Open All-Photonic Network Functional Architecture

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[APN]

Legal

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1. Introduction

This document supersedes Open APN Functional Architecture Release 1 [APN FA R1].

1.1. Market Dynamics and Needs

Today's world has experienced faster-than-ever growth, due to advancements in communication and computing technologies. Moving forward, another quantum leap in computing and communication capabilities is expected to empower the world, enabling a new era of growth.

This leap forward being 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. To this end, the Forum has released detailed use cases outlining how these technologies may be implemented. Examples include Cyber-Physical Systems (CPS) [IOWN GF CPS] and AI-Integrated Communications (AIC) [IOWN GF AIC].

The Area Management use case in CPS realized by many monitoring devices with beyond-human cognition will help people reduce accidents and security incidents, as well as respond to them more effectively when they occur. The Mobility Management CPS achieved by digital twin computing will enable Level 4 autonomous driving [SAE J3016]. The Industry Management use case in CPS modernizes the operation of factories and industrial plants by enabling AI-based monitoring/control and remote monitoring.

AIC use cases will give businesses that once relied exclusively on in-person attendance for their services to endure in the face of remote work challenges such as those posed by the recent pandemic. For example, future music concert halls and sports stadiums will have volumetric-capturing facilities so the performances of artists or athletes can be enjoyed remotely with a 6DoF view. Educational institutions and healthcare facilities can also provide many services remotely.

The industry has already begun implementing these use cases at a more simple level. However, the evolution of sensing/capture technologies suggests that the critical requirements of these use cases will be much higher than those achievable with existing technologies. CPS enhanced with beyond-human sensors should handle data at hundreds of Gbps and respond to events in the physical world within tens of msec, and in some advanced industry use cases, within a few msec. AIC enhanced with volumetric capturing should gather real-time streams over 100 Gbps and deliver the presentation data to the receiving users within tens of msec. Moreover, some use cases will enable feedback within a few msec, providing ultra-rich user experiences (e.g., real-time haptic feedback). When the viewer is equipped for motion/posture capturing, the feedback should be achieved less than 10 msec motion-to-photon.

1.2. Overview of the IOWN Global Forum Architecture

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.

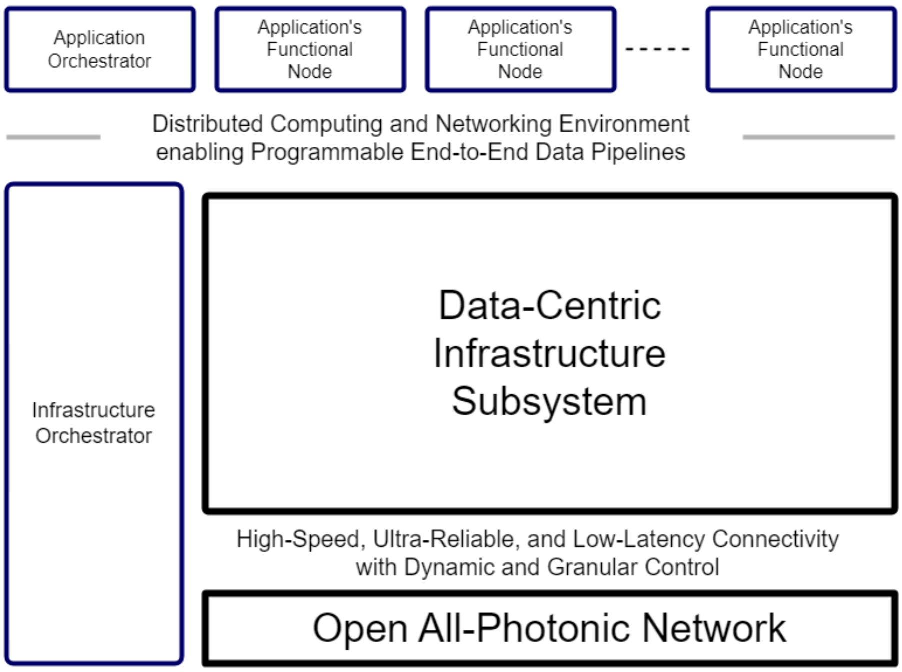


Figure 1.2-1: IOWN Global Forum Overall Architecture

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. In today's network, optical paths are disjointed and operated segment-by-segment, i.e., local area network (LAN), access network, and inter-data-center network. By contrast, the Open APN will enable one optical path to span 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 database, for data pipelines with multiple data sources and sinks.

DCI's support of heterogeneous networking will allow service providers to select data transfer and network protocols 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 will be able to accelerate data flow without isolating their systems from today's Internet ecosystems.

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

The DCI subsystem exposes service interfaces to the Application's Functional Nodes for 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 **Infrastructure Orchestrator** is the infrastructure's central management function that controls various infrastructure resources and exposes the 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 application programming interface (API) of the infrastructure orchestrator to create a runtime environment, e.g., a logical node.

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

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

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

Energy efficiency: Today, with the increasing use of big data and AI processing of large amounts of data, the power consumption of network equipment and data centers tends to increase. 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 properly 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 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 CPS and AIC use cases, new optical networking that is easily adaptable to distributed computing is needed. It connects computing resources in distant locations with high-capacity optical paths on-demand, with target quality of transport definable by computers.

Automated resource reallocation: The network will need to efficiently scale bandwidth up and down per endpoint as user demands shift over time. During the day business parks may need more bandwidth, while 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 freeness will improve as the IOWN GF update the specifications of the Open APN.

Intelligent monitoring: To realize more dynamic operations of the Open APN, the network control, and management systems must obtain sufficient information from Open APN devices. The Open APN monitoring mechanism should be more granular and comprehensive to obtain enough information faster 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.

(*The user's connection with their transceiver is an example case. There will be cases where the APN-T is installed within the carrier network or where the APN-T is owned by carriers but located at the user's site, as shown in Annex E.)

1.4. 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.

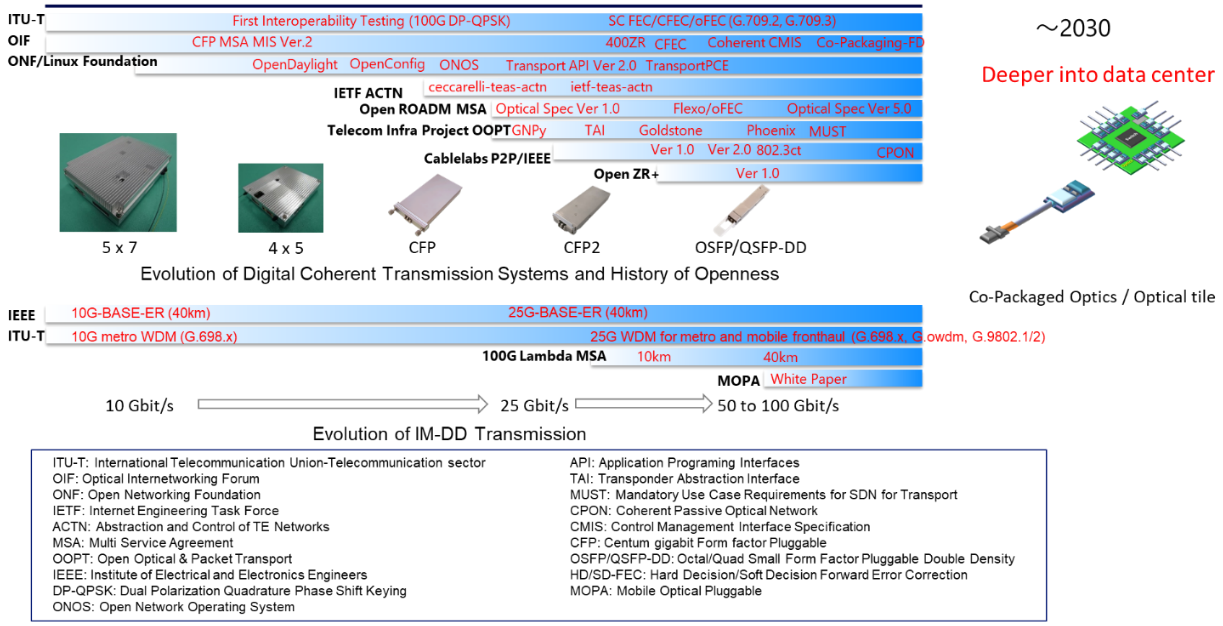


Figure 1.4-1: Evolution of Transmission Systems and History of Openness

The upper part of Figure 1.4-1 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 Open ROADM [Open ROADM], which defines interfaces and specifications to make ROADM systems interoperable among vendors, and the Telecom Infra Project Open Optical & Packet Transport (TIP OOPT) [TIP OOPT], which aims to define open technologies, architectures, and interfaces in optical and IP networking, the openness of optical transmission technologies accelerated with the participation of telecom carriers and hyperscalers. CableLabs, which works with the suppliers to the cable industry to develop interoperable technologies, has adapted coherent technology for use in metro access networks. The Optical Internetworking Forum (OIF) published Implementation Agreements (IAs) for 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 1.4-1 are mapped in Figure 1.4-2.

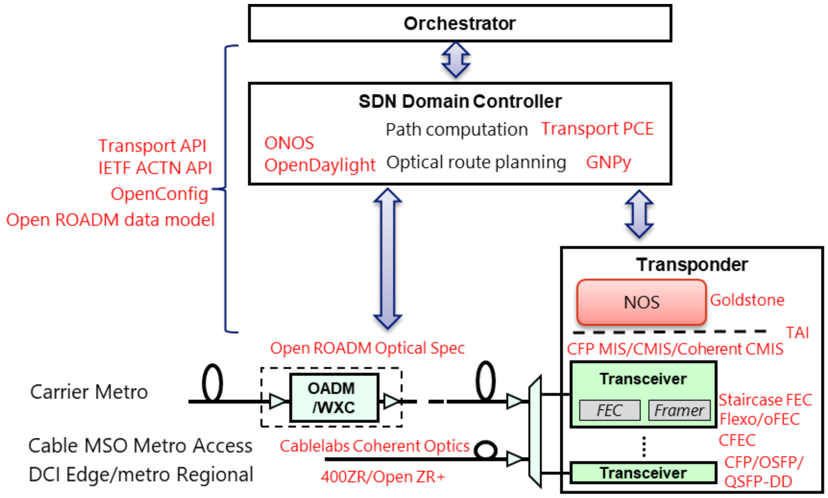


Figure 1.4-2: Interface Specifications and Tools of Each Organization

Through the activities of these organizations, international standards for coherent technology have been established by IEEE and ITU-T. IEEE802.3 defined 100GbE 80km DWDM optical interface based on coherent technologies. 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 1.4-1 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 1.4-1.

Table 1.4-1: Standardized Data Plane Modes

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

400G	DP-16QAM	CFEC	59.8	OIF [OIF spec], ITU-T [Y.1331][Y.1331.3]

The application of digital technology provides the 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 3.2.1).
- 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 1.4-1). 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].

1.5. Gap Analysis

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

Non-continuous optical paths: In today's optical transport networks, optical paths are non-continuous, and separated by frame-based switches. That is, optical paths are created for access, metro, and core networks, respectively. As 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.

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. The Open APN should allow for dynamic path creation, re-setup, and deletion, which require dynamic online optical path design. Anticipated technology gaps include the following.

- Automatic provisioning. Selecting the optimum transmission mode of a coherent module based on the quality of the fiber link system is a key factor in dynamically provisioning optical paths. It has been necessary to take into account the generation of a coherent Digital Signal Processing (DSP) LSI, the characteristics of Forward Error Correction (FEC) and the optical components installed, and the quality of the optical fiber path about the total required transmission capacity, and to have a skilled engineer carry out the optimum design of each of these conditions, taking into account the bit-error rate (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 1.4-1, but there is no standardization of control signals to interconnect modules of different types and vendors.
- Fast route planning/ensuring reliability. Path computation time would be limited, and the reliability of the communication service could be degraded due to 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 currently takes a long time manually.
- Support for multi-environments. Online optical path design should consider the networking environment of multiple network operators, multiple administrative domains, and/or optical transport devices from multiple vendors, so it is multi-technology, multi-vendor, and across administrative or ownership boundaries. Also, online optical path design should consider 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 for identifying an endpoint device. Furthermore, a user should notify a network operator of 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 (TRxs), there are several gaps against the target Open APN. Such gaps include (but may not be limited to) the following.

- Optical paths cannot be set between TRxs under the same ROADM.
- A control/management channel is not supported for the remotely located TRxs in the conventional ROADM node.
- A typical loss of access fiber (e.g., 15 dB @ Class S and 20 dB @ Class A for point-to-point optical access in ITU-T G.986 [G.986]) and its variation cannot be supported in the network based on conventional ROADM nodes with the remote location of TRxs.
- Advanced control of optical amplifier chains will be needed to support wavelength reconfiguration, 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, which 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 traffics. For instance, video streaming quality should not be affected during quality measurement.

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

Lack of support of various optical signals: Today's optical network is designed to support specific optical signals. DWDM-based networks are commonly used for high-capacity transmission. Fiber sensing technologies and QKD are promising for IOWN use cases, but these signals cannot be transmitted through today's DWDM-based network. Since these signals cannot pass through optical amplifiers, it is necessary to provide an optical path that does not pass-through optical amplifiers.
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 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.

2. Services of Open APN

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

The Open APN offers two types of optical signal transport paths to accommodate diverse optical requirements. The first type is a path that aligns with a DWDM grid and travels across a DWDM-based network. This is called a wavelength path. The second type is a path equivalent to a direct fiber connection. This is called a fiber path.

Figure 2-1 shows a summary of Open APN services based on various use cases described in Annex D. An Open APN endpoint is a transmission/termination point of an optical path. 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.

