDM passive device each wavelength is routed to a specific drop fiber (Wavelength Routed WDM-PON).

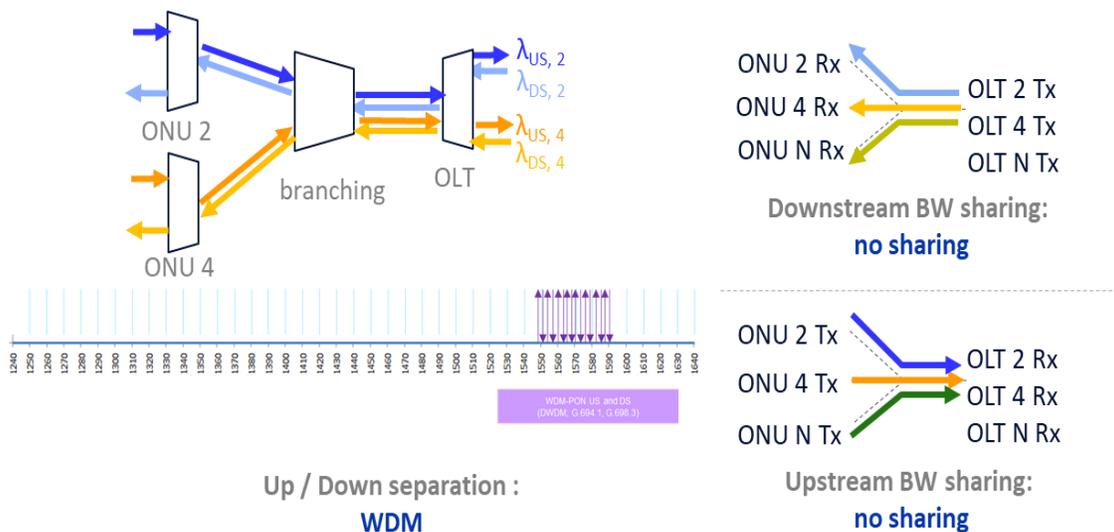


Figure F.1-3: WDM PON: Up- and Downstream Separation by WDM, without Up- and Downstream Bandwidth Sharing

The third is TWDM PON, which is an overlay of multiple TDM PONs each using a different wavelength pair (upstream + downstream). With TWDM PONs there are multiple point-to-multipoint connections in a point-to-multipoint fiber infrastructure (See Figure F.1-4).

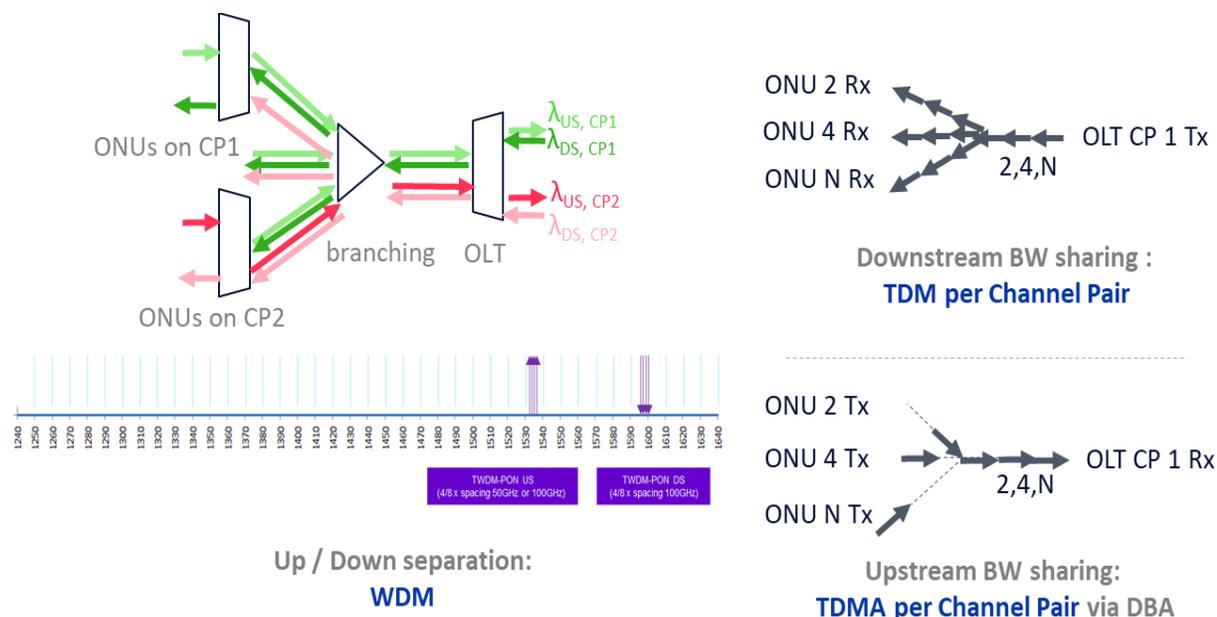


Figure F.1-4: TWDM PON: Up- and Downstream Separation by WDM, Up- and Downstream Bandwidth Sharing by TDM(A) per Channel Pair

The fourth is Sub-Carrier Multiplexing (SCM), which uses subcarrier technology to divide a single wavelength into several smaller wavelength pairs (upstream + downstream) via the DSP. These individual subcarriers can be allocated for upstream or downstream transmission. In Figure F.1-5 you can see a single 400 Gbps wavelength divided into 16 x 25 Gbps subcarriers and then specific subcarriers can be allocated for upstream or downstream transmission.

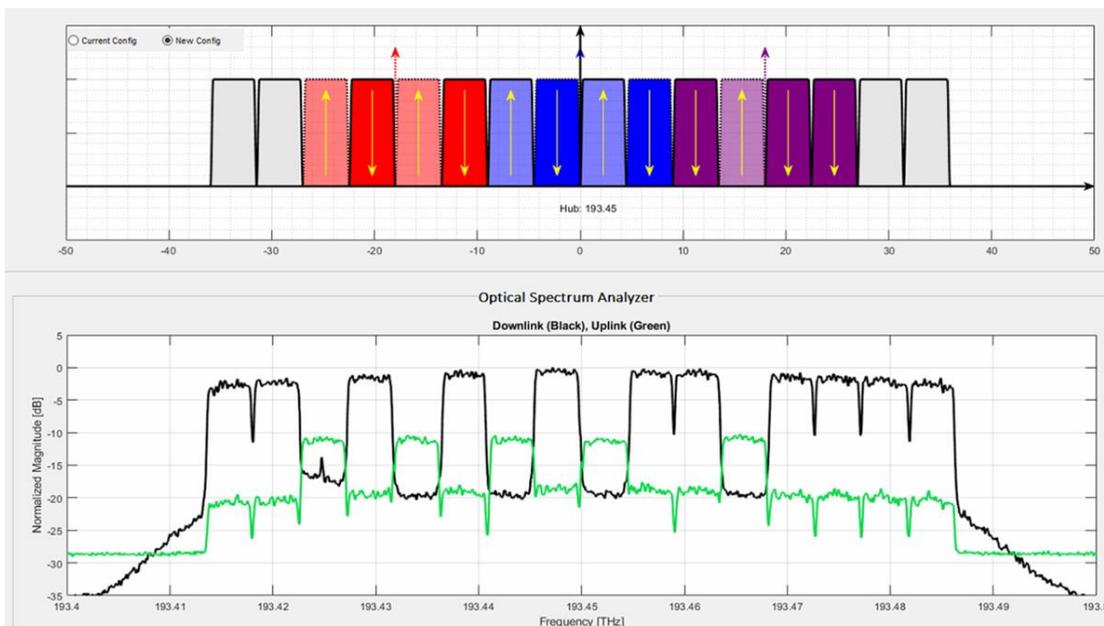


Figure F.1-5: SCM; Up- and Downstream Allocated from Several Subcarriers

An example of SCM is XR optics [XR optics]. Its channel spectral width is 64 GHz where all SCs are allocated. Therefore, a 75 GHz filter can be applied to XR optics (See Figure F.1-7).

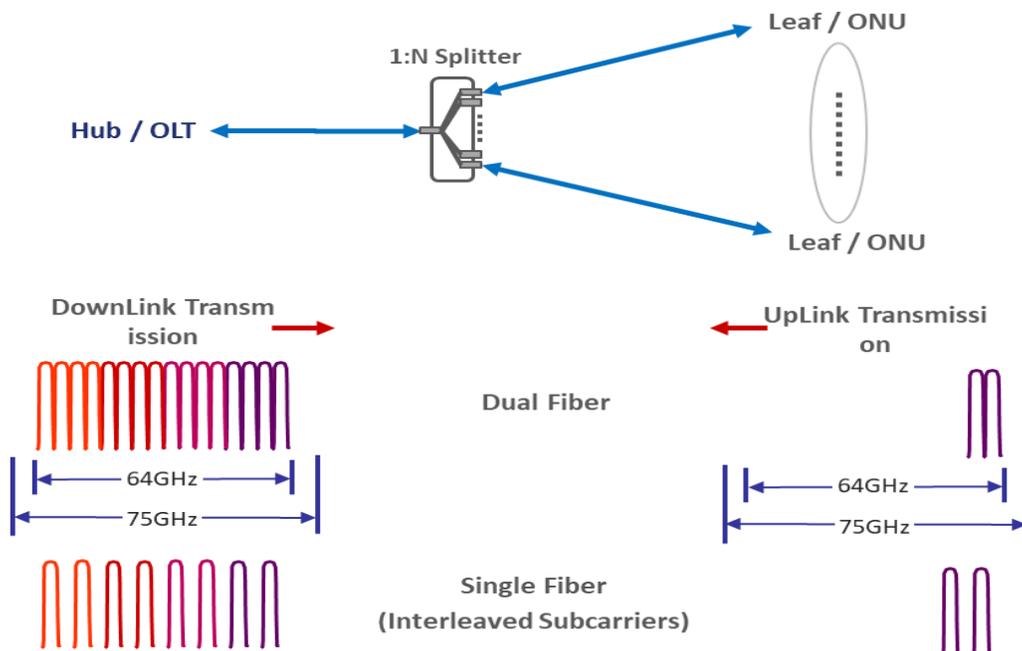


Figure F.1-6: Subcarrier Implementation Methods for Point-to-multipoint

An important capability of PON technologies is the ability to overlay multiple PON variants over the same point-to-multipoint fiber infrastructure based on WDM separation of the different allocated wavelength bands. Wavelength range of XR optics (1528 - 1567 nm) resides in C-band (1530 - 1565 nm) (See Figure F.1-7).