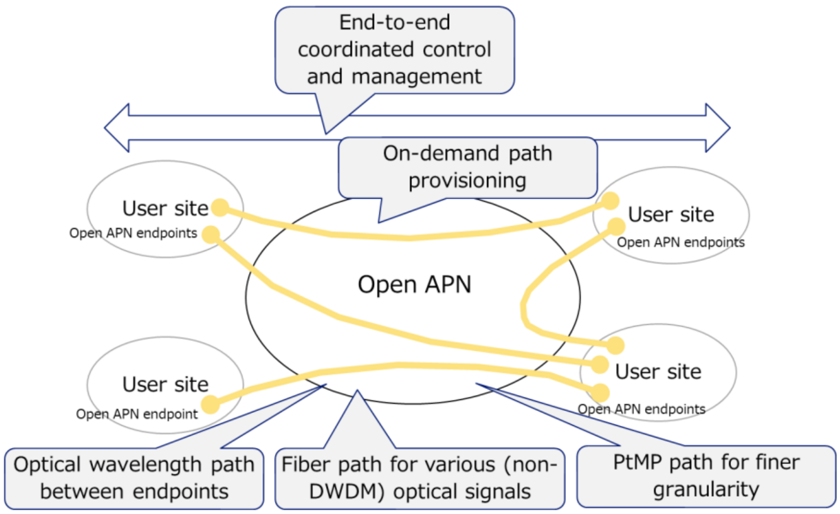


Figure 2-1: Brief Summary of Open APN Services

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 assuring 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, recovery is performed.

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. This Open APN endpoint type is named APN-T and is defined as an optical transceiver that terminates a wavelength path. Note that we use APN-T to explicitly indicate the Open APN endpoints with DWDM transmission capability.

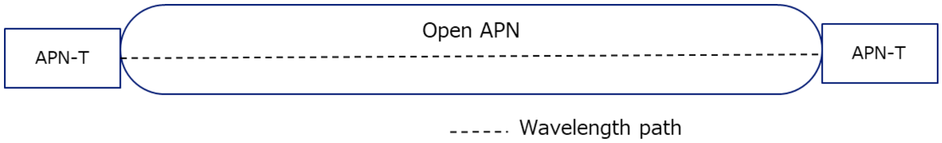


Figure 2.1-1: Point-to-point Wavelength Path Service

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

This service provides a shared wavelength path from (or to) more than one leaf Open APN endpoints to (or from) a one hub Open APN endpoint. These endpoints are optical transceivers, and the hub optical transceiver communicates with the multiple-leaf optical transceivers using this PtMP wavelength path. 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.

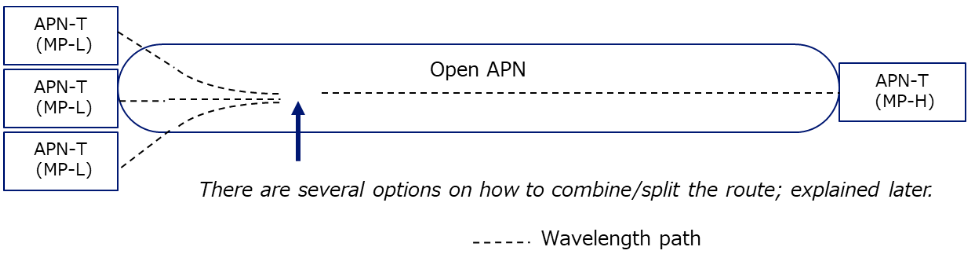


Figure 2.1-2: Point to Multi-point Wavelength Path Service

2.1.3. PtP Fiber Path Service

This service provides a dedicated fiber path between two Open APN endpoints. 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.

An Open APN endpoint for this service may be connected with an optical device such as an optical transceiver or an optical node; see Section 3 for the architecture. The optical transceiver connected to the endpoint of this service 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.

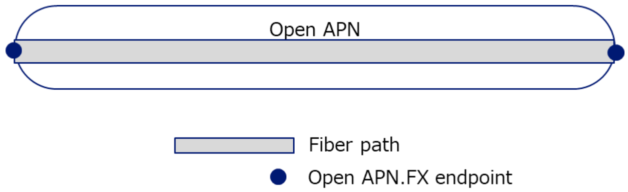


Figure 2.1-3: Point-to-Point Fiber Path Service

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 endpoint via an optical splitter. Note that there can be multiple optical splitters cascaded within a fiber path.

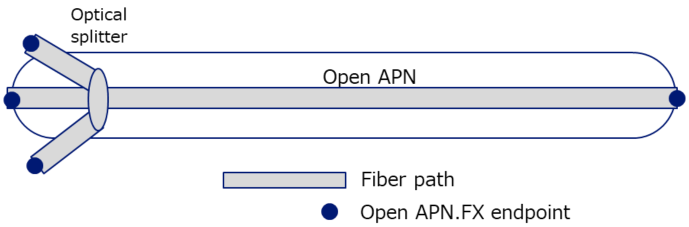


Figure 2.1-4: Point to Multi-point Fiber Path Service

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 (which is 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.

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

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

1. W 100-200G 31.6 Gbaud of Open ROADM MSA Optical Specification Version 5.1
2. W 200-400G 63.1 Gbaud of Open ROADM MSA Optical Specification Version 5.1
3. NRZ 10G (N, W) of ITU-T G.698.2
4. NRZ 2.5G (N, W) of ITU-T G.698.2

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

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

- Physical information of the wavelength path (e.g., used fibers, wavelengths, 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 3.3.4 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 PtP fiber-path specification.

The optical interface at each end of a PtMP fiber path is defined as PtMP fiber-path specification.

Each fiber-path specification will provide 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. Summary

Figure 2.2-1 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.
- 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.

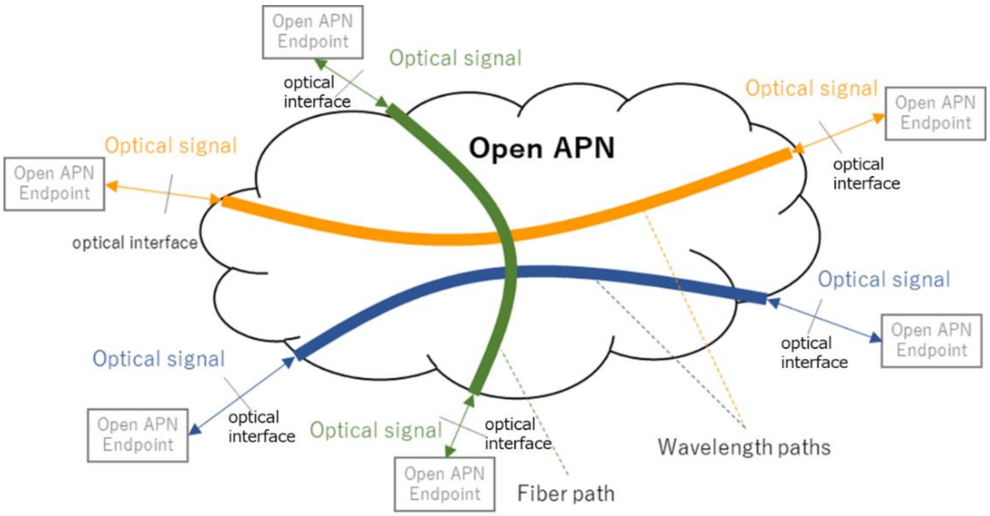


Figure 2.2-1: Open APN User Plane Service

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 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>

- Users can request the following path setup requests specifying Open APN endpoint addresses; (a) path creation, (b) path deletion, and (c) path re-setup.
- Users can request the following requirements in a path setup request; (a) bandwidth, (b) latency, (c) jitter, and (d) redundancy.
- Upon request, the Open APN service provider setups 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 different users (e.g., including 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. 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 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-trigged mode, in which the parameters are acquired on the defined thresholds are trigged within the subscription sessions.
- Open APN service providers may post collected data to the IOWN Data Hub and have some intelligent applications retrieving the data from the Data Hub. The Open APN supports a network configuration strategy to communicate with 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. Functional Architecture of the Open APN

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. Figure 3-1 shows the relationship between Open APN.FX and Open APN.WX for release 1 and 2 of this document. The function blocks shown in Figure 3-1 (e.g., APN-T, APN-G, APN-I) are described in Section 3.1.1. Note that a fiber path is provided by Open APN.FX between two of the functional blocks of Open APN.WX. So, 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.

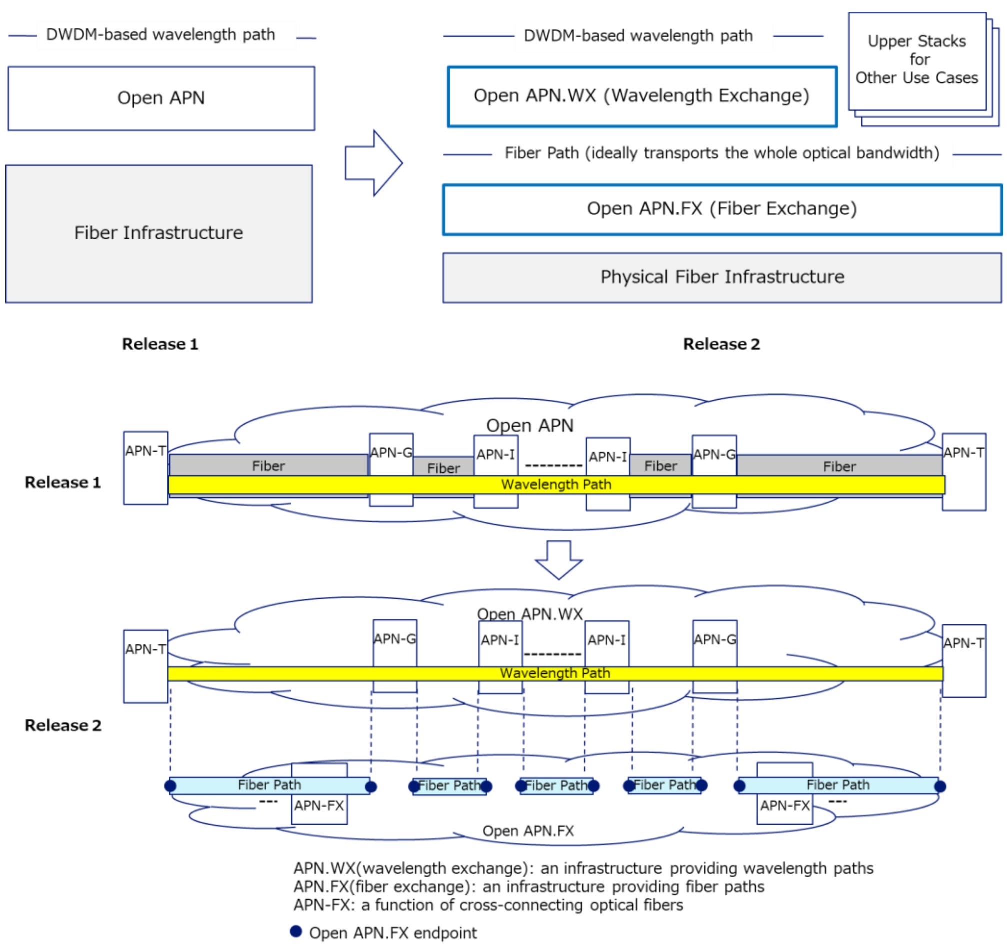


Figure 3-1: Relation between Open APN.WX and Open APN.FX

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

3.1. High-level Reference Architecture

3.1.1. Basic Architecture

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

Figure 3.1-1 shows a high-level reference architecture of Open APN.WX for PtP wavelength path services.

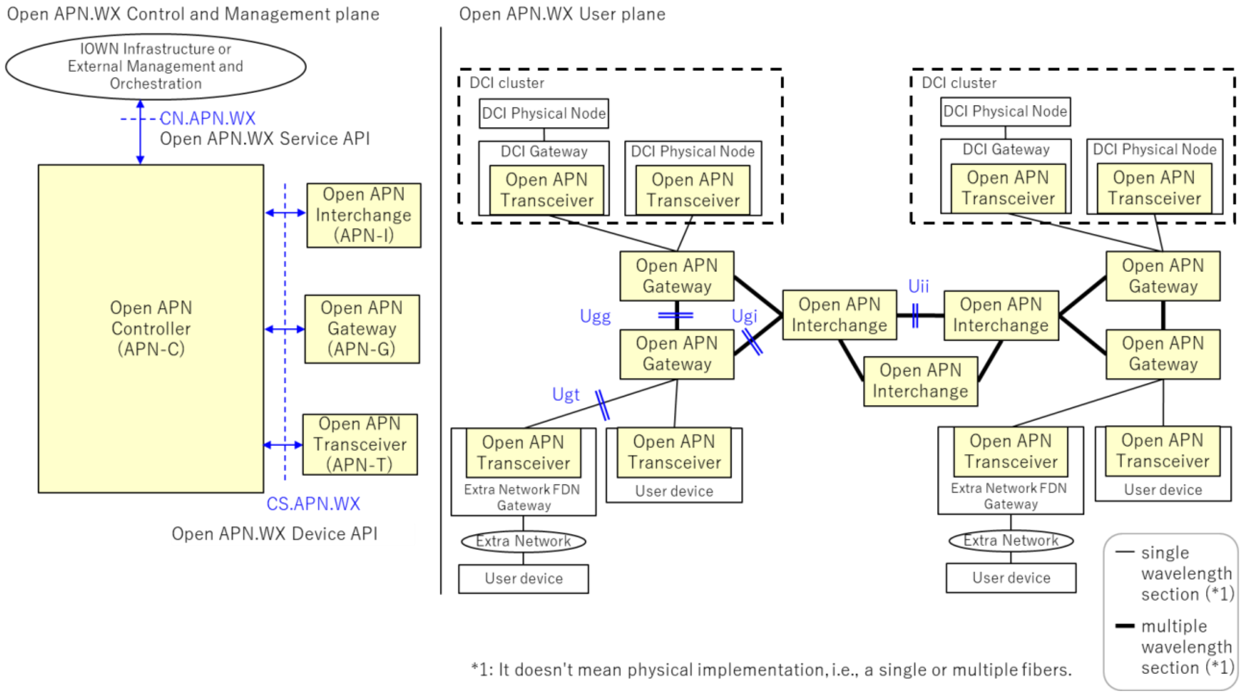


Figure 3.1-1: Open APN.WX High-level Reference Architecture for PtP Wavelength Path Services

Open APN.WX User plane consists of Open APN Transceiver (APN-T), Open APN Gateway (APN-G), and Open APN Interchange (APN-I). 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 might be placed as a WAN interface of Extra Network FDN Gateway or DCI Gateway defined in [IOWN GF DCI], which provides QoS-aware mux/demux and forwarding services between external links and optical signal transport paths (See Annex A. IOWN Global Forum Flexible Bridging Services). In the other deployment pattern, the APN-T might be placed as a network interface of a user device. The functional split and interface between the APN-T and the remaining components of a user device or a gateway are for further study.

APN-G is a gateway 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) provision of control channels to communicate with the connected APN-Ts, (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-Ts (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 User plane (2) is to provide 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 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 he shortest path between the PAN-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.

APN-I is an interchange for wavelength switching at the midpoint of an Open APN optical path. For providing a direct optical path between any two endpoints, APN-I shall have the following three functions; (1) wavelength cross-connect, (2) amplification, and (3) adaptation between APN-G and APN-I as well as APN-I and APN-I. The wavelength cross-connect function (1) enables each incoming optical path to be output to any direction (any port) without the need for electronic processing. The amplification function (2) enables each incoming attenuated signal to be amplified to maintain transmission quality without the need for electronic processing. The adaptation function (3) enables any combinations of APN-G and APN-I to be interconnected. Such combinations are “APN-I and APN-G” and “APN-I and APN-I.” Please note that a valid example of such an adaptation is described in Section 3.3.1.5.

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.
- 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.

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

Ugt is either a single-wavelength or a multi-wavelength interface as defined in Section 3.3.2 while the implementation examples of APN-G shown in Annex C allows a single-wavelength Ugt. APN-G implementation to allow a multi-wavelength Ugt is for further study.

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

Figure 3.1-2 shows a high-level reference architecture of Open APN.FX for PtP fiber path services.

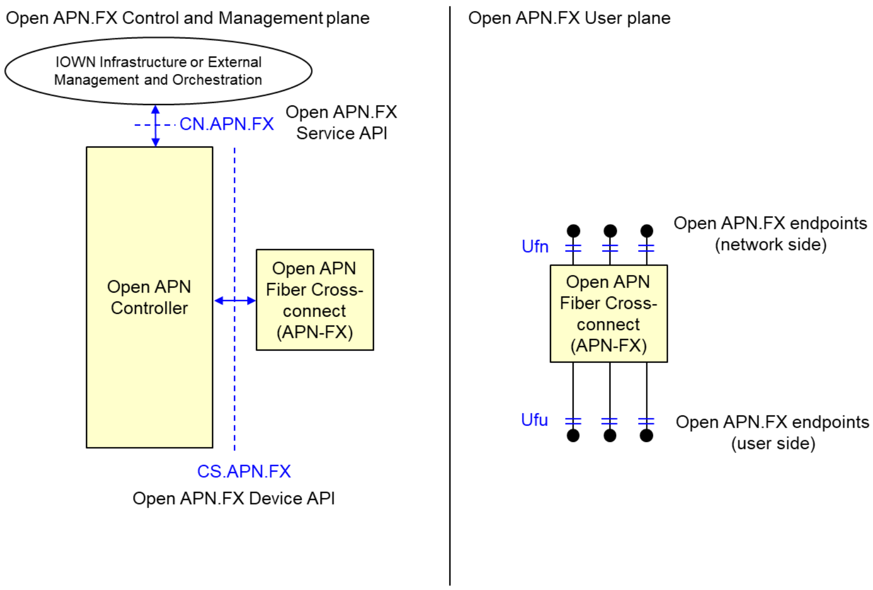


Figure 3.1-2: Open APN.FX High-level Reference Architecture for PtP Fiber Path Services

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 of Open APN.FX. APN-FX shall have (1) cross-connect function in a unit of fiber and (2) a turn-back function in a unit of fiber. The fiber cross-connect function (1) dynamically provides a fiber-to-fiber connection to create a path for the fiber path services.

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.
- 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 3.1-3 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.

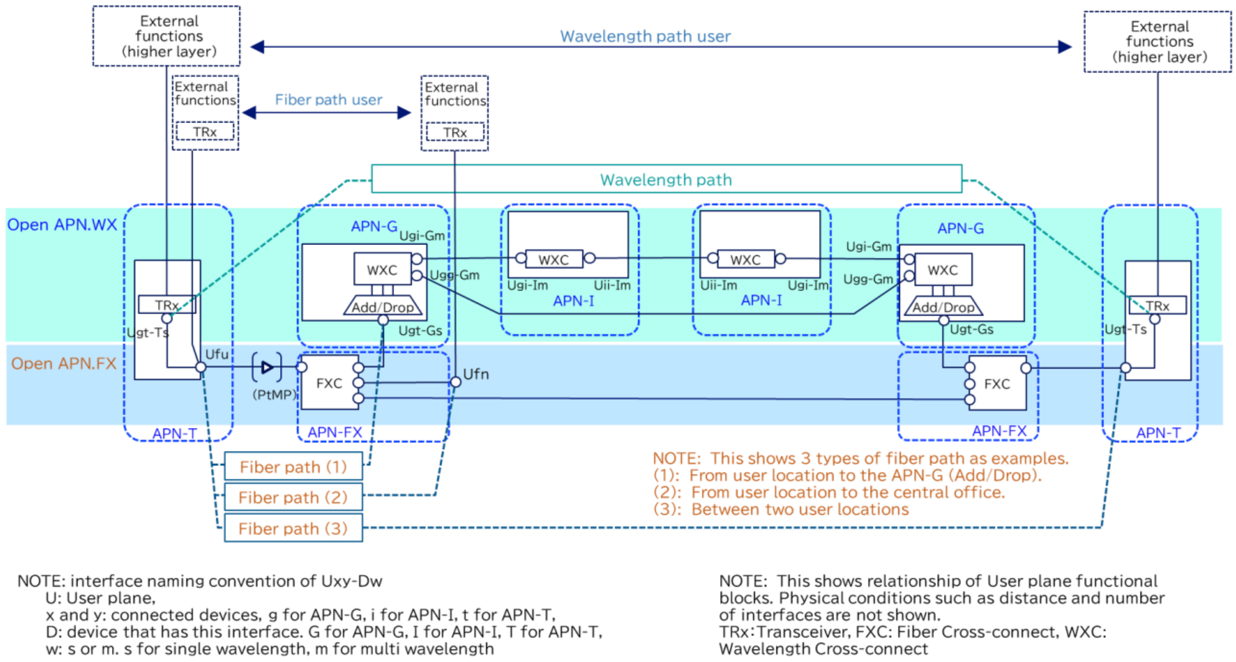


Figure 3.1-3: Example of the Relationship between Open APN.WX and Open APN.FX

3.1.2. 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. Detail 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.

Since the required functions of an APN-T may differ based on the location within the topology, the APN-T is subdivided into the following types.

1. APN-T(P): APN-T(P) can follow the transmission/reception specifications of PtP technologies described in Section 2.1.1.
2. APN-T(MP-H): This type of APN-T is used for point-to-multipoint connections; in which MP of MP-H means Multi-point and H means Hub. One APN-T(MP-H) accommodates multiple APN-T(MP-L)s.
3. APN-T(MP-L): This type of APN-T is used for a point-to-multipoint connection, where L of MP-L means Leaf.

Some of the above APN-Ts have an optional line-rate selection function.

Figure 3.1-4 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.

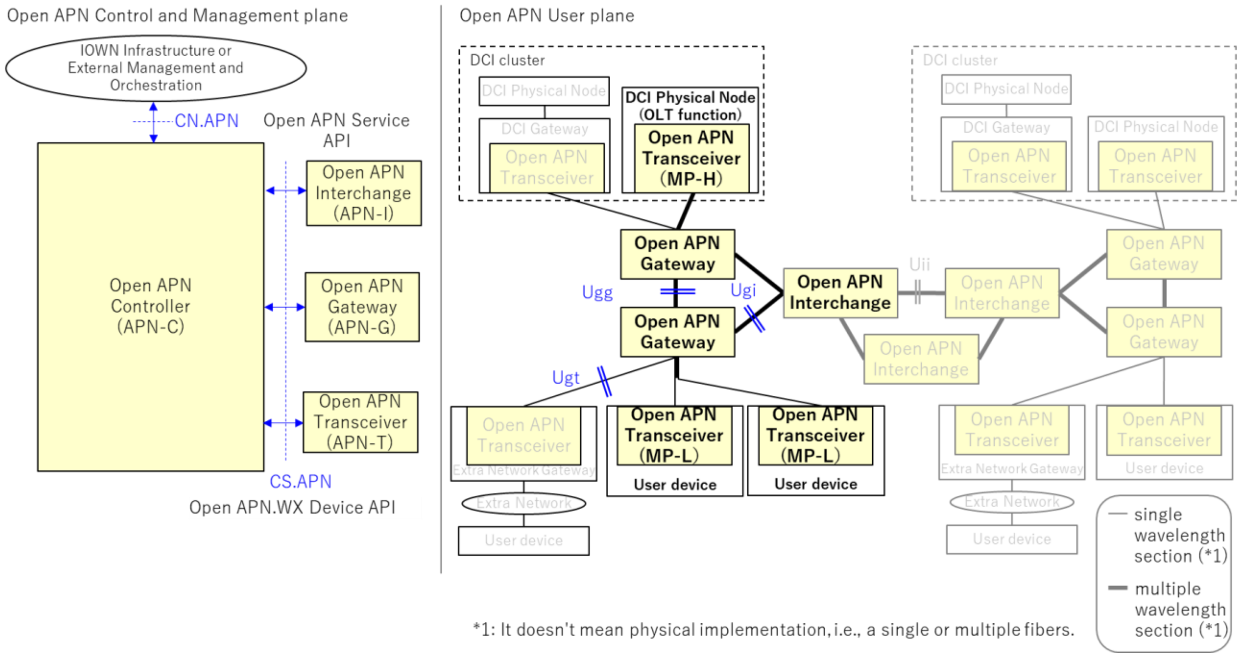


Figure 3.1-4: Open APN.WX High-level Reference Architecture for PtMP Wavelength Path Services

Figure 3.1-5 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.

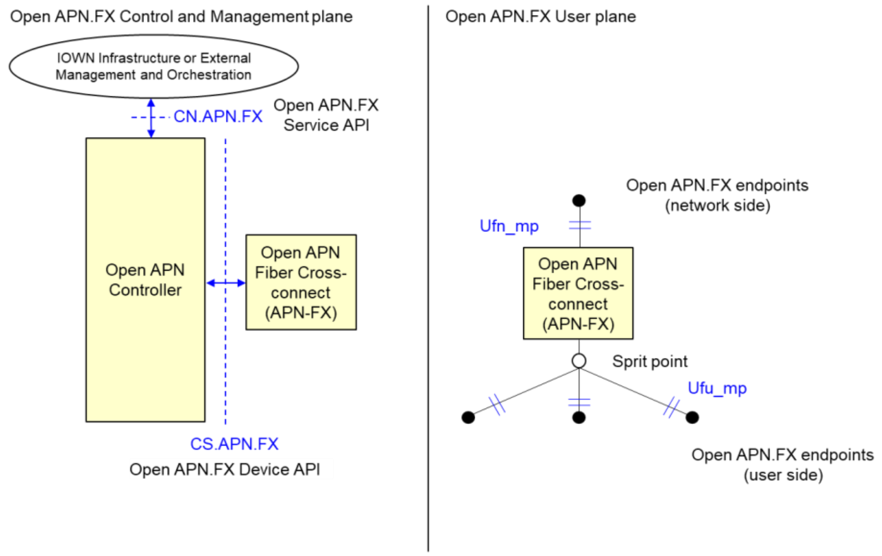


Figure 3.1-5: Open APN.FX High-level Reference Architecture for PtMP Fiber Path Services

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 same as in Section 3.3.4.1. 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)s. 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.

3.1.3. Object Model for Control Plane Services

Figure 3.1-6 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 3.1-6. Open APN Gateway (APN-G), Interchange (APN-I), and Transceiver (APN-T) are introduced in Section 3.1. The Group of Optically Interconnectable Ports (GOIP) is introduced in Section 3.3.1.

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.

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 Open APN.FX Endpoint to either APN-G, APN-I, or APN-T.

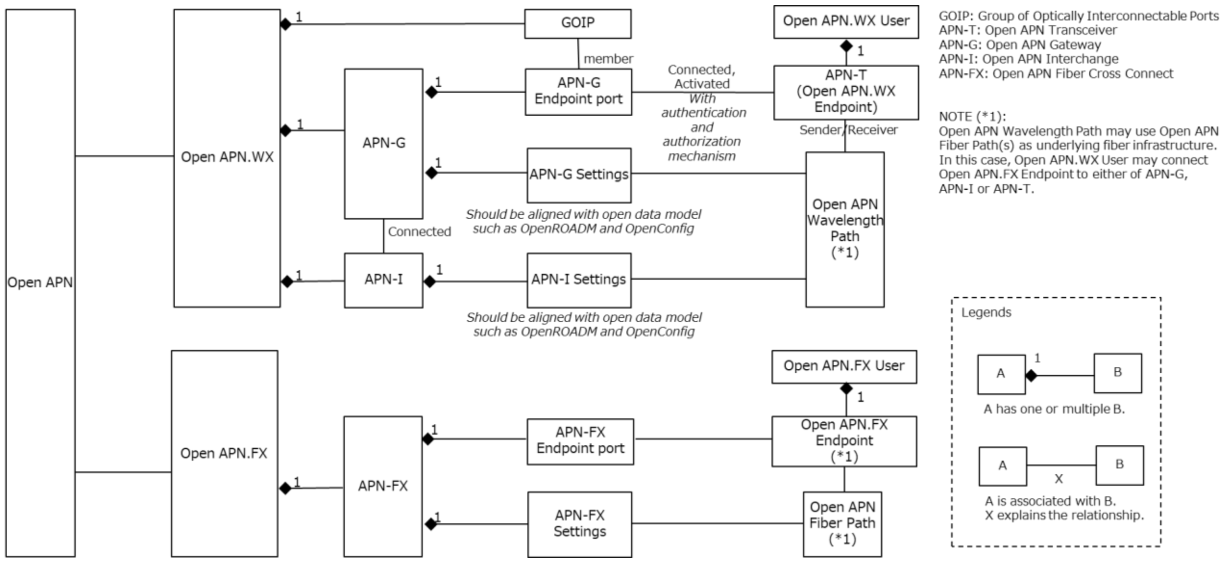


Figure 3.1-6: Object Model for Open APN Control Plane Service

3.1.4. Reference Network Models

This section describes how the services described in Section 2 are realized by the Open APN architecture, along with reference network models with a specific focus on PtP wavelength path service.