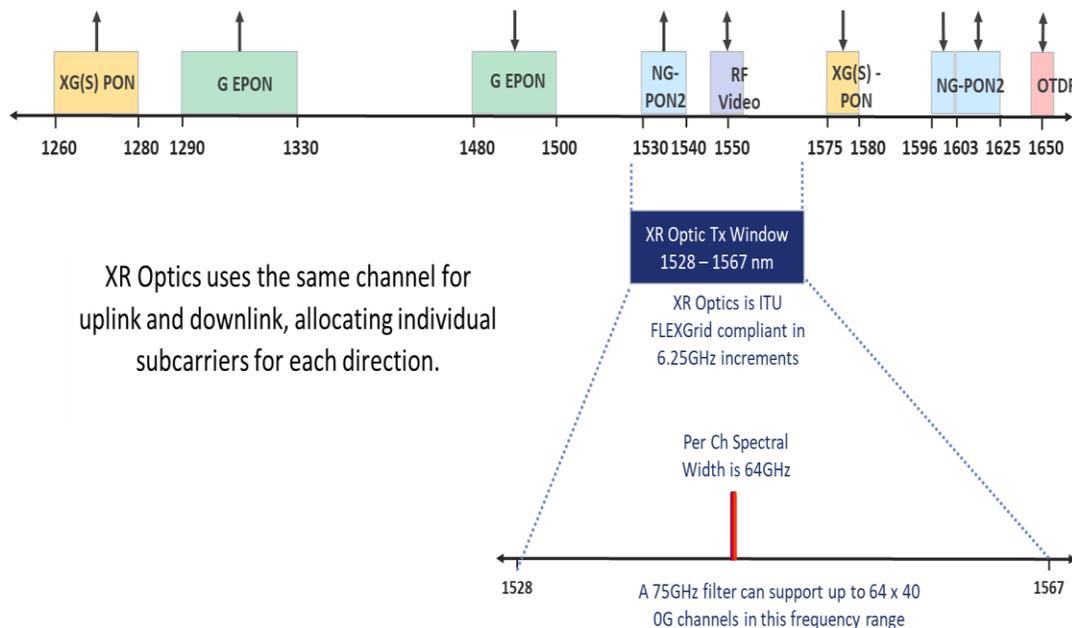


Figure F.1-7: Relative PON Wavelength Chart

F.2. Open APN Fiber Topology

The Open APN can be split into two domains: the 'metro and aggregation' part of the Open APN and an 'access and distribution' part of the Open APN. This is illustrated in this simplified figure (See Figure F.2-1);

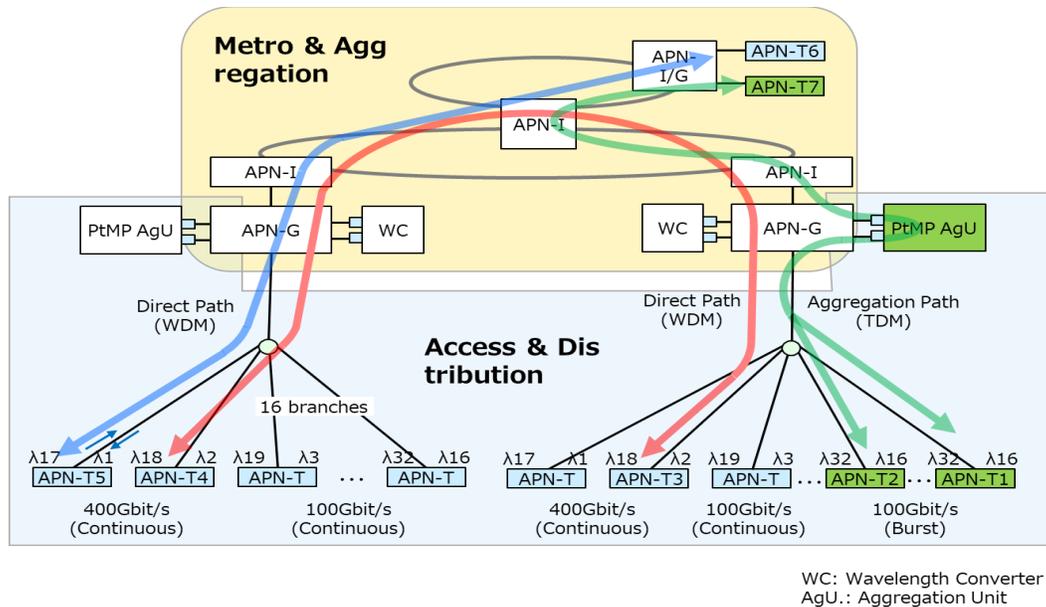


Figure F.2-1: Fiber Topology Example

The metro & aggregation Open APN is a (100-1000 km) domain where the evolution is characterized by increasing throughput per wavelength and wavelength density (densify the grid in DWDM), which requires an upgrade scenario for more dense technologies and/or higher data rates per wavelength on the (reconfigurable) Optical Add and Drop Multiplexers (ROADM) as network nodes.

The access domain (max 20 km), on the other hand, has long been dominated by copper (DSL), Coaxial cable, or wireless media. Yet today, fiber is the greenest of all access technologies. It is 6-8 times more energy efficient than copper, coaxial cable, or wireless. As a result, fiber plays a critical role in lowering the industry's energy consumption and carbon footprint. Fiber is also resilient against harsh environmental conditions and boasts a life expectancy of more than 75 years, ensuring long-lasting connectivity that is also the fastest and the most efficient.

Fiber broadband access networks are key to the rapid growth in data connectivity. By the end of 2030, Fiber-To-The-Home (FTTH) is expected to make up 75% of all global fixed broadband subscribers. Fiber as a broadband access technology is gaining from significantly accelerated demands and investments, many of which triggered by the COVID pandemic. PtMP passive optical network technologies (TDM-PON as in Annex F.1.) are currently widely deployed for FTTH connectivity services, accounting for >95% of total FTTH market. This installed base of PtMP FTTH is based on optical splitters. When applying WDM deployments on such fiber networks (see Annex F.1.) the ITU-T defined their characteristics as having wavelength selection at the Termination point (ONT) which is referred to as Wavelength selective Optical Distribution Network (WS-ODN).

One of the best properties of PtMP access fiber (even WS-ODN) is its ability to increase its capacity by simply adding new wavelengths on the existing fiber cabling - each wavelength carrying traffic at higher speeds and co-existing next to the other wavelengths without impacting their capacity. Fiber speeds in access today have reached 25 Gbps, with demonstrations of future 100 Gbps services already taking place.

The same fiber that passes our homes also passes businesses, commercial campuses, schools, hospitals, and public buildings. This network monetization is expanding the use of fiber. It can meet the connectivity needs of small-medium enterprises (SMEs) and even larger enterprises, Industry 4.0, smart cities, and 5G mobile transport. The investments in PtMP access fibers can be maximized by supporting mobile cell site traffic transport to Edge Data Centers and Central Offices (CO). With the addition of mobile traffic, the FTTH Optical Distribution Network (ODN) provides an attractive common access platform, for both fixed and mobile broadband services over an existing last mile fiber infrastructure – significantly improving deployment times, cost, and ultimately the financial returns for the network operator. Hence it is the concept of adding new wavelengths for different service types rather than upgrading the entire access domain, that will allow a smooth evolution.

The first consideration for smooth network upgrades is the design of the PtMP Optical Distribution Network (ODN) itself. An ODN is characterized by multiple choices, namely the fiber type (typically ITU G.652.1), the minimal and maximal fiber distance, the splitter stage (single or cascaded), wavelength-agnostic power splitter or wavelength-selective multiplexer such as an Arrayed Waveguide Grating (AWG), total split ratio, symmetrical splitters for tree topology or asymmetrical splitters for chain topology. The choices of the ODN determine its usability for PtMP technologies such as TDM PON. Multiple ITU-T-based TDM PON technologies can be used in overlay over a common ODN, allowing for a smooth and gradual upgrade from one technology to the next, as long as they fit in the optical budget of the ODN.

An ODN design is always a matter of balancing investment versus flexibility, but in terms of being capable of being upgraded, it is important for the ODN to remain untouched when upgrading or adding a new PtMP technology in its endpoints. In other words, the best upgrade scenario is where only the OLT and ONU equipment needs to be upgraded while avoiding any changes to the ODN itself. In terms of scalability, a useful metric for the design of ODNs is called the PON Service Area (PSA), which is the total area that a single ODN can span on average, depending on the geographical density of OLT ports and the distance that can be reached per ODN. This can be used to determine how many sites (e.g., single-family units for FTTH, or mobile sites for Mobile xHaul) can connect per PON.

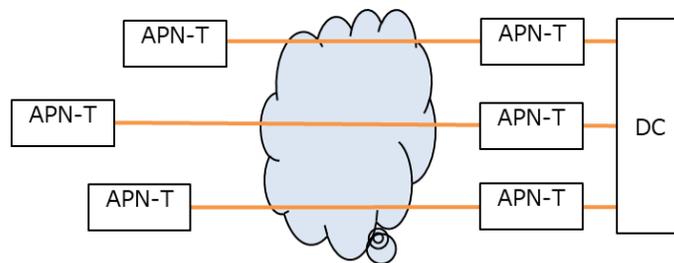
In brownfield deployments, an existing ODN can be re-used for new applications (e.g., a FTTH ODN is re-used to connect some mobile sites for xHaul). When the installed ODN corresponds to a given ITU ODN class, an overlay with PON technology equipment with a compatible class can be introduced. The ODN is now shared but the original PON service is not impacted by the new PON service thanks to the WDM separation between both services. Existing users do not have to migrate all at once, since the migration to the new technology or adding of new users can be gradual. Once all users from the legacy technology have been migrated, the legacy PON can be decommissioned and its WDM bands become free for use by overlay PtP deployments if applicable.

For greenfield deployments, the potential of future overlaying in the design must be safeguarded by following PON ODN specifications that have an open path to overlays (e.g., 20 km range ODNs of the lowest possible class like N1). It is also advisable to include margins for aging and repairs (splices).