Figure 3.1-7 shows a reference network model, when APN-Ts are located at user sites. Such APN-Ts may be user-owned. For the PtP wavelength path service type, the Open APN provides an optical wavelength path between APN-Ts. Such 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 Open APN service provider and users must coordinate to control and manage wavelength paths using APN-C. Details are described in Section 3.2.

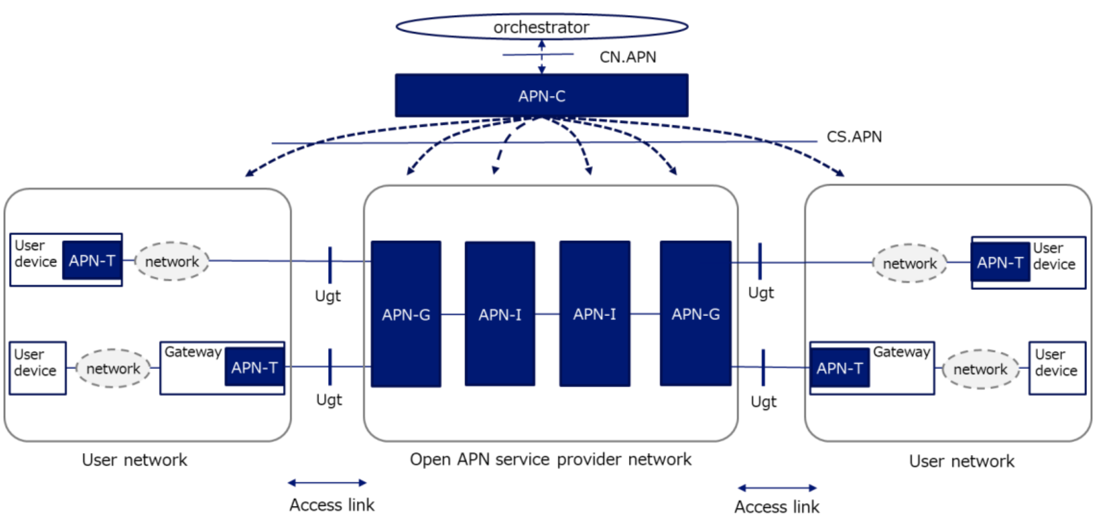


Figure 3.1-7: Example Network Reference Model

An access link connects APN-T and APN-G located in remote sites. There are various configurations of access links. Figure 3.1-8 shows example configurations of access links. Details on interface definitions are described in Figure 3.3-6 of Section 3.3.2.

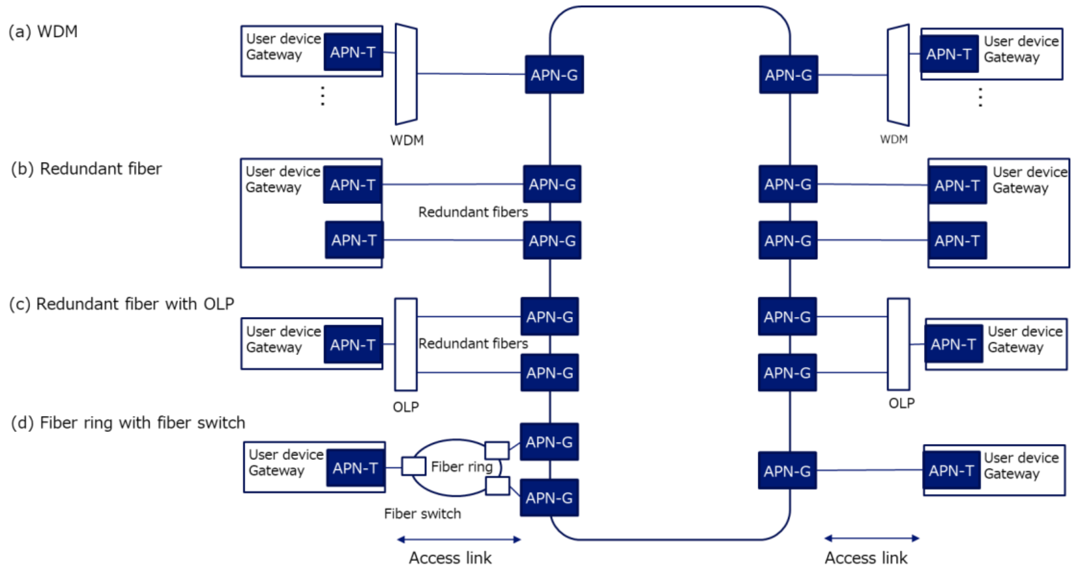


Figure 3.1-8: Example Configurations of Access Links

(a) uses WDM. Note that Multi-Wavelength (MW) interface support of the APN-G port (connected to APN-T) is for further study. (b) and (c) are for redundancy. Redundant fibers may be geographically diverse, and two APN-Gs may be geographically diverse. (b) uses two APN-Ts with redundant fibers. Switchover is realized at user devices or gateways (FDN/DCI gateways) (e.g., optical layer, OTN layer, or packet layer). (c) uses one APN-T with Optical Line Protection (OLP) and redundant fibers. Switchover is realized at OLP. Note that there are other techniques for redundancy, such as recovery between APN-Gs. (d) is for flexible connection of APN-T and APN-G, using a fiber ring and fiber switch. It is possible to reconfigure which APN-G each APN-T is connected, based on demand or failure.

Note that these configurations are not mutually exclusive. For example, (a) and (b) can be combined to save the number of access fibers used and improve redundancy.

3.2. Control and Management Plane Reference Architecture

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

3.2.1. Control and Management Scope of APN-C

APN-C controls and manages APN-I, APN-G, and APN-T and sets up wavelength paths between two APN-Ts. APN-T 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 3.2-1. 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 maintain monitoring information of APN-Ts. The blue line in Figure 3.2-1 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.

For such a purpose, APN-C may be permitted to control and manage APN-Ts directly. In other words, APN-T control and management is delegated to APN-C after network attachment and authentication of APN-T. An alternative model is that a user network controller or application exists, and APN-C communicates through the user network controller or application.

When APN-C directly controls and managements APN-Ts, APN-C communicates with APN-Ts as shown in the following list.

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

Note that APN-T is a part of the gateway. A gateway could be an FDN gateway or a DCI gateway. 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.

It may be preferable 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 part of gateways. The APN-C mentioned in this section applies to both Model #1 and #2 in Annex E.1.

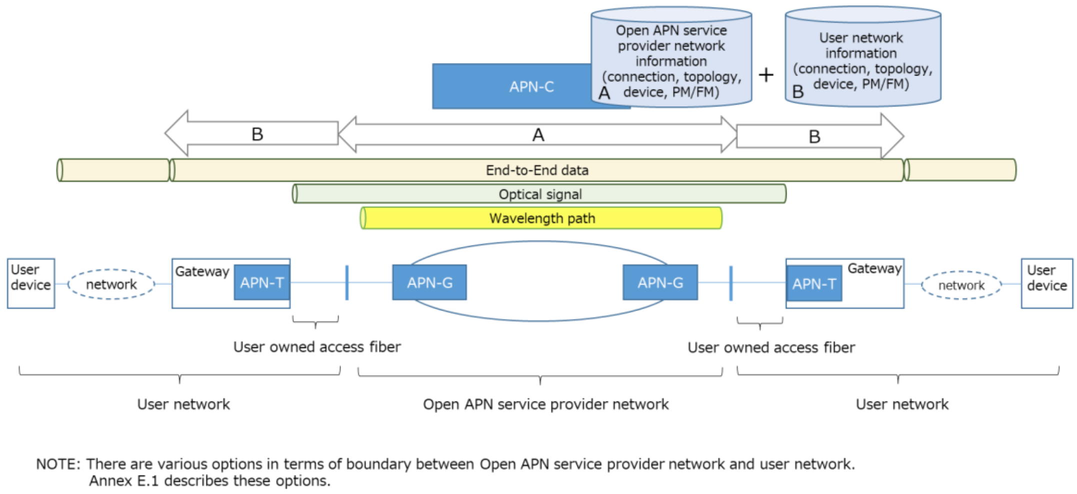


Figure 3.2-1: An Example Control and Management Scope of APN-C

Figure 3.2-2 shows the alternative case of Model#1 in Annex E.1, where APN-T is placed as a network interface of the user device. When APN-T is directly connected to APN-G, the control and management functions of APN-C are identical to Figure 3.2-1. Further work is required when there are APN-Is/APN-Gs in the user network, such as controlling and managing APN-Is/APN-Gs located in user networks (shown as dotted objects in Figure 3.2-2).

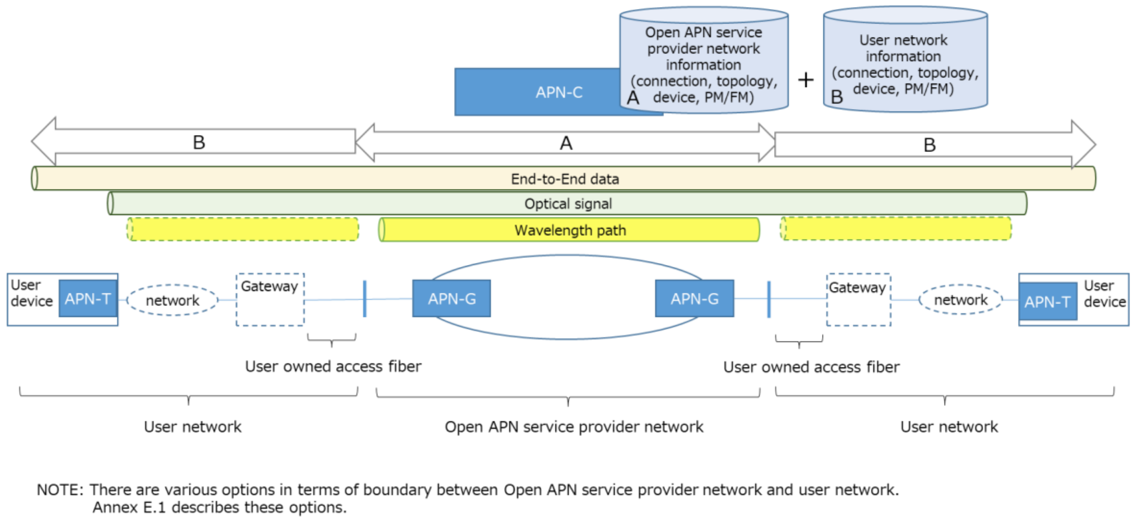


Figure 3.2-2: Another Example of Control and Management Scope of APN-C

3.2.2. APN-C Functions and APIs

Figure 3.2-3 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 3.2.1, APN-C maintains not only Open APN service provider network information, but also user network information. APN-C may be privileged to directly control and manage user network devices. 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.

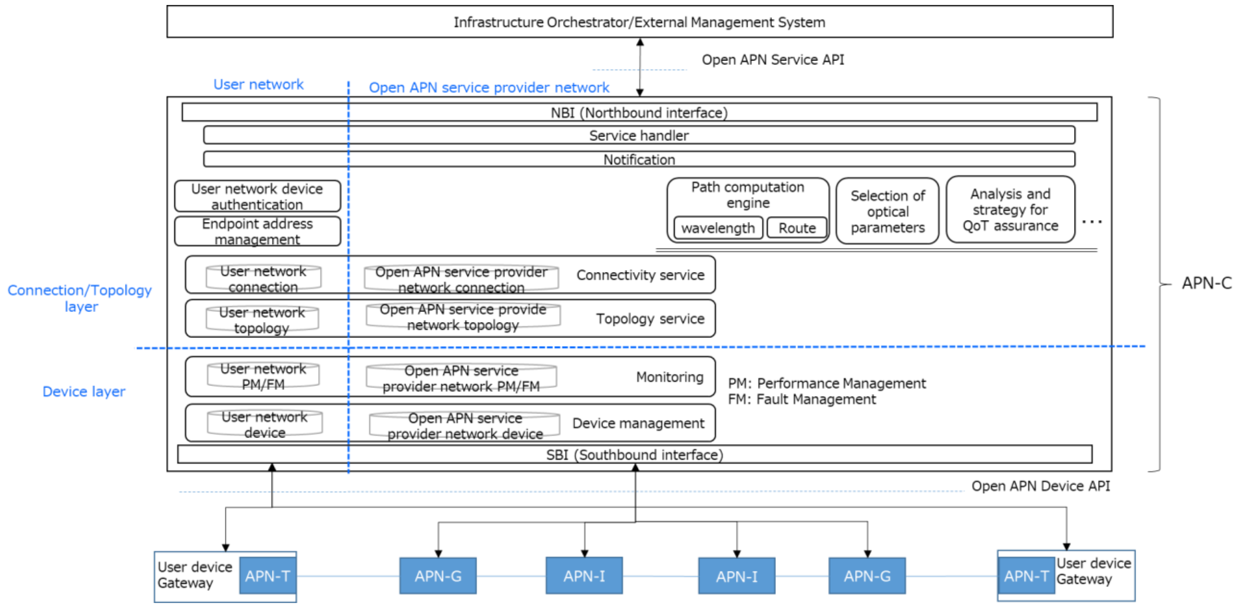


Figure 3.2-3: An Example Reference of APN-C Functional Model

Note that the communications channel from APN-C is terminated at APN-T or may be terminated at the gateway if there is no clear demarcation between APN-T and other parts of the gateway. This communication channel must be secure and may be in-band or out-band.