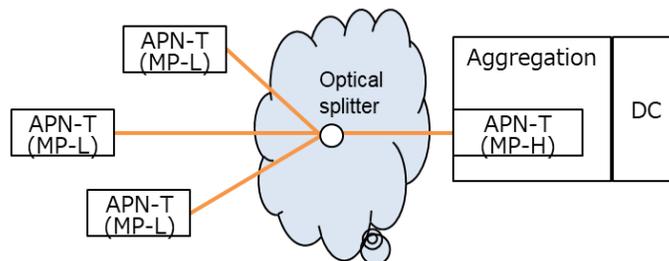
As a general consideration, next to the design of the ODN, it is also important not to use the ODN for PtP wavelengths that may conflict with PtMP WDM bands, especially to avoid the O-band which is the band in which the higher speed ITU and IEEE PONs are being defined (e.g., ITU-T G.9804 has multiple WDM band options for upstream and downstream in the O-band).

F.3. PtP/PtMP Co-existing Systems

Both PtP and PtMP connectivity have their own advantages. Therefore, it is preferable to deploy a co-existing PtP / PtMP system. In addition, when APN-Ts have PtP/PtMP mode selective function, it may improve the efficiency of wavelength resource utilization ratio or reduce their energy consumption. Figure F.3-1 provides an example of the allocation of PtP/PtMP optical connections. In the figure, PtP/PtMP modes and line rate are changed according to traffic or applications. For example, APN-T1 is connected to APN-T2 with 400 Gbps PtP optical connection (1) for heavy daytime traffic (as like as PtP optical connection which connects APN-T(16) and APN-T(17) excepting a splitter is not inserted (4)). In comparison, when midnight and traffic volume is reduced, ANP-T1 will be connected to APN-T7 with a maximum 100 Gbps PtMP optical connection (2) as same as the other accommodated APN-Ts like APN-T3 to APN-T6. Then aggregated signal will be sent from APN-T8 to APN-T9 with PtP optical connection (3).



(1) An Example Configuration of APN with PtP



(2) An Example Configuration of APN with PtMP

Figure F.4-1: Example Configuration of Open APN with PtP and PtMP

In these configurations, energy consumption of PtMP (22 W) is about 30% lower than that of PtP (28 W); each APN-T of 100 Gbps is 3.5 W [QSFP] and APN-T of 400 Gbps is 8 W [QSFP-DD].

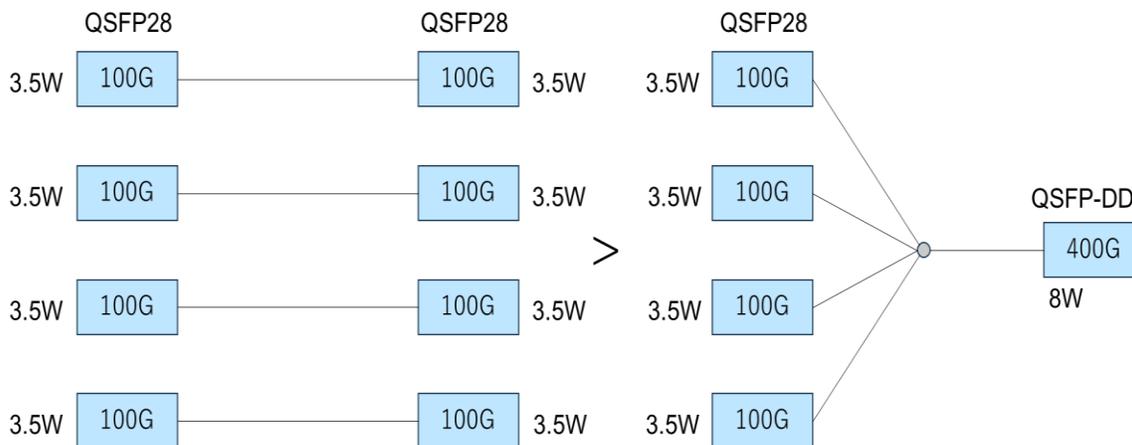


Figure F.4-2: Compares Estimated Energy Consumption between PtP and PtMP Configuration Focusing the Number of APN-Ts

F.5. Specification for PtMP wavelength paths

The specification for PtMP wavelength paths is for further study.

G. Energy Saving

G.1. Introduction

One of the major objectives of the Open APN is reducing the energy consumption of network systems. An All Photonic Network can reduce the energy consumption by eliminating the electrical circuit between end to end transmission. In these networks, most of the energy is consumed by APN-Ts. In addition, some techniques make use traffic features that can increase the benefits of Open APN energy saving.

The situations that can be optimized are described in the following examples;

- In some networks, bandwidth utilization ratio is not always 100%, such as access networks or mobile backhaul.
- In the case of burst transmission such as PtMP, the relation between the energy consumption and the amount of data transferred is ideally near to proportional. Therefore, the burst transmission can reduce energy consumption compared with continuous transmission, including idle signal. (The benefit of energy saving depends on the traffic volume in the network.)

The following subsection describes energy saving technologies for APN-T.

G.2. Energy Saving by Burst Transmission and Sleep Control

The further reduction of energy consumption in the Open APN may be expected by using burst transmission (*1) and high-frequency sleep control.

Some of the sleep control functions considered for PtMP communication include APN-Ts that change their mode from active to sleeping when they are not working on transferring data. For example, ITU-T SG15 has been studying energy saving in optical access networks. By using such energy saving techniques for APN-Ts as shown in Table G-1, a significant reduction in energy usage can be expected (*2).

A similar technique may be used for PtP communication for further energy saving.

(*1) *The burst transmission in this sentence does not mean the APN-T sends idle data when there is no data to transfer. It means the APN-T stops to send any optical signals. And when the data transfer is restarted, the receiver can recover the synchronization of data clock using very small preamble signals or training signals.*

(*2) *Note that some of the sleep technologies need time to “wake up” time, making them ill-suited for some of low-latency applications.*

Table G-1: Examples of energy-saving techniques

TECHNIQUES	DESCRIPTION
APN-Ts Power Shedding	Powering off or reducing power to non-essential functions and services while maintaining a fully operational optical link.
APN-Ts Dozing	Additional powering off of APN-Ts transmitter for substantial periods of time on the condition that the receiver remains continuously on.
APN-Ts Deep Sleep	Transmitter and receiver remain off for the entire duration of the power save state sojourn
APN-Ts Fast Sleep	Power saving state sojourn consists of a sequence of sleep cycles, each composed of a sleep period and an active period.

G.3. Line Rate Selection for Energy Saving

When the bandwidth of application data traffic is smaller than the line rate, the dummy (wasted) data must be sent as shown in Figure G.3-1(a). For the other way, the data will be sent with a small-time interval as shown in Figure G.3-1(b). In that case, the sleep control described in the previous subsection must be useful. However, it must be difficult to reduce the energy consumption to zero when APN-Ts are sleep state.

Therefore, when the bandwidth of traffic fluctuates and does not exceed the line rate, the reduction of energy consumption may be expected by using communication rate optimization as shown in Figure G.3-1(c).

For the functions described in this Annex G, APN-C is expected to support the following capabilities. APN-T with PtP/PtMP selectable mode can be used for energy saving with the line rate selection; because PtP is used for ultrahigh-speed transmission and PtMP is used for relatively lower speed.

- Traffic information gathering/prediction: APN-C is expected to gather user’s real-time traffic and predict future traffic to allocate optimal control for energy saving.
- Management for sleep control: APN-C is expected to manage the APN-T’s sleep mode.
- Management for Line rate selection: APN-C is expected to manage the optimal line rate selection based on the traffic situation.
- Management for PtP/PtMP mode control: APN-C is expected to control PtP/PtMP mode selection dynamically according to the user’s services.

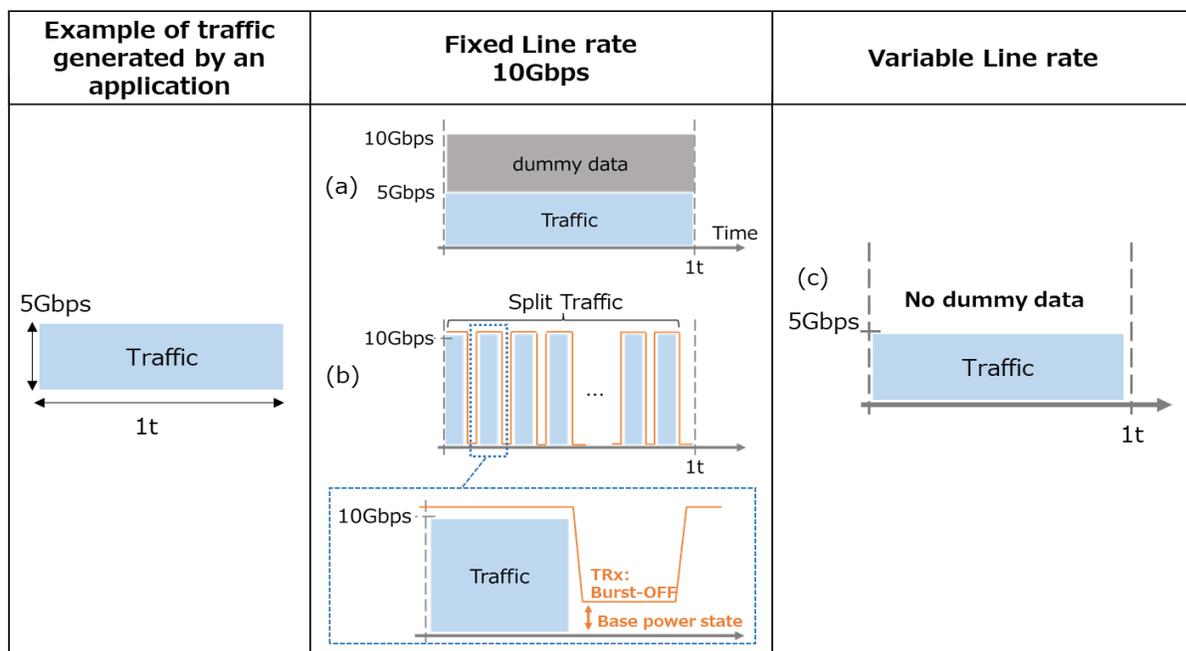


Figure G.3-1: The Relationship between Application Traffic, Fixed Line Rate, and Variable Line Rate

H. An Evaluation of Telemetry

The streaming telemetry function can be implemented in an Open APN controller and Open APN devices, and the information of attached devices can be collected with such streaming telemetry function. An evaluation result is illustrated below.

A partially open and disaggregated Open APN system is evaluated for a video-streaming use case, where Figure H-1 depicts the setup. The streaming telemetry function is implemented in the Open APN controller, and both APN-Ts are monitored.

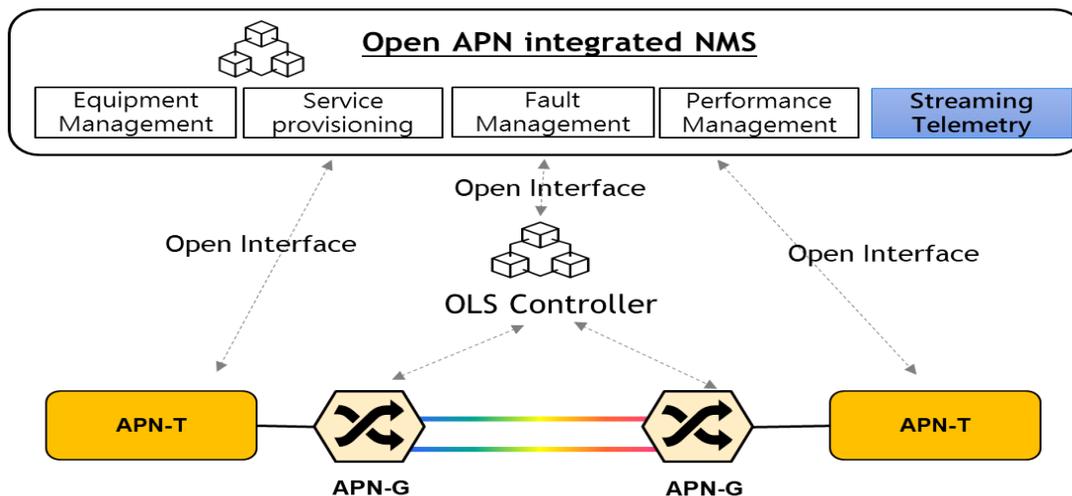


Figure H-1: An Evaluation Setup for Streaming Telemetry Function

A result of this evaluation is shown in Figure H-2, where the blue curve is the transmitted traffic, and the red curve is the received traffic. Please note that the monitoring period in this evaluation is 10 seconds, which is chosen with the consideration of the data processing ability of the homemade Open APN controller.

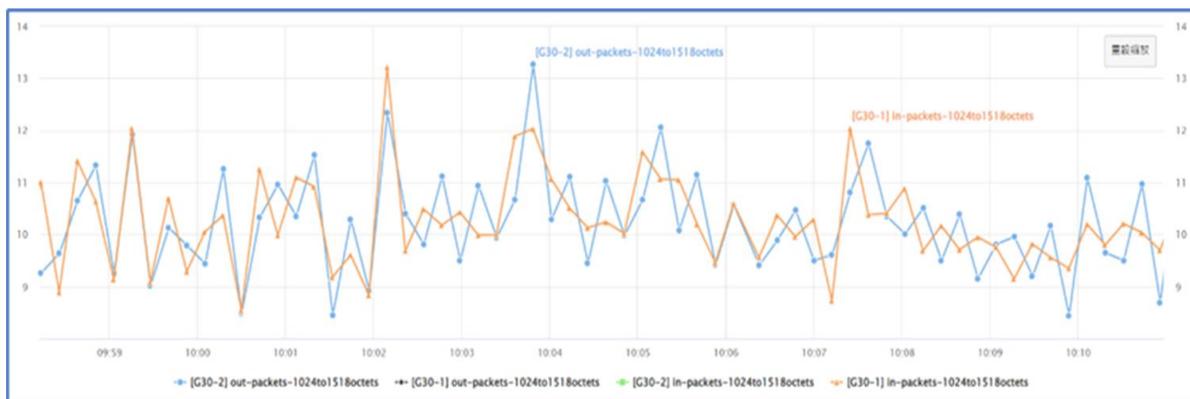


Figure H-2: A Traffic Monitoring with Streaming Telemetry (10 second period)

I. Relation between Open APN.WX and Open APN.FX and Examples of Service Implementations

I.1. Examples of Service Implementation with Open APN.WX and Open APN.FX

I.1.1. PtMP Wavelength Path Service over PtMP Fiber Path

This example provides a PtMP wavelength path service with Open APN.WX using a PtMP fiber path in Open APN.FX. XR optics [XR optics] that use a specific pair of DWDM channels correspond to this model. Optical broadcast/multicast corresponds to this model as well.

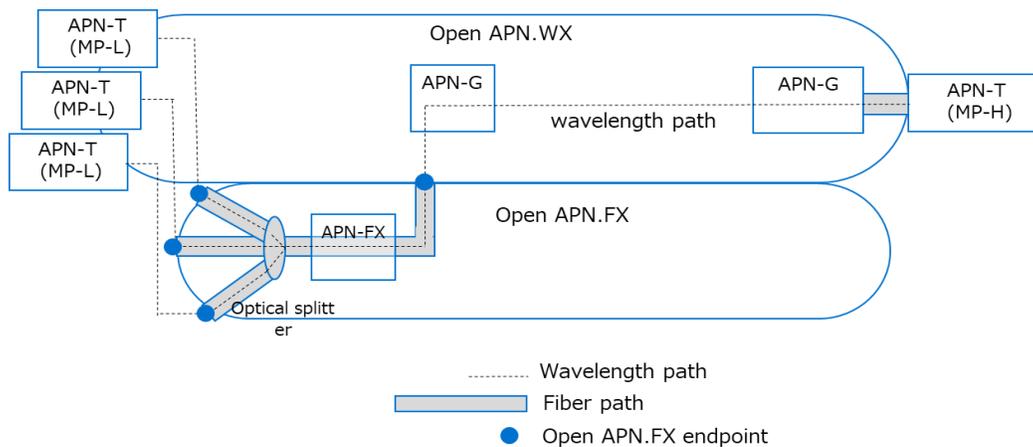


Figure I.1-1: An Example of PtMP Wavelength Path Implementation with PtMP Fiber Path

I.1.2. PtMP Wavelength Path Service within Open APN.WX

This example provides a PtMP wavelength path service within Open APN.WX. Optical broadcast/multicast corresponds to this model. In this model, APN-G splits and combines wavelength path to/from multiple APN-T(MPT)s. How to implement APN-G (and APN-I if needed) to allow the wavelength split/combine requires further study.

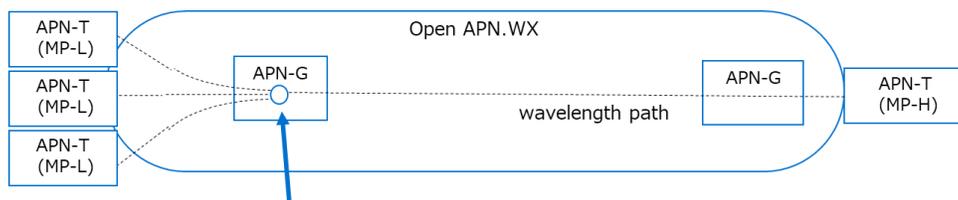


Figure I.1-2: An Example of PtMP Wavelength Path within Open APN.WX

I.1.3. Access Line Sharing for Multiple PtP Wavelength Paths

The use of PtMP fiber path allows for sharing the same access line among multiple PtP wavelength paths. This model requires further study on how to implement an APN-G that drops (adds) the corresponding wavelengths to (from) the same port in APN-G as well as how to extract the assigned wavelength for each APN-T between the Open APN.FX endpoint and each APN-T.

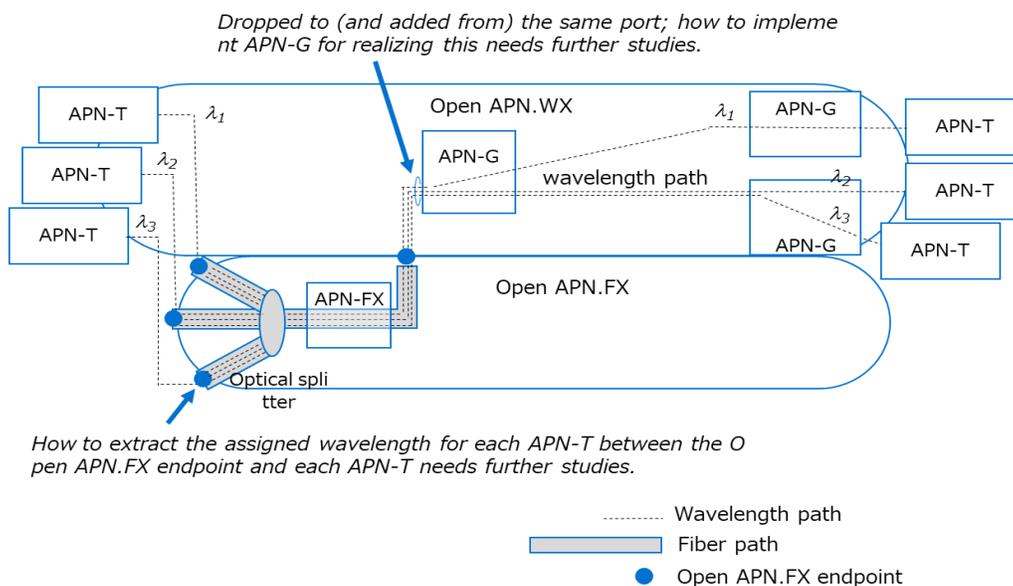


Figure I.1-3: An Example of Access Line Sharing for Multiple PtP Wavelength Path

I.1.4. PtMP Fiber Path Service for Non-DWDM Optical Access

The PtMP fiber path can provide a shared access service based on a non-DWDM optical access system.