APN-C may have eCTI-API [IOWN GF IMN] as an interface for mobile systems, as shown in Section 3.2.5.1.

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 common addressing space between Open APN service provider and user. The endpoint address is specified in a path setup request.
- Device management: a mechanism to maintain devices. In addition to Open APN service provider network devices, user network devices are supported after authentication. Device management includes management of device configuration and configuration history.
- Topology service: a mechanism to maintain topology and to provide topology information. In addition to Open APN service provider topology, user network topology is maintained after authentication as access links between APN-T and APN-G.
- Connectivity service: a mechanism to maintain connectivity service (i.e., service provided by connection through path setup request) and to provide connectivity information. A connectivity service is provided based on path setup requests. Furthermore, re-setup may be performed to modify the parameters of existing paths or reroute the existing paths when QoT is unsatisfied using redundancy mechanisms.
- Path computation engine: a mechanism to compute route and wavelength for wavelength paths. The path computation engine selects the transmission mode to satisfy QoT of wavelength paths. Technologies such as GNPy may be used to estimate QoT of wavelength paths computed.
- 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 consist 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 an user network device is complete.
- 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-time and possibly end-time as well.
- 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 re-setup service API: The Infrastructure Orchestrator or user applications request APN-C to re-set up 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 user requirements or to reroute the path.

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

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

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 re-setup is requested when user requirements are not satisfied based on real-time QoT monitoring.
- Analysis and strategy of QoT assurance: a mechanism to support the analysis and strategy functions of 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 network configuration strategy conducted in those computing units. 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 consist of the following.

- Network strategy request API: APN-C notifies an external entity of the delivery of the QoT information. The external entity conducts storage, processing, and all decisions based on the QoT information.
- Network strategy receiving API: An external entity notifies APN-C of the conducted network configuration strategy delivery.

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

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

3.2.3. A Recommendation Set of Southbound Interfaces

Figure 3.2-4 shows a recommendation set of Southbound interfaces (SBIs) of APN-C. The APN-C sends/receives information through the SBIs to/from APN-I, APN-G, 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 [Open ROADM], and TAPI [TAPI]) and the current technical trend of disaggregated architectures, there are three options for SBIs as shown in Figure 3.2-4.

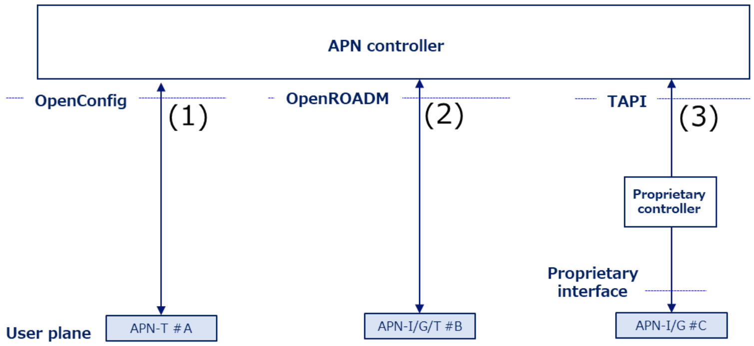


Figure 3.2-4: Recommendation Set of Southbound Interfaces (SBIs) for APN-C

- 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, and APN-T

OR-compliant APN-I, APN-G, and APN-T are controlled and managed through OR. This option can expect 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 Open APN controller or APN-T.

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

APN-I and APN-G 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 be applicable for migration or as a near-term solution. However, from the viewpoint of an Open APN architecture, APN-I, and APN-G should have open interfaces as Options (1), (2), and (3).

3.2.4. Example Procedures for Controllers

(1) Registration of 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 request.
2. APN-C authenticates user network device.
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 endpoint address.

(2) 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/I (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.

(3) 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.
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 user network device.

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

3.2.5. 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 with such 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-band mode, via a dedicated link; (b) in-band mode, sharing the data traffic link. In (b) in-band mode, the dedicated link could be an optional implementation (See Figure 3.2-5).

Figure 3.2-5: Two Modes for Telemetry

A collector will be implemented in APN-C to collect the telemetry information of Open APN devices (APN-T, APN-G, and APN-I). A telemetry engine will be implemented in Open APN devices (APN-T, APN-G, and APN-I) to send the telemetry information to APN-C (See Figure 3.2-6).

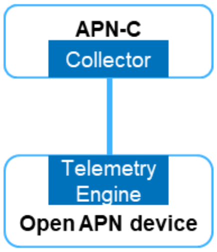


Figure 3.2-6: Collector and Telemetry Engine

Figure 3.2-7 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.

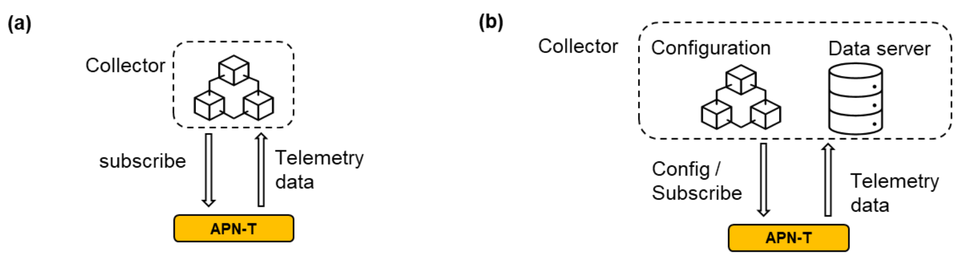


Figure 3.2-7: Streaming Telemetry and Two Collector Configurations

In Figure 3.2-7(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 3.2-7(b), another streaming telemetry collector is depicted. Such a collector is comprised of two parts. The left part is responsible for sending subscription 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 of 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 the defined threshold is triggered.
- he monitoring interval can be second level (with state-of-the-art technology.)
- A collector can accommodate multiple telemetry engines, as Figure 3.2-8 shows.

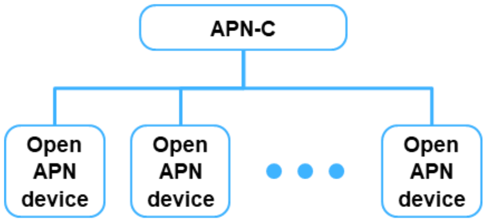


Figure 3.2-8: Accommodation of Multiple Telemetry Engines

3.2.5.1. Extended Cooperative Transport Interface for Open APN

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

Figure 3.2-9 shows an example of controller configuration for eCTI. The eCTI between APN-C and mobile systems is defined as eCTI-APN. In this example configuration, APN-C includes a real-time control function, which plays the role of the real-time control of APN-G and/or APN-T respectively to assure QoT. Annex D.3 shows an example of eCTI use cases.

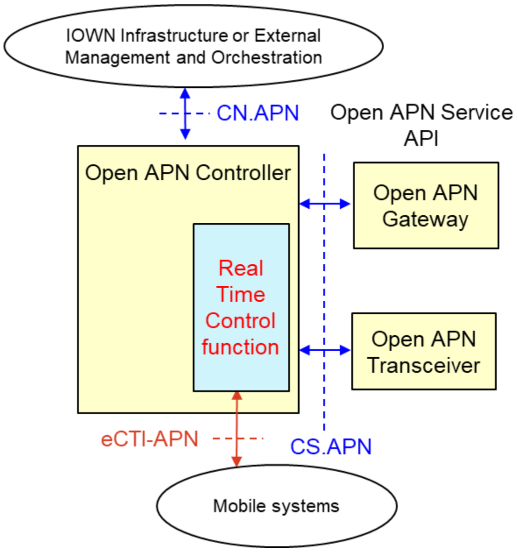


Figure 3.2-9: Example of Controller Configuration for eCTI

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

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

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

3.2.5.2. Real-time Transmission Quality Measurement

As noted in Section 1.4, 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 parameters of transmission quality 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 measure 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.

3.3. User Plane Reference Architecture

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. In the current release, this section focuses on Open APN.WX, and defines Group of Optically Interconnectable Ports (GOIP) for such a purpose. It then describes the design criteria of the Open APN using GOIP and how to leverage the ultra-wideband optical transmission technologies.

3.3.1. 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, 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 followings.

- 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.

3.3.1.1. 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 far as the wavelength-path characteristics are met to the signal)
- To minimize 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, there is at least one route that can establish a direct optical connection between ports. However, this doesn't guarantee that a direct optical connection between ports can be established by any route and at any time. It is because the transmission performance may not be guaranteed when choosing a detour path. It means that there is a possibility that you cannot establish a direct optical connection when the shortest route is not available due to any reason, 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 3.3-1 shows a schematic diagram of GOIP, in which one GOIP is formed for the Data Center Interconnect and the other GOIP is created for the Radio Access Network.

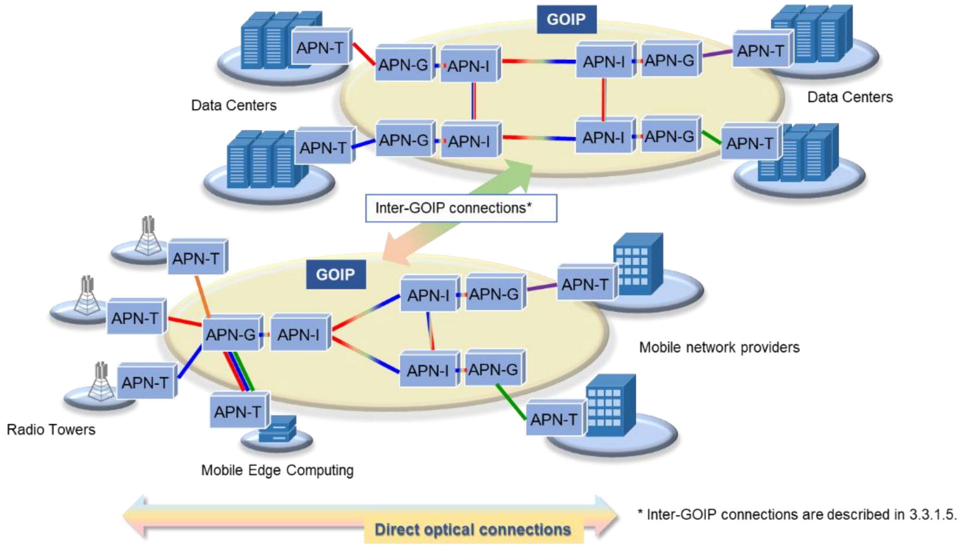


Figure 3.3-1: Schematic Diagram of GOIP

3.3.1.2. 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 multi-vendor environments. It is possible to achieve ideal wavelength resource utilization at any time without dependence on the bitrates of APN-T and geographic factors.

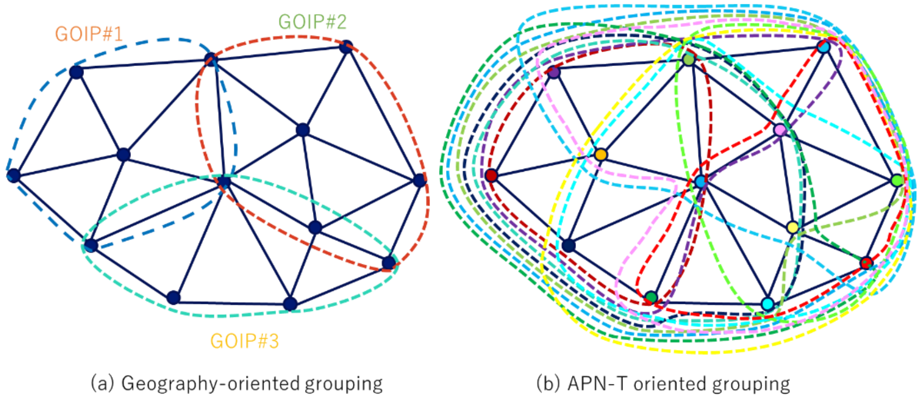


Figure 3.3-2: Groping Types of GOIP

Table 3.3-1: 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 be considered 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 boundary 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, if direct optical paths can be connected in Inter-GOIP discussed in Section 3.3.1.3, the maximum distance at each bitrate can be obtained.	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.

3.3.1.3. Design Criteria for the Geography-oriented Grouping

At least for the short-term and mid-term deployment of the Open APN, it is recommended to assume the geography-oriented grouping to design 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 needed 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 the geography-oriented grouping, inter-GOIP connections can be realized by methods described in Section 3.3.1.5.

3.3.1.4. 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.

3.3.1.5. 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. Figure 3.3-3 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 setup direct wavelength paths across the multiple GOIPs as far 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.

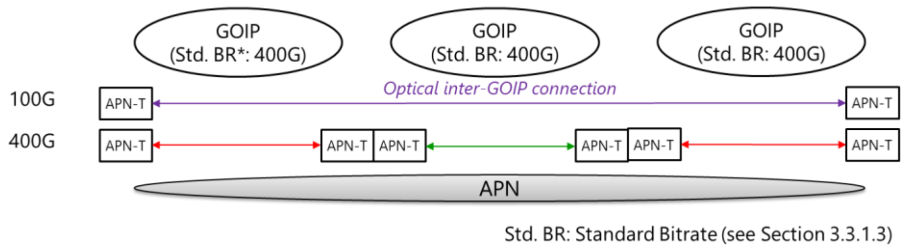


Figure 3.3-3: Inter-GOIP Connections

Another advantage of inter-GOIP is that it enables the direct accommodation of user data across multiple GOIPs. Figure 3.3-4 illustrates three cases: the upper case has an O/E/O repeater at the border of two GOIPs. 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, it is once terminated at the APN-T of the O/E/O repeater, and again user data is transmitted from another APN-T at the O/E/O repeater to the GOIP on the right(/left) side. Thus, an end-to-end connection can be established through the inter-GOIP connection of two wavelength paths in the two different GOIPs. The middle case 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 floors. The last case is that a single end-to-end direct path accommodates user data from multiple users. In this case, user data from multiple users are accommodated in a single Ethernet or OTN by Flexible Bridging Services.