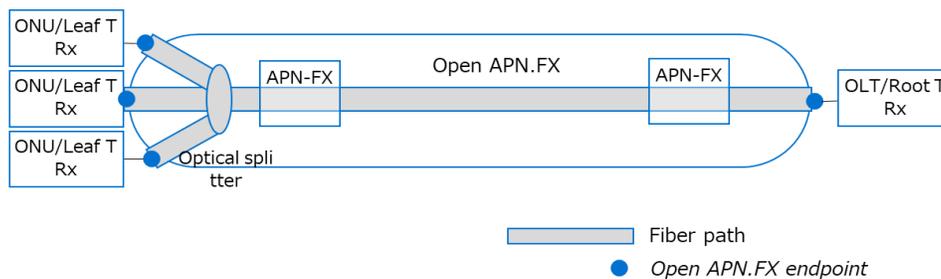


Figure I.1-4: An Example of PtMP Fiber Path Service for Non-DWDM Optical Access

I.1.5. Combination for Multiple Service Provision

As shown in Figure I.1-5, Open APN.FX will enable a multi-service access network through the use of fiber paths, which allows service providers to use optical access infrastructure for multiple services such as mobile fronthaul, fiber sensing, and PON-based fiber broadband, and wavelength path services on the top of the fiber paths (see Figure 3-1).

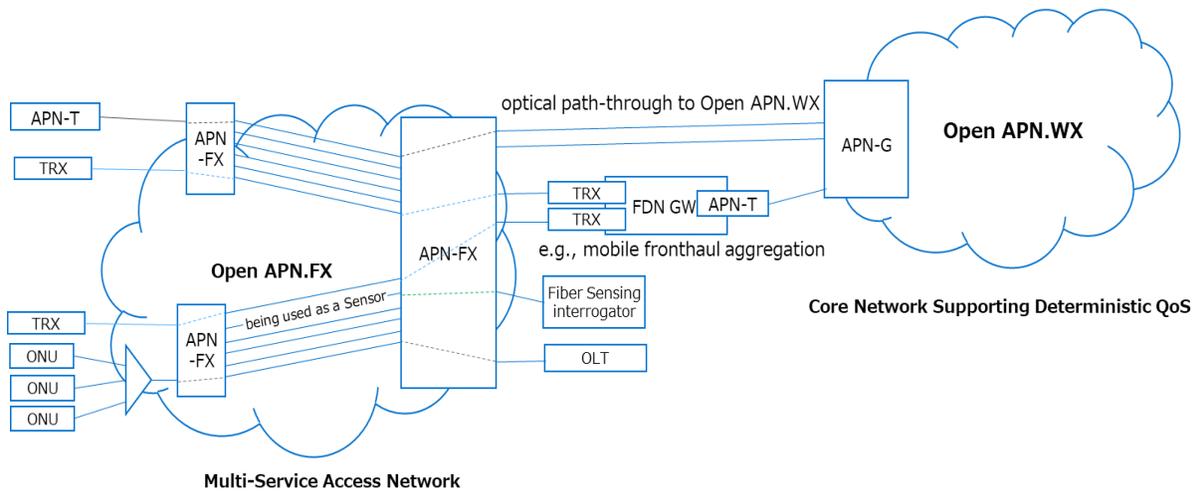


Figure I.1-5: An Example for Multiple Service Provision

Open APN.FX can be used as a network inside a data-center (DC) as shown in Figure I.1-6. Open APN.FX, as the core of intra-DC network will enable the creation of dynamic optical paths to achieve deterministic QoS.

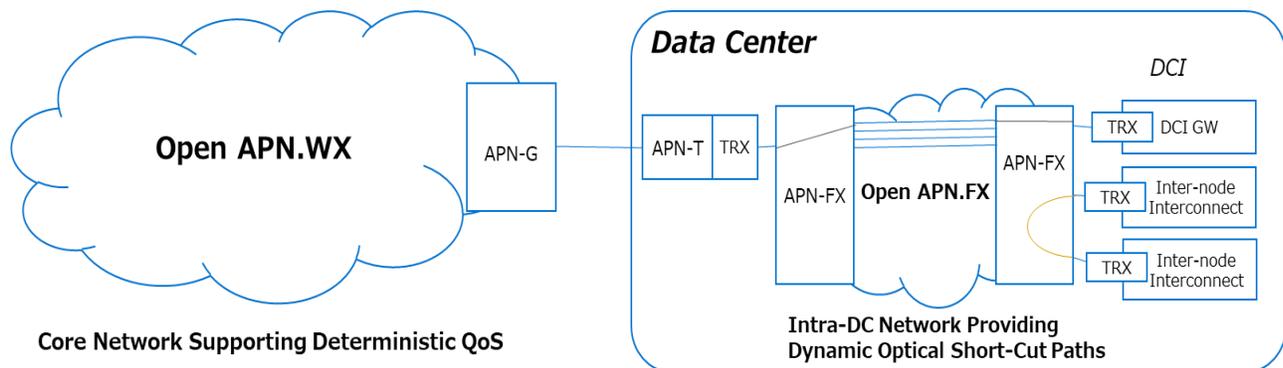


Figure I.1-6: Open APN.FX as Intra-DC Network

I.2. Service Types Supported by Each Release

Table I.2-1: Service Types Supported by Each Release

	RELEASE 1	RELEASE 2 and 3	NOTE
PtP Wavelength Path Service	✓	✓	How to share the same access line among multiple PtP wavelength paths needs further studies.
PtMP Wavelength Path Service		✓	How to realize PtMP wavelength paths within Open APN.WX needs further studies.
PtP Fiber Path Service		✓	
PtMP Fiber Path Service		✓	

J. QKD Signal Transmission over Open APN

This Annex describes the objective and framework for QKD signal transmission over Open APN.

J.1. High level description of QKD

Background

Cryptographic communication based on data encryption is effective to countermeasure against security threats such as tampering and information disclosure. Prior to the data encryption, two legitimate parties need to share cryptographic key with key exchange methods. Commonly used public key-based key exchange methods including Diffie-Hellman and RSA are regarded as secure, because they are based on complex mathematical problems which take a long time to solve with conventional non-quantum computers. However, some new quantum computer algorithms can solve some of the above mathematical problems in real time. Therefore, commonly used key exchange methods will no longer be secure in a quantum computing era. PQC (Post-quantum cryptography) based key exchange method has been proposed which is regarded as secure since it uses cryptographic algorithms that are difficult to solve even by a quantum computer. The selected key establishment algorithm of NIST's PQC standardization can be found here [NIST PQC Selected Algorithms 2022].

QKD is a promising alternative approach for the quantum-safe key exchange. It produces and distributes keys whose security relies on quantum mechanics theory, instead of mathematical and computational complexity of cryptographic algorithms. As shown in Figure J.1-1, eavesdropping by a third party unavoidably introduces errors to the quantum system through additional noise, based on the principle that the measurement of quantum states itself causes disturbances to the states. The legitimate parties are able to detect such hacking attempt by detecting errors exceeding a defined threshold and discard the corresponding quantum states that cannot/should not be used to produce the key.

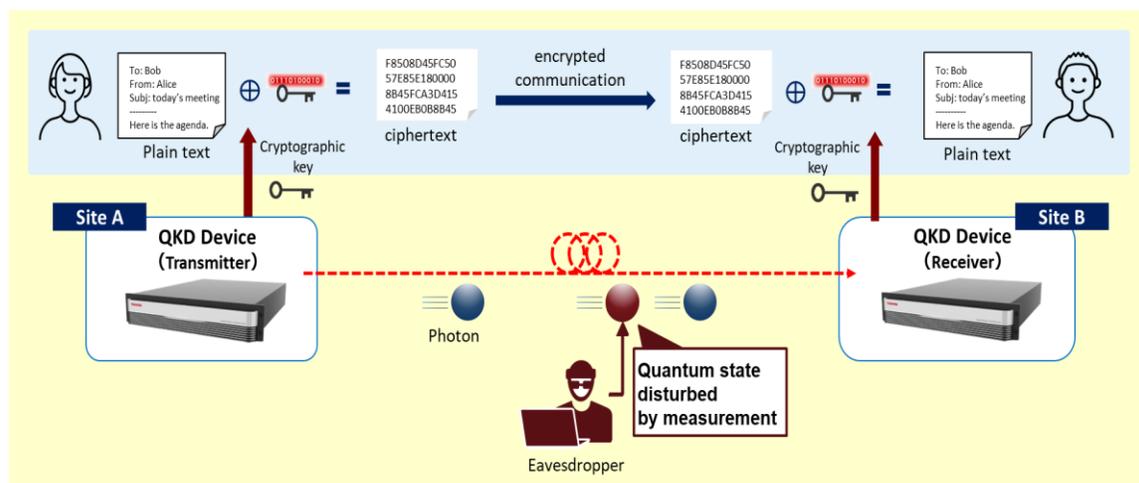


Figure J.1-1: Concept of QKD-based exchange method

Key sharing over point-to-point QKD link

In order to create and agree on the cryptographic keys between two distant sites, a point-to-point (P-t-P) QKD link between two QKD devices needs to be setup. The QKD link consists of a “quantum channel” and one or more “classical channels”. A unidirectional quantum channel is used to transmit quantum state such as a set of single photon signals or continuous coherent light pulses from the sender to the receiver. A bidirectional “classical channel” is used to exchange information between the transmitter and the receiver for post processing such as basis selection, forward error correction and privacy amplification to complete the key generation process. For correct ultra-low power quantum signal detection, a classical channel is used for synchronization of the clocks at transmitter and receiver.

Typical examples of the QKD link implementation are described below.

- Discrete Variable QKD (DV-QKD) emerged in the 1980s. It is based on the corpuscular nature of light. Various implementations have been proposed so far, with information encoded in, for example, polarization of a photon. The BB84 is the first protocol that was proposed for DV-QKD application (others have followed: B92, SARG04, etc.). Single photon detectors are required at receiver side.

- Continuous Variable QKD (CV-QKD) dates from the early 2000s. It leverages the wave properties of light. Small pulses are emitted at Alice’s site, carrying qubits via the phase and/or amplitude of the pulse, which require coherent detection by Bob. The gaussian modulation signal-based protocol (GG02) and its modified one that uses a discrete value modulation signal are proposed.
- Twin Field QKD (TF-QKD) has even more recently been proposed in 2018 to increase the reach of the QKD link, using random phase small pulses with phase code difference, but emitted by both Alice and Bob and using an intermediate (non-trusted) measurement node (Charlie) that halves the signal transmission loss, but extracts the information from the first-order interference rather than two-photon coincidence so as to gain the advantageous repeater-like rate-loss scaling.