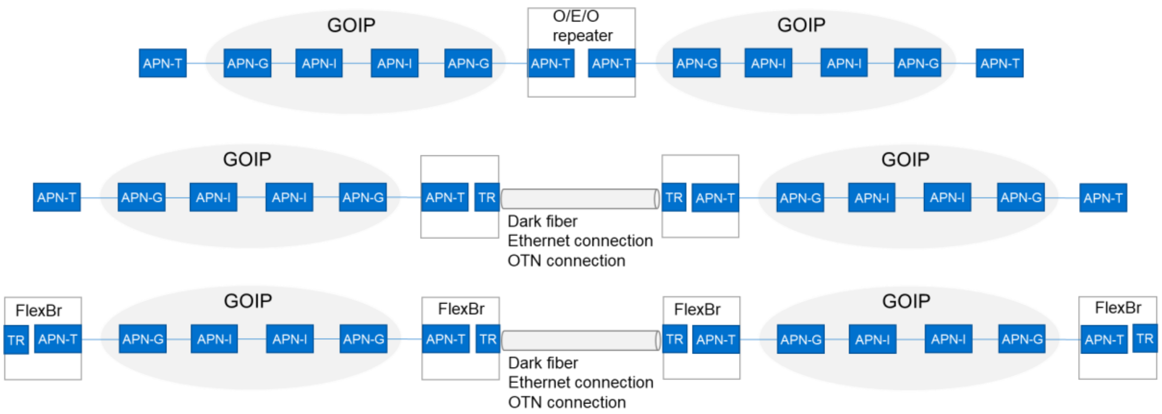


Figure 3.3-4: Direct Accommodation of User Data across Multiple GOIPs

Moreover, another case of inter-GOIP connection realized by APN-I is shown in Figure 3.3-5, where multiple types of fiber lines coexist. In conventional network operation, physical attributes of optical paths are generally optimized for each type of fiber line, e.g., the L-band is used on G.653 fiber while the C-band is used on G.652 fiber. This typically forces GOIPs to be separated into each fiber type or each wavelength band. For realizing inter-GOIP connections in such cases, an adaptation function provided by APN-Is can be essential. Note that wavelength conversion technologies can achieve such a wavelength-band adaptation, potentially eliminating unnecessary path terminations. Also note that, as the GOIP port is defined as the interface between APN-T and the access link (see Section 3.3.1.1), the ports of the APN-I in the middle of the two GOIPs in the figure are not GOIP ports.

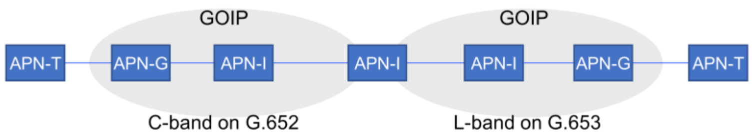


Figure 3.3-5: An Example of Inter-GOIP Connection Realized by Adaptation Function of APN-I

3.3.2. User Plane Reference Architecture within a GOIP

This section describes a single-GOIP network. Figure 3.3-6 shows the architectural diagram of GOIP.

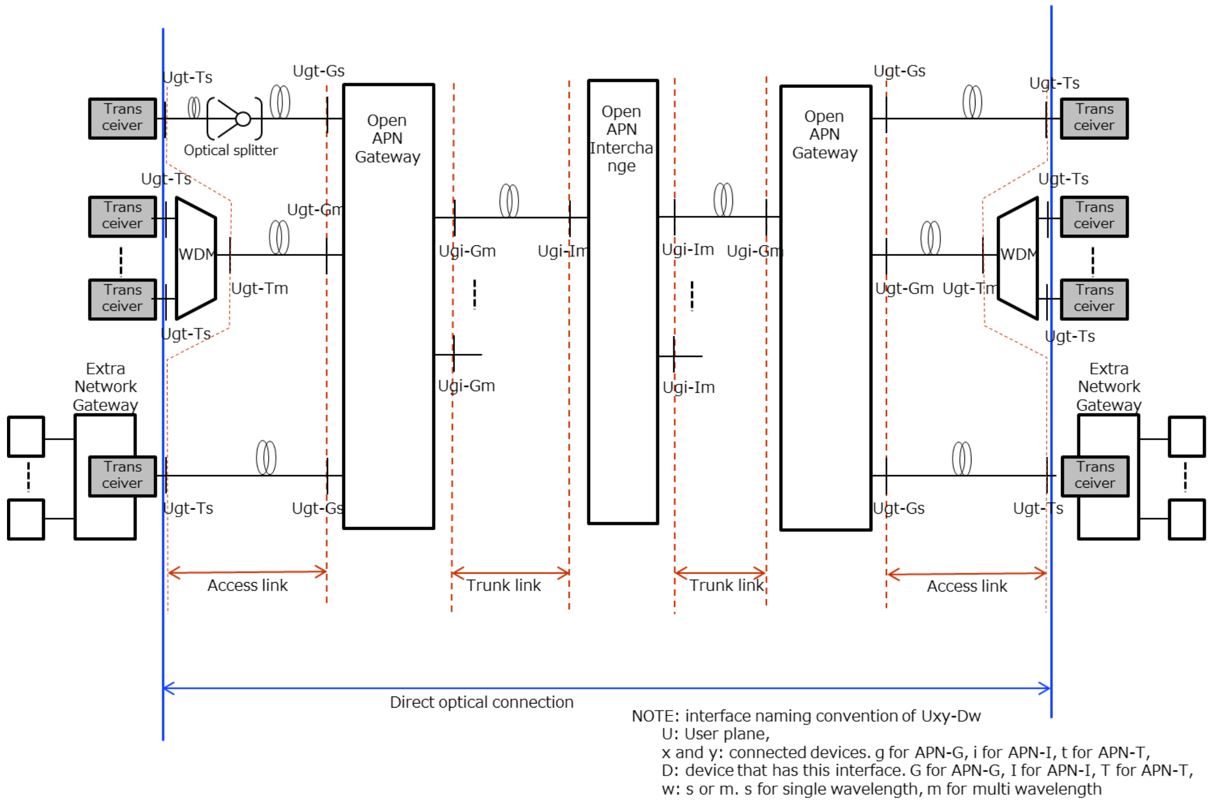


Figure 3.3-6: Architectural Diagram of GOIP

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

Regarding sending and receiving, bi-directional transmission is implemented with a single fiber (through 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 3.3-6 is one or two.

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

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 of 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, 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 topology. In this case, the wavelength paths for the single-fiber bi-directional transmission may be assigned in order 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 uni-directional fiber paths and single-fiber bi-directional 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 of APT-T, APT-G, and APT-I, focusing on the wavelength path services.

Figure 3.3-7 illustrates the relationship between the conventional ROADM, which comprises Wavelength Cross-Connect (WXC), Add/Drop, Transceivers (TRxs), and the Open APN.WX function blocks, while focusing on the wavelength connection services.

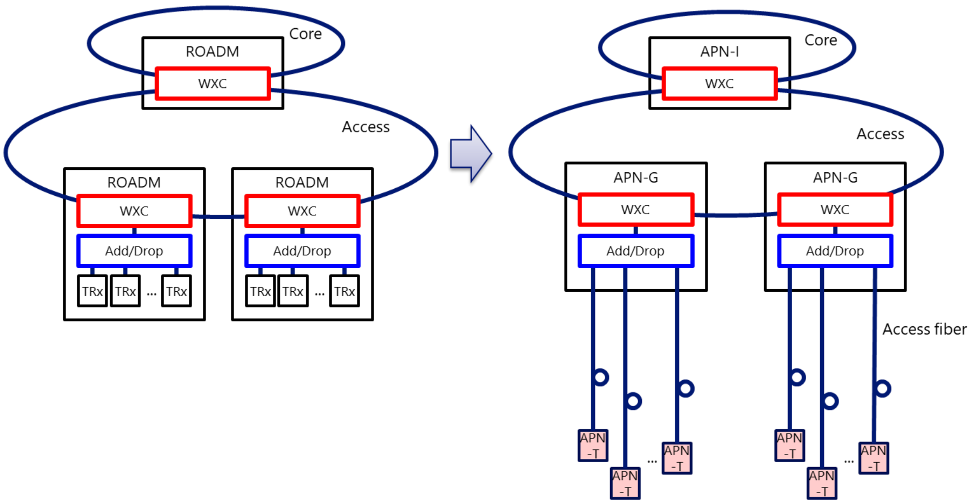


Figure 3.3-7: Relationship between ROADM and Open APN.WX Function Blocks

ROADM nodes in core and access can be considered to evolve to APN-I and APN-G, respectively. Their functions are described in detail in Section 3.1. The following gaps stated in Section 1.5 will be filled with the continued evolution of the Open APN architecture.

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

While the evolution from the conventional ROADM to Open APN.WX to fill such gaps is highly encouraged, the minimum version of Open APN allows the use of conventional ROADM systems compliant with Open ROADM MSA YANG model version 7.1 and optical specification version 5.1. In that case, APN-G consists of WXC and Add/Drop, and APN-I consists of WXC. Transponders are located at remote sites (i.e., user sites) as APN-Ts. Other functions for APN-I and APN-G defined in this document can be considered optional. For more clarification, Gaps 1 and 2 in the above will be filled by implementing APN-I and APN-G functions described in Section 3.1. Gap 3 will be filled by reviewing the optical interfaces for the transceivers, i.e., Ugt-Ts, in the future.

3.3.3. Optical Interfaces

Ugt-Ts in Figure 3.3-6 correspond to the optical transmission/reception interfaces listed in Section 2.2 (User plane services). Specifications of other optical interfaces in Figure 3.3-6 are for further study.

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

3.3.4.1. Wavelength Paths Connecting Optical Interfaces

This section describes the required information on wavelength paths connecting optical interfaces, the physical information required 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 3.3.1, the ability to interconnect optical ports shall be managed according to the network management system, based on physical layer information and network requirement. 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 paths
  - 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 requirement in bandwidth. The optical path between the APN-T should be selected so that the characteristics of the factors limiting the reachability are within the specification of the connected APN-T for error-free operation for the setting of the APN-T. The information on such characteristics may be obtained through telemetry as described in Section 3.2.5.

3.3.4.2. 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 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 3.3.4.1, the specificities of ultra-wideband technologies apply as below:

- The physical reference of the wavelength paths using ultra-wideband technologies
  - Physical information of the wavelength path using dimensions offered by 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 specificities of ultra-wideband technologies
  - Noise may depend on transmission characteristics on 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 3.3.1.1. However, different GOIPs may have different implementations and therefore different characteristics on the above dimensions. As a result, regeneration or conversion is possible between different GOIPs. This difference in possible implementations is illustrated in Table 3.3-2 for several use cases. The characteristics given in Table 3.3-2 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 3.3.4.1.

Table 3.3-2: Examples of Architectures of Ultra-wide Bandwidth for Open APN

PATH ALLOCATION POSSIBILITIES (PHYSICAL DIMENSION)	MINIMAL VIABLE VERSION	EXAMPLE A DESIRABLE VERSION BASED ON STATE OF THE ART DEPLOYED TECHNOLOGY	EXAMPLE A DESIRABLE VERSION BASED ON TECHNOLOGY TESTED BY SEVERAL VENDORS
Optical band	**Single-band (C)**	Dual-band (C+L)	more than three bands (C, L, and more)
Carrier wavelength and bandwidth	**16 wavelengths on C band**	~100 wavelengths on C and L bands	More than 100 wavelengths on C, L, and extended bands

Number of spatial channels (numbers of fibers in a cable, fiber type, and number of cores)	**Single**	100 to 300 channels (100 to 300 standard single mode fibers[1] in a cable)	More than 300 channels (more than 300 standard single mode fibers[1] in a cable) More than 400 channels (more than 100 4-core multicore fibers in a cable) Up to 7,000 channels (up to 7,000 standard single mode fibers[1] in a cable[2])
Number of wavelength paths	**16**	~10,000 to ~30,000	More than 30,000

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

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

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

Concerning the implementation of APN-T, APN-G, and APN-I in an ultra-wideband context, two options exist to match the characteristics of the wavelength 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 as described in Section 3.1.1 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, it may appear advantageous to assign APN-T with analog signals or based on direct detection technology, i.e., without electrical compensation of chromatic dispersion, to such wavelength 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, inter-band WXC can be helpful when multiple bands are activated, and inter-core WXC can be useful when multi-core fibers are used.

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

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.