QKD network (QKDN) for network-wide end-to-end key sharing

The QKD link described above realize key sharing between two parties connected in a P-t-P manner. From application network perspective, two or more parties which require network-wide cryptographic communication need to share the end-to-end keys. It therefore is desirable to extend P-to-P QKD links to multi-point QKD network. Currently, trusted key relaying scheme is the only known solution widely adopted for large-scale connectivity QKD networks. In this scheme, keys are stored in QKD nodes (trusted nodes) and relayed to their neighbor QKD nodes with highly secure encryption.

Figure J.1-2 illustrates the conceptual structures of key relaying-based QKD network (QKDN) and a user network [ITU-T Y.3800]. In each QKD node, QKD module(s), key manager (KM) and QKDN controller are located. Pairs of QKD modules are connected with each other via QKD links, thus forming a quantum layer. KMs provide key management functions including the key relay capability. Keys are supplied from the KM to applications, and used for cryptographic communications in a user network. The KMs in the different nodes are connected by KM links, thus forming a key management layer. QKD modules, QKD links, KMs and KM links are controlled by the QKDN controller(s). Key relay routes can also be controlled by the QKDN controller(s). A QKDN manager monitors and manages the QKDN as a whole.

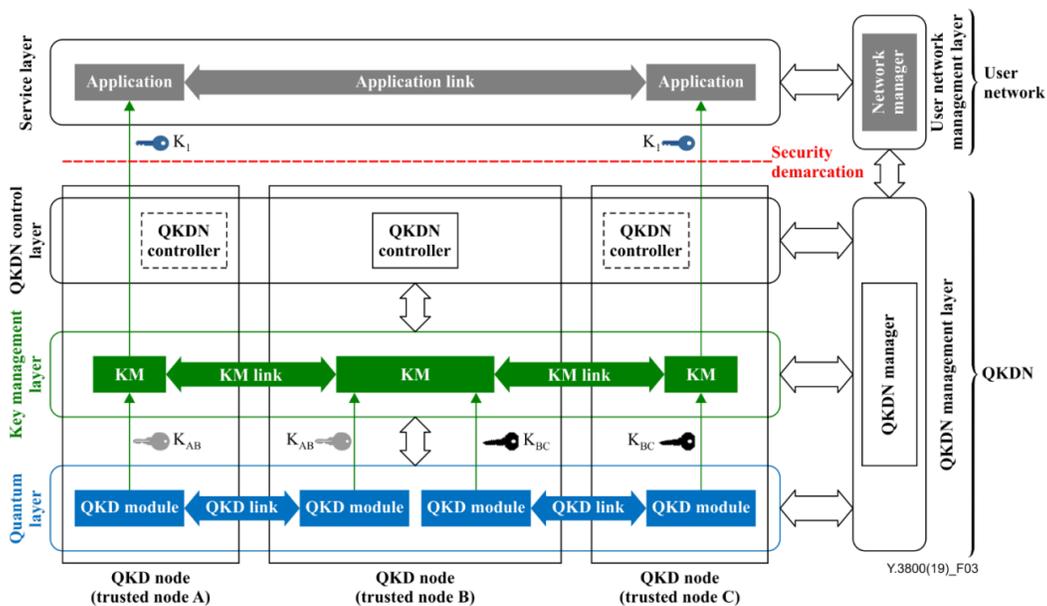


Figure J.1-2: Conceptual structures of a QKDN and a user network (ITU-T Y.3800)

J.2. Motivation and objectives of QKD over Open APN

Motivation

To accommodate many users in real-world applications, QKD networks are being deployed mainly as trial environments provided for potential users in various regions of the world. These networks are designed with a QKD-centric architecture, focused on ensuring quantum channel in near-ideal conditions through use of dark fiber and

maximizing the key generation rate for each QKD link. Consequently, isolated infrastructures governed by their own operational rules, have been built separately from conventional optical transport networks for telecommunications. While these networks have achieved significant technological advancements, they are extremely costly because of deploying dedicated fibers and providing specialized management and maintenance procedure through the vendor-proprietary and non-interoperable interfaces. This has severely limited further scaling-up of the network and the commercialization of user services.

Objectives

Integration into and reuse of IOWN infrastructure will be essential to accelerate the deployment of QKD networks for wider use and provide cost-effective QKD key delivery service in IOWN era, although much effort is needed to design such single network infrastructure. Figure J.2-1 illustrates several integration levels of QKDN into IOWN infrastructure. The IOWN infrastructure consists of Open APN and FDN/DCI layers, which are controlled and managed by the APN controller (APN-C) and FDN manager (FDN-M) respectively. APN-C and FDN-M are also connected to the higher-level orchestrator.

At level 0 (no integration), QKDN and IOWN infrastructure are built separately and do not interact with each other. At integration level 1, QKD signal transmission for the quantum layer of QKDN is provided using physical resources of Open APN: either a fiber's whole bandwidth or a set of wavelength bandwidths. This level of integration eliminates the need for dedicated fiber infrastructure for QKDN, dramatically reducing deployment costs. In the section of J.3, the framework for this integration level will be described in detail. Level 1 integration is a target for specific description in release 3 document.

For integration at higher layers of Open APN (integration level 2), integration of QKD module and key manager (KM) into IOWN-defined network equipment (e.g., FDN/DCI gateway and logical node) may significantly reduce construction cost of dedicated management communication network for QKDN, because a management communication network for already-deployed IOWN infrastructure, which connects the APN-C/FDN-M with a large number of network equipment on the data-plane, can be reused by QKDN. This is made possible by accessing the QKD module from the QKDN manager using a common management southbound interface via APN-C/FDN-M. In addition, the consolidation of the QKDN management function into IOWN-defined management function (e.g., APN-controller, FDN/DCI manager) may reduce the workload of operators by unifying maintenance procedures and centralizing management. The details and feasibility of the level-2 architecture are for further study and left open to be covered in a future release.

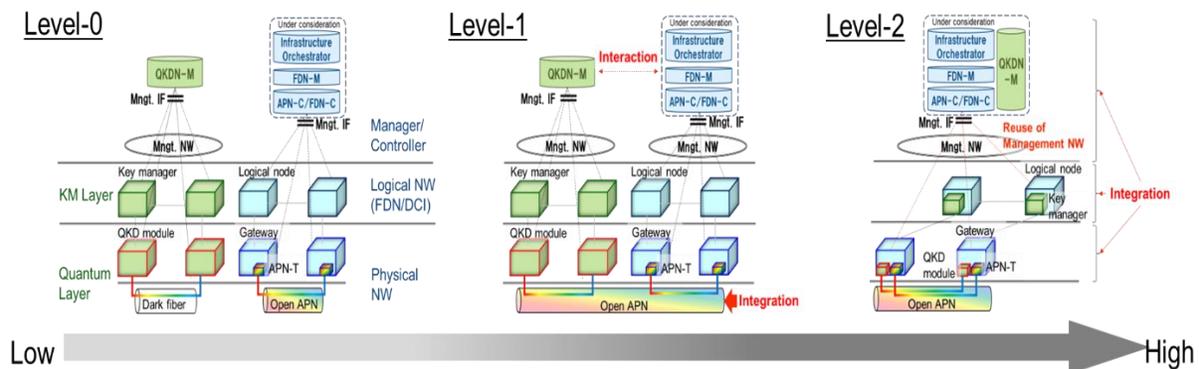


Figure J.2-1: Integration levels of QKDN into IOWN infrastructure

J.3. Functional framework of QKD over Open APN

This subsection describes a functional framework of QKD signal transmission over Open APN (integration level 1) as shown in Fig. J.3-1. This framework consists of user-plane and management/control-plane. In the user-plane, the QKD link can be provisioned with a specified wavelength by utilizing the PtP fiber path service defined in Section 2.2.3 and the one-span PtP fiber path service defined in Section 2.2.4 on the Open APN.FX and the Open APN.WX layers, respectively. For control and management of these two types of QKD link on the user-plane, QKDN management function can interact with IOWN-defined management function (e.g., APN-controller, FDN/DCI

manager) in the management and control-plane to synchronously configure QKDN and Open APN equipment, and negotiate the QKD wavelength allocation.

User-plane

Figure J.3-2 shows the user-plane framework for implementing the QKD link over Open APN. There are two cases, QKD link at APN-FX layer and QKD link at APN-WX layer. QKD modules or transceivers correspond to Open APN endpoints for one-span PtP wavelength path and PtP fiber path services.

In APN.FX layer, the QKD link is provided using PtP fiber path service, which is mainly applied at APN access segment. QKD-related signals are input into and output from the optical fibers through APN-FX in a fiber-exchange manner. In this configuration, the whole fiber bandwidth is allocated for the QKD link configuration so that there is no need to be aware of interactions from telecom DWDM signals during fiber propagation, except for interactions from optical signals on other fibers due to device imperfection at APN.FX. QKD-related signal over fiber-path service may support multi-span fiber transmission going through more than one APN-FXs. The fiber-exchange function of APN-FX can support not only one-to-one QKD transmission between a transmitter and receiver but also the following practical use cases of QKD networks.

- Cost-effective one-to-many QKD transmission among multiple parties
Open APN.FX network switches combination of QKD module pairs (transmitters and receivers) in a time-scheduling manner as shown in Fig. J.3-3, enabling to reduce the required pairs and to cost-effectively deploy QKD network [H. Brunner, TuB2.2, ICTON2023]
- Enhanced resilience through protection of QKD modules and/or links
Enhance resilience with three protection schemes as shown in Fig. J.3-4, thereby maintain acceptable key supply service levels even in the network failures [ITU-T Y. 3815].

In APN.WX layer, the QKD link can be provided using one-span PtP wavelength path service, which is mainly applied at APN metro/core segment. QKD-related signals are directly inserted to and extracted from the optical fibers using add/drop function immediately after the APN node (i.e., APN-T/-G/-I) output and before the input, to avoid passing through optical amplification and wavelength cross-connect. In this configuration, center wavelengths and used bandwidths aligned with ITU-T frequency slots are individually allocated for the quantum, control and clock signals. The wavelength allocations for those QKD-related signals should be determined so as not to affect the transmission qualities of telecom DWDM signals and to maximize the QKD performance considering the interaction from telecom DWDM signals during fiber propagation.

In order to deliver QKD derived keys to a pair of user sites, KMs on the path need to play a role for relaying keys hop-by-hop between them over APN. How to transmit key relay messages between KMs in APN environment is considered as a matter of implementation and is out of scope of this document.

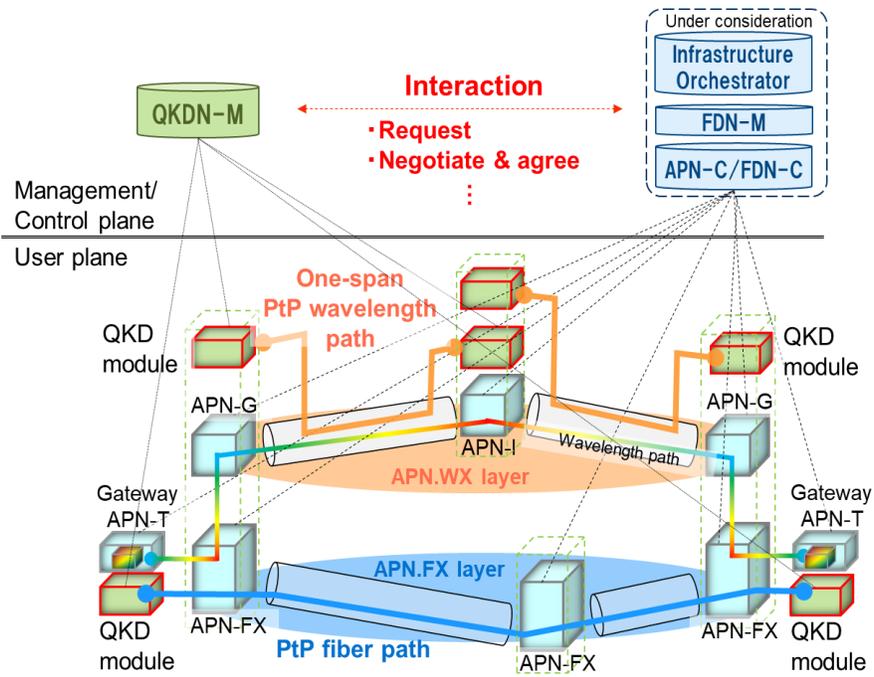


Figure J.3-1: Functional framework of QKD over Open APN

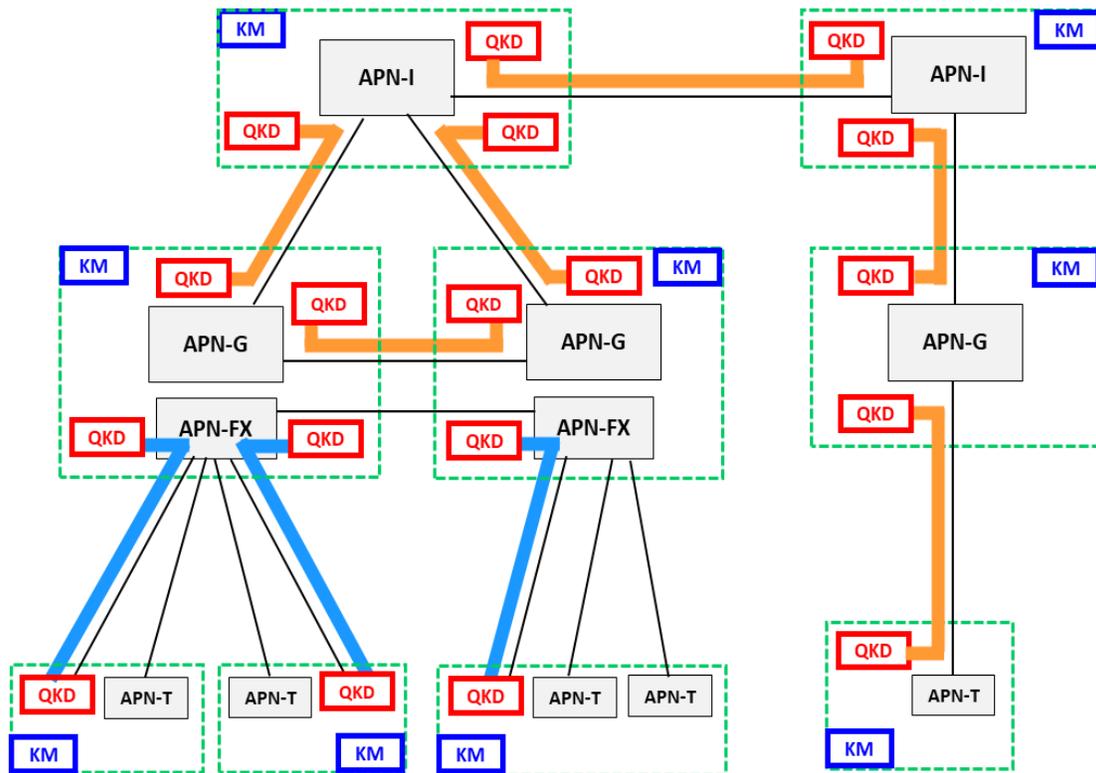


Figure J.3-2: User-plane framework for implementing the QKD link over Open APN

Full-mesh 4-node networks

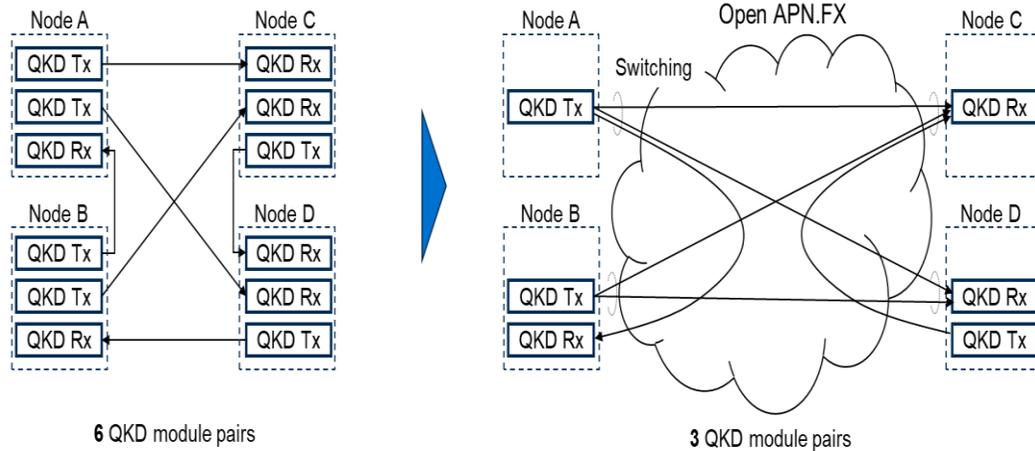


Figure J.3-3: Cost-effective one-to-many QKD transmission among multiple parties

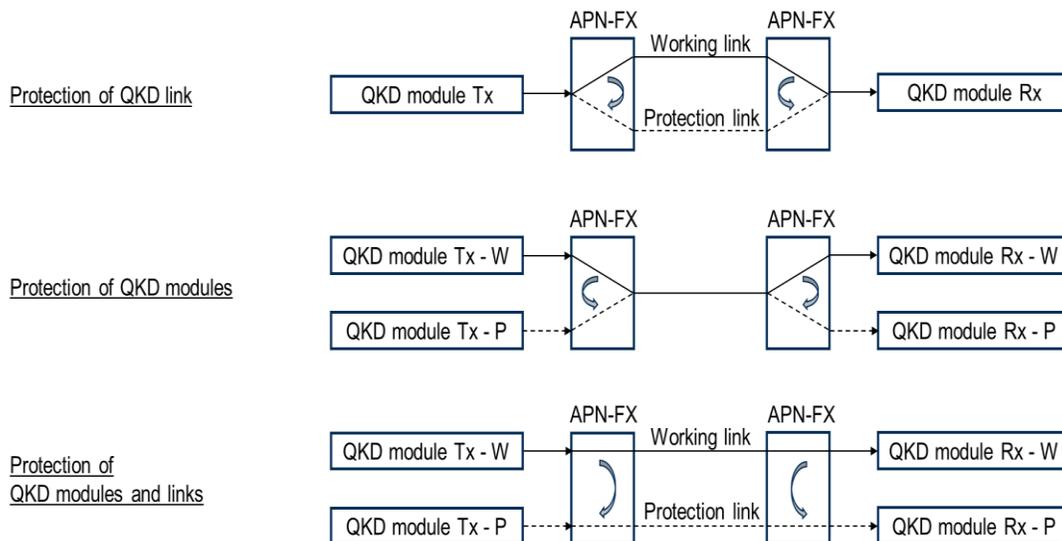


Figure J.3-4: Enhanced resilience through protection of QKD modules and/or links

Management and control-plane

When the QKDN manager instantiates QKD links over Open APN environment, it interacts with Open APN controller to secure the optical signal transmission resources for executing QKD key generation procedure as shown in Fig. J.3-1. The interface between QKDN manager and IOWN-defined management function need to be considered with existing standards as reference [ETSI GS QKD 018]. Below is an example sequence of interactions between QKDN manager and Open APN controller.

- QKDN manager sends a path service request to the Open APN controller.
- Based on the requested path service type, the APN controller executes path configuration design for either one-span PtP wavelength path service or PtP fiber path service.
 - For the one-span PtP wavelength path service, the wavelength allocation of QKD-related signals is negotiated and agreed by QKDN manager and APN controller based on physical information such as the telecom fiber condition, status of wavelength allocation and channel powers of telecom DWDM signal maintained by APN controller.
 - For the PtP fiber-path service, APN controller executes the configuration of APN-FX based on the creation request of the QKD link by QKDN manager.

K. Evolution of Optical Transport Technologies

In the recent router market, Software Defined Wide Area Network (SD-WAN) technology has become commercially available, which disaggregates the physical network and hardware equipment from its control plane and uses software to manage and control it. However, 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 (with prices dropping over 25 %/year), energy saving, and control interface commonality of transmission systems were accelerated.