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

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

Annexes

A. IOWN 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.

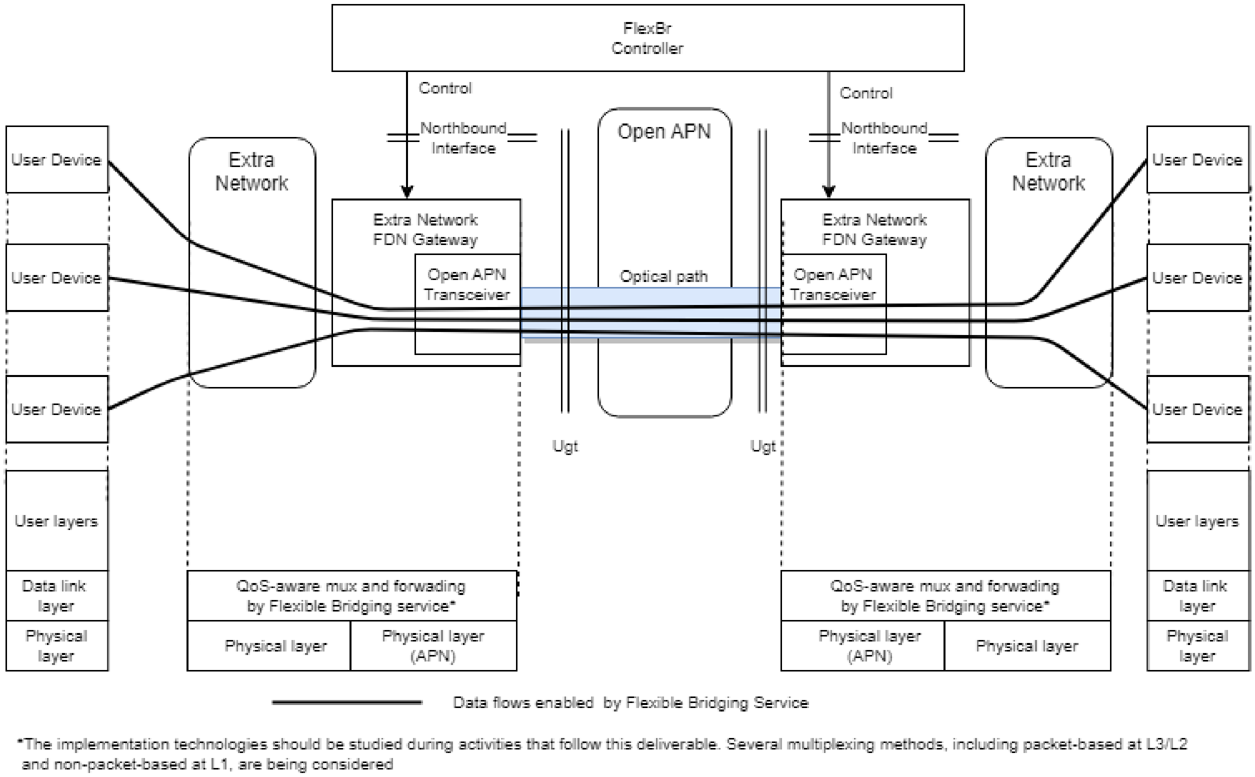


Figure A.2-1: Data Flows Enabled by Flexible Bridging Services

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)				

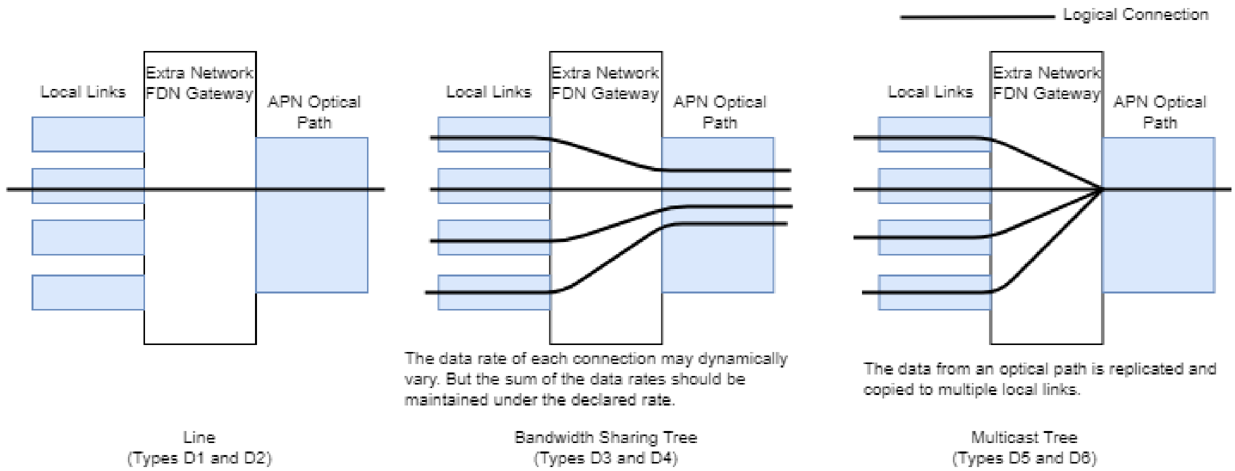


Figure A.2-2: Line, Bandwidth Sharing Tree, and Multicast Tree

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).

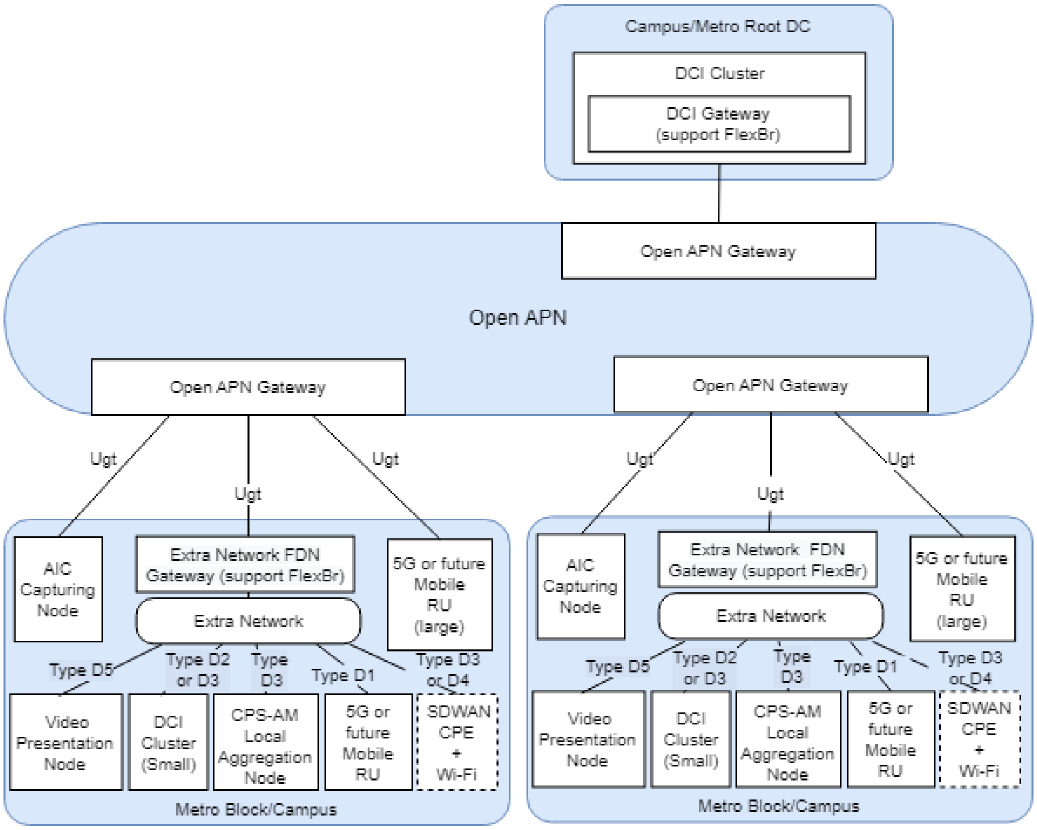


Figure A.3-1: Converged Network Service for Campus/Town/Metro

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).

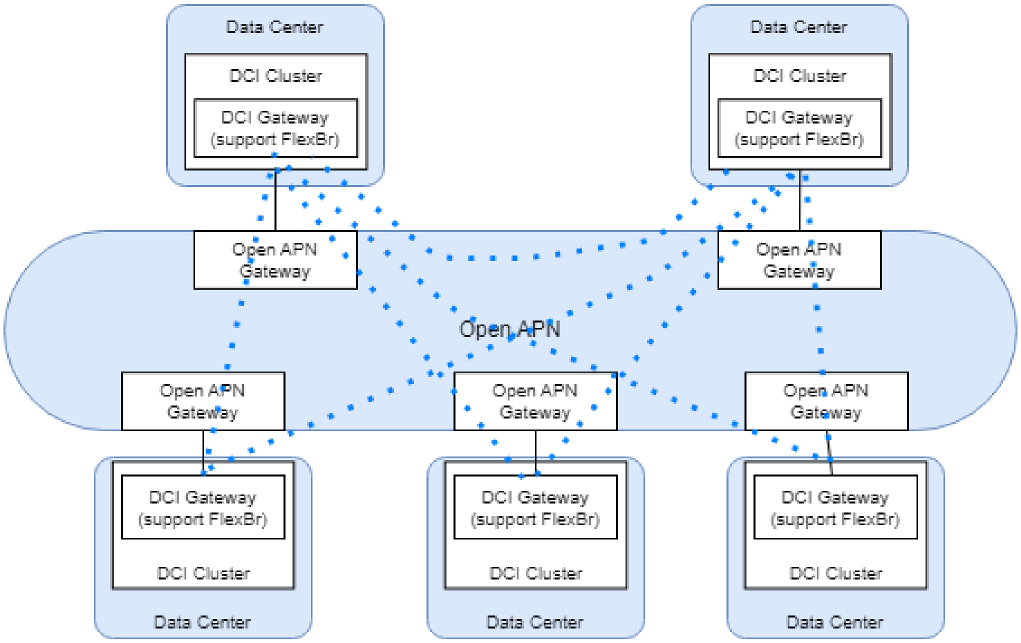


Figure A.3-2: Data Center Interconnect Service

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.

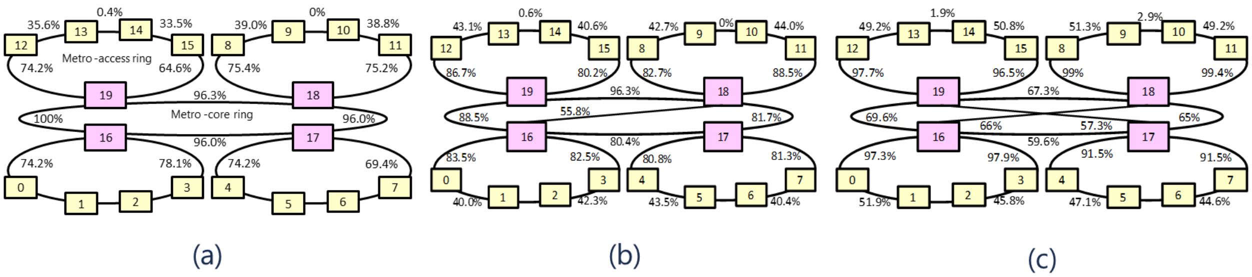


Figure B.2-1: Simulation Results of Wavelength Utilization in Two-tiered Ring Model; The Number of Wavelengths: 480, Routing and Wavelength Assignment (RWA): Shortest Path First (SPF) / FirstFit, No Wavelength Conversion

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.

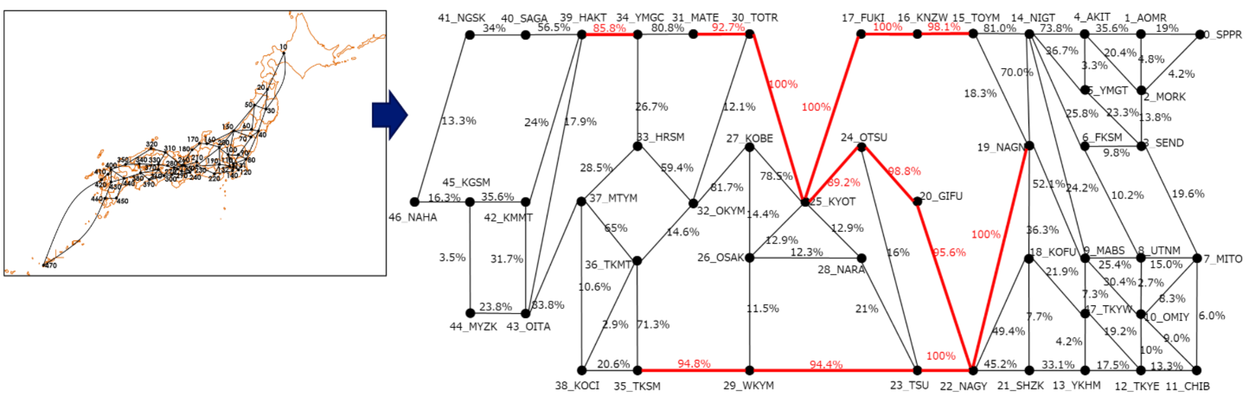


Figure B.2-2: Simulation Results of Wavelength Utilization in Japanese Network Model; The Number of Wavelengths: 480, RWA : SPF / FirstFit, No Wavelength Conversions, 3,000 Path Request

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 for various reasons,

Ultra-wideband optical transmission technologies offer the possibility to expand the wavelength resources of the Open APN and cope with the fiber capacity limit stated in the gap analysis described in 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 ultra-wideband optical transmission will be classified among Wavelength-Division Multiplexing (WDM) technologies and Space-Division Multiplexing (SDM) technologies. Bidirectional transmission technology can be used with WDM and SDM technologies to offer additional, 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.

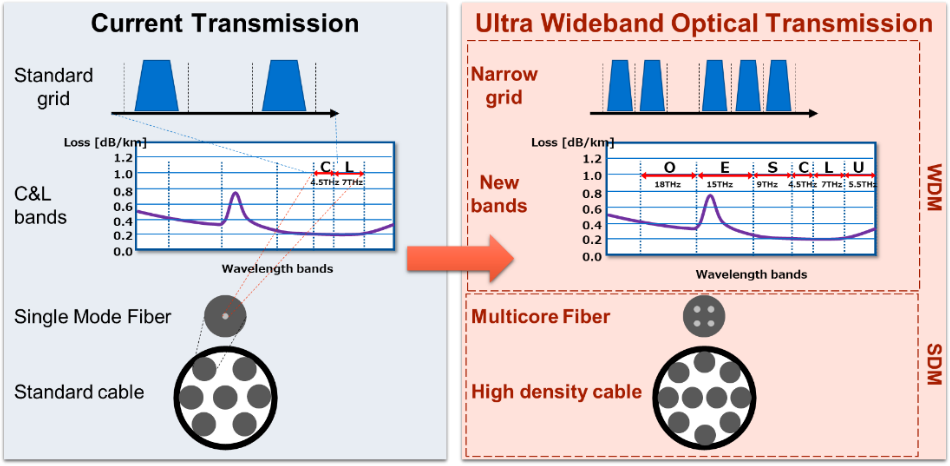


Figure B.3-1: Illustration of the Technological Options for Ultra-Wideband Optical Transmission

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 in a high number of wavelength paths will be a motivation for their adoption. These four technologies, i.e., narrow grid, new bands, multicore fiber, and high-density cable, can be used independently in any combination, including current transmission technologies. Especially, in a scenario to increase wavelength resources, one or several technologies may be introduced first and progressively inside the network, depending on potential and challenges.

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

To expand wavelength resources by creating newly available wavelengths using ultra-wideband optical transmission, it is required 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 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 (S_s) and Rx (R_s) are to be set at the interface of APN-T.
2. The number of available wavelengths between the reference points Tx and Rx can be estimated according to any of the following options:

A) Counting the number of wavelengths, for which 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 (GSNR) 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 End to End path.