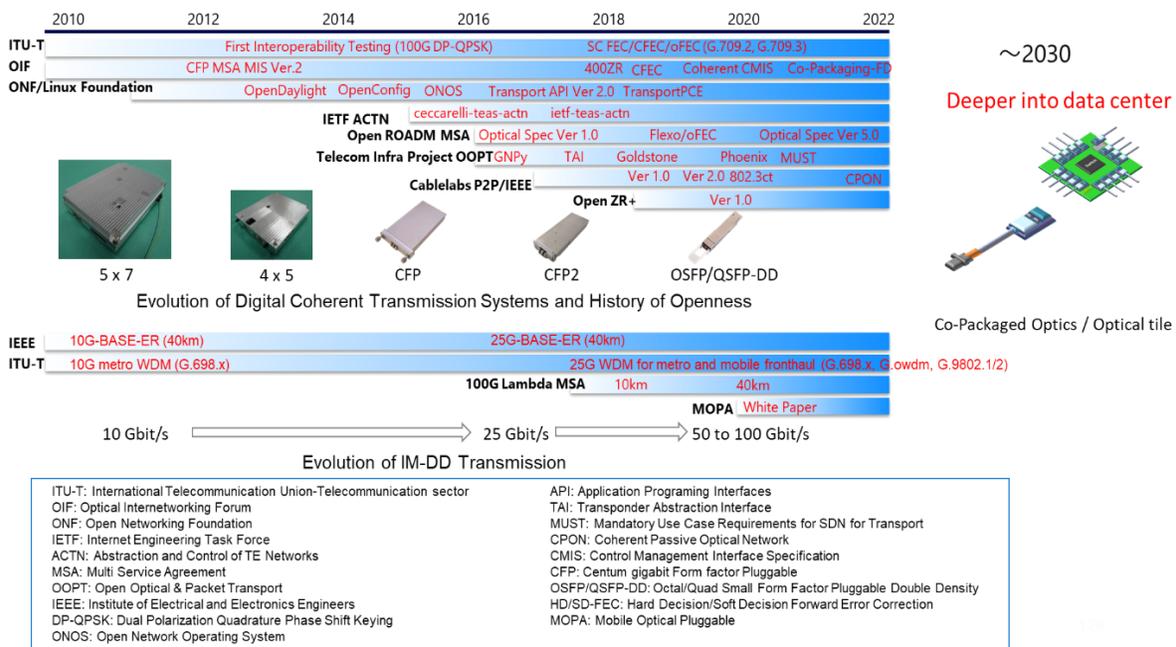


Figure K-1: Evolution of Transmission Systems and History of Openness

The upper part of Figure K-1 shows the evolution of digital coherent transmission systems and the history of open architecture 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. The 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 OpenROADM [OpenROADM], 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 data center interconnect 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 K-1 are mapped in Figure K-2.

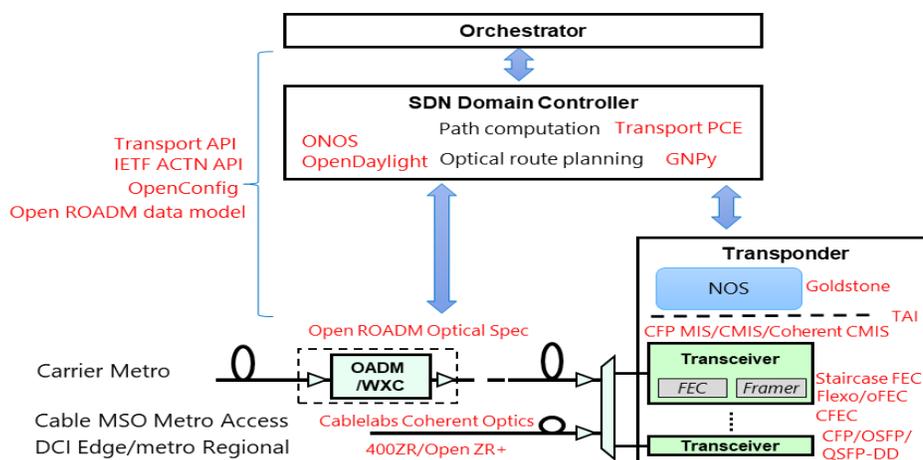


Figure K-2: Interface Specifications and Tools of Each Organization

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. A 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. Table K-1 shows the status of compatibility in the data plane. Communicating transmission methods such as modulation, forward-error-correction (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 K-1.

Table K-1: Standardized Data Plane Modes

LINE RATE [bps]	MODULATION	FEC	BAUD RATE [GBd]	ORGANIZATION
100G	DP-QPSK	SC FEC	28.0	OpenROADM [OpenROADM optical spec], CableLabs [CableLabs P2P], ITU-T [Y.1331][Y.1331.2], IEEE802.3 [IEEE802.3ct]
100G	DP-QPSK	oFEC	31.6	OpenROADM [OpenROADM optical spec]
100G	DP-QPSK	oFEC	30.0	OpenZR+ [OpenZR+ spec]
200G	DP-16QAM	oFEC	31.6	OpenROADM [OpenROADM optical spec], CableLabs [CableLabs P2P]
200G	DP-QPSK	oFEC	63.1	OpenROADM [OpenROADM optical spec], CableLabs [CableLabs P2P], ITU-T [Y.1331][Y.1331.3]
200G	DP-QPSK	oFEC	60.1	OpenZR+ [OpenZR+ spec]
300G	DP-8QAM	oFEC	63.1	OpenROADM [OpenROADM optical spec]
300G	DP-8QAM	oFEC	60.1	OpenZR+ [OpenZR+ spec]
400G	DP-16QAM	oFEC	63.1	OpenROADM [OpenROADM optical 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 following advantages.

- Chromatic dispersion compensation circuits have made the transmission line and its design simple and flexible.
- Real-time measurement of transmission quality (pre-FEC bit-error rate (BER)) without affecting the transmission quality (See Section 5.1 (in Part-II)).

- Gaussian noise model for rapid estimation of transmission line characteristics that determine transmission distance and capacity (See Annex B.3.3) [GN model].

These advantages have raised expectations for Optical Spectrum as a Service (OSaaS) [OSaaS], a transparent optical path service connecting two endpoints in a single or multi-operator's optical line system. In OSaaS, the user owns and manages the optical transceivers, while the network operator manages the Open Line System (OLS). Currently, small countries need signal regeneration at their borders for international connectivity, but if OSaaS can be implemented in a multi-domain environment, extra signal regeneration can be avoided. As a result, power and latency can be significantly reduced. K. Kaeval et al. applied probe light to a network operator's OLSs and verified a method to establish margins for static open spectrum services [OSaaS]. Furthermore, a paper [AAL] proposes a network architecture for users to connect to carrier links using user transceivers and alien access links (AAL: an access network whose components, quality, and parameters are unknown). This paper also proposes a protocol for users and carriers to coordinate and optimize the user-end to user-end optical path. Thus, the digital technologies are expected to serve as the basis for more advanced services never been seen before.

The application of digital technology has also impacted the architecture of device platforms. Hardware and software of transponder/muxponder have been disaggregated with a common hardware abstraction interface [TAI] or CMIS/Coherent CMIS [OIF CMIS], allowing each to evolve independently and shorten development time. This trend started in the switch and router markets where "white box"-based hardware from a vendor can be paired with software from a different vendor [Disaggregation]. The most significant advantage of this architectural transition is improved operational flexibility for computing facilities. The new architecture is more compliant with Open Source Software (OSS) and can apply many automation features developed for cloud operations. For example, large cloud operators are applying whitebox switches to their networks and using OSS to enable automatic provisioning of servers and switches. If optical transport devices become whitebox-enabled and automatic provisioning with OSS becomes possible, every device from the server to the optical network outside the data center could be automated. In the era of full-fledged IOWN, such a mechanism for integrated control of computing and networking will be necessary. (Reference: Annex D. 1. Plug and Play Data Center).

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 (The lower part of Figure K-1). For example, in 4G and 5G mobile networks, some mobile operators are applying WDM technologies to MFH to efficiently accommodate a large number of cells as well as cell sites with high radio counts. The bitrate of the MFH link per antenna is increased from 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 in the context of applying WDM, 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 has been standardized as a part of 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 (PtP) 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. The Open APN is expected to support 6G mobile network and future Fiber To The Home (FTTH) as an evolution of these systems.

In the next decade, the convergence of computing and networking is expected to accelerate with the advent of co-packaged optics. OIF launched a co-packaging framework implementation agreement project and released a co-packaging framework document in 2022 [OIF CPO].

Abbreviations and acronyms

For the purposes of this Reference Document, the following abbreviations and acronyms apply:

ABBREVIATION	FULL DESCRIPTION
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
BER	Bit Error Rate
CPS	Cyber-Physical Systems
CTI	Cooperative Transport Interface
CU	Central Unit
DCI	Data-Centric Infrastructure
eCTI	extended Cooperative Transport Interface
FDC	Function-Dedicated Computing
FDN	Function Dedicated Network
GOIP	Group of Optically Interconnectable Ports
GSNR	Generalized Signal to Noise Ratio
NBI	Northbound Interface
OLS	Open Line System
OSaaS	Optical Spectrum as a Service
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
SBI	Southbound Interface
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
2.0	October 19, 2023	<ul style="list-style-type: none"> - Service: In addition to PtP wavelength service (which is covered in Release 1), PtMP wavelength path service, PtP fiber path service and PtMP fiber path service are newly introduced. - Architecture: Open APN Wavelength Exchange (Open APN.WX) and Open APN Fiber Exchange (Open APN.FX) are introduced, in a layered structure. Open APN.WX corresponds to Open APN in Release 1. - APN-C details: More details on APN-C, such as functions, API, and procedures, are described. We expect this will help readers to understand how APN-C can be realized/implemented. - Implementation examples: Implementation examples of APN-T/G/I are described. We expect this will help readers to understand how APN-T/G/I can be realized/implemented.
3.0	June 12, 2025	<p>The following items are main additions and updates:</p> <ul style="list-style-type: none"> • Addition of APN-S to support of multi-lambda access from user sites • Addition of one-span wavelength-path services to support QKD, etc • Update of the APN-C function to support Life Cycle Management • Update of the APN-I function to support multi-domain networking • Alignment to the latest discussions on deterministic networking