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

While ultra-wideband optical transmission technologies enable to expand network capacity and wavelength resources, they present challenges, especially for APN-I. In particular, ultra-wideband technologies will make the optical layer more heterogeneous in terms of fiber type and transmission band. APN-I should handle optical signals efficiently for providing 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

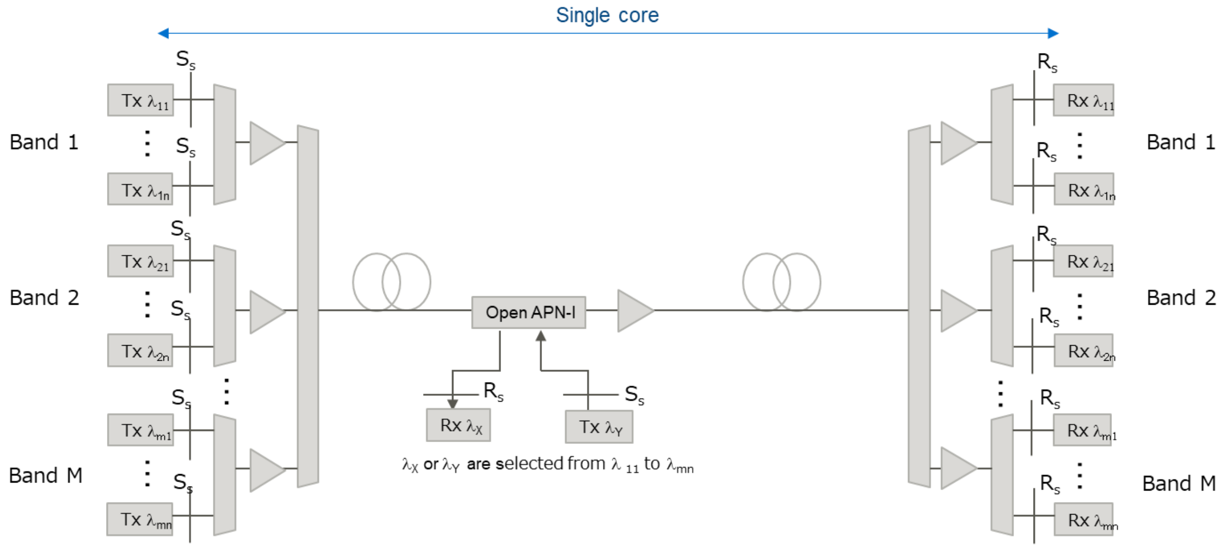


Figure B.3-2: The Additional Bands' Reference Mode

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 the band, such as L-, S-, U-, E-, and O-bands. On the other hand, there are issues to overcome in utilizing the additional bands. The influence of the wavelength-dependent characteristics of deployed fibers on QoT should be considered which involves transmission loss, dispersion, nonlinearity, etc. In each band, QoT via GSNR should be examined where the interband effect of the stimulated Raman scattering should be treated appropriately. In addition, when the above reference model is considered, the following is a list of technical gaps that need to be filled.

- TRx used in the ultra-wideband range including tunable lasers and 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 interfaces of Uii and Ugi. Specifically, the difference in band operation will limit the interconnection pattern. For providing end-to-end optical connectivity efficiently, intra-connection (in APN-I) should be supported with no limitation. To address this issue, wavelength conversion technologies may be useful, and they may include all-optical conversion and O/E/O-type conversion.

b) Narrow grid

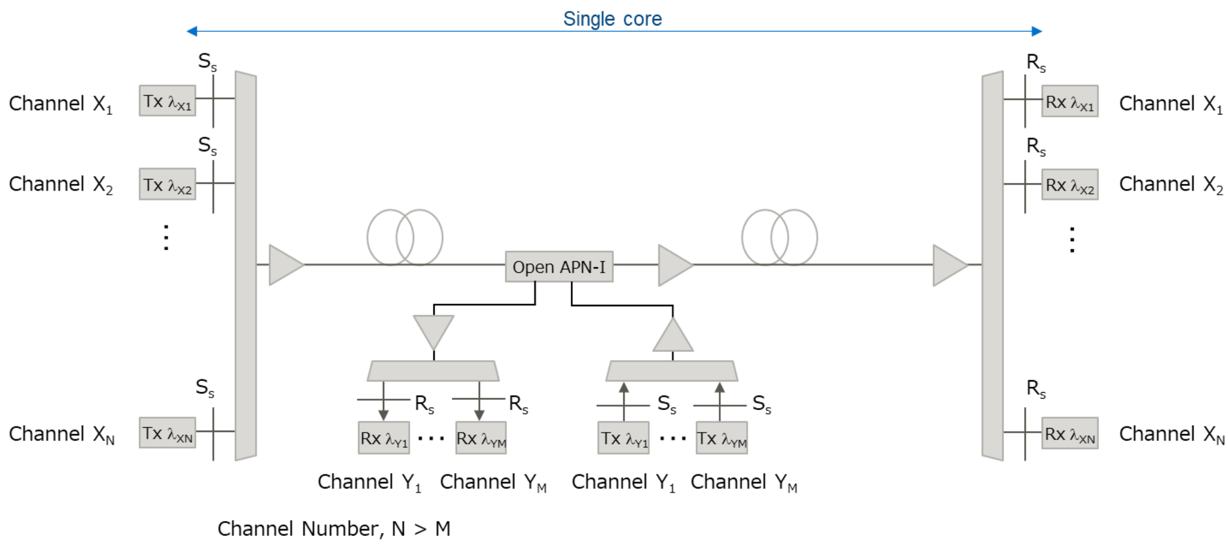


Figure B.3-3: The Narrow Grid Reference Model

The second method to expand wavelength resources is to narrow down the wavelength grid. Hereafter, 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 the moderate interface with the current network system

c) Multicore fiber transmission

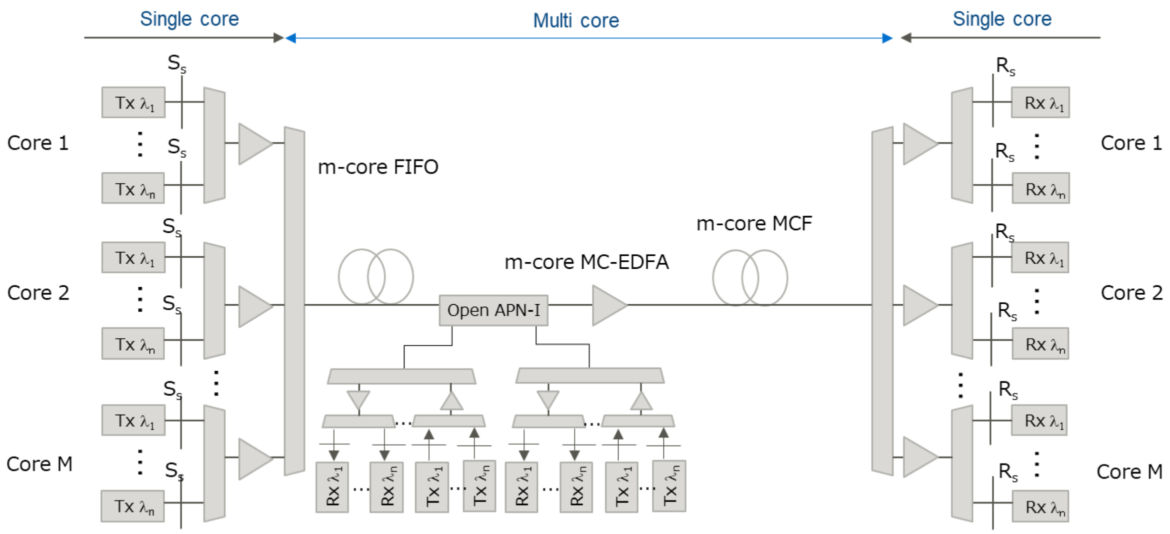


Figure B.3-4: The Multicore Fiber Transmission Reference Model

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

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

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

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

d) High-density cable

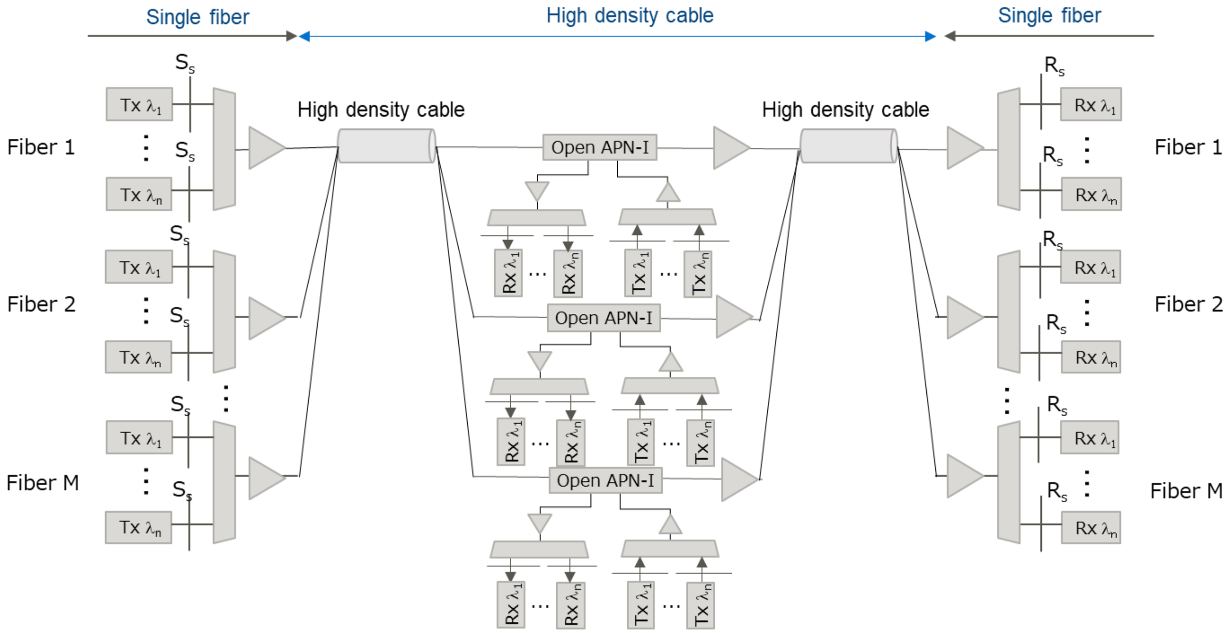


Figure B.3-5: The High-density Cable Reference Model

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

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

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

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

e) Bidirectional transmission

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

B.3.3. QoT for Ultra-Wideband Optical Transmission

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

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

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

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

The approximated closed form in the expression reduces computation resources and time dramatically 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

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

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

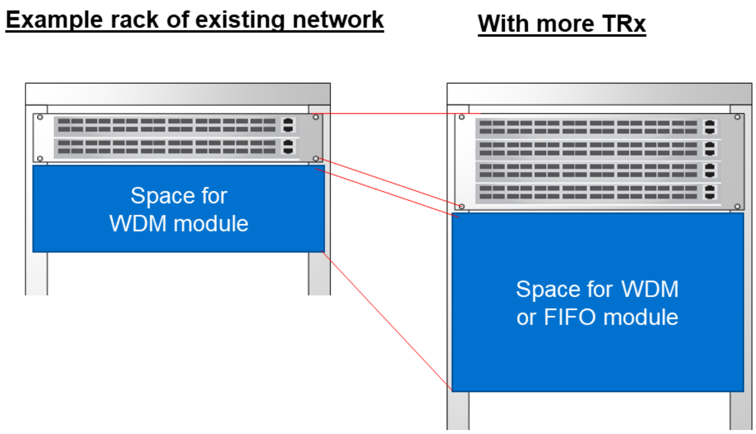
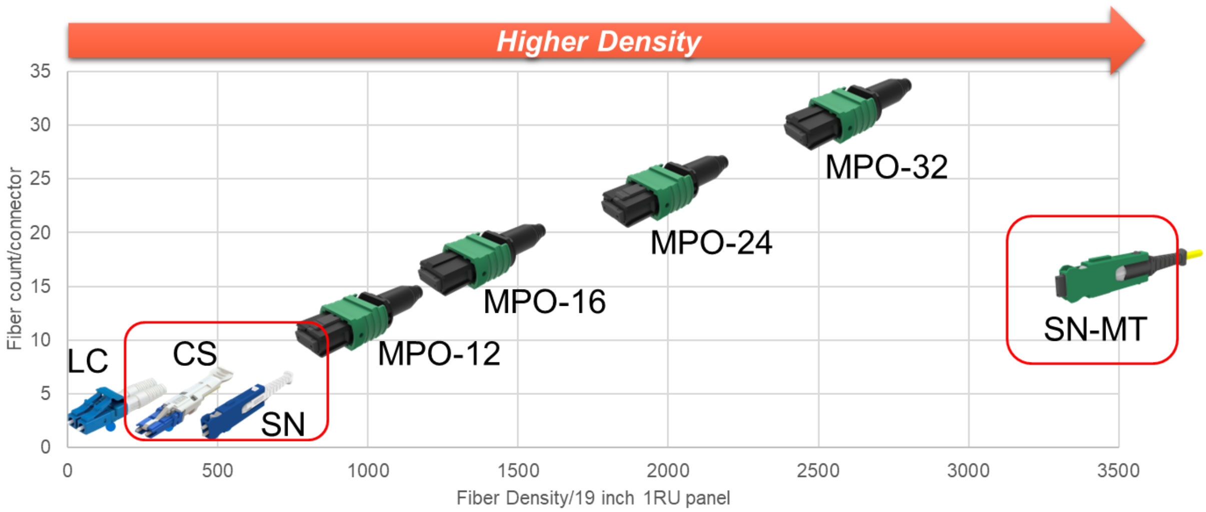


Figure B.3-6: Illustration of Rack Space Required for TRx Ports and WDM/FIFO Module Using Existing Components

Using 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.



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

LC ferrule base (LC, CS, SN) — Multi-fiber ferrule base (MPO-12, MPO-16, MPO-24, MPO-32, SN-MT)

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 the 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).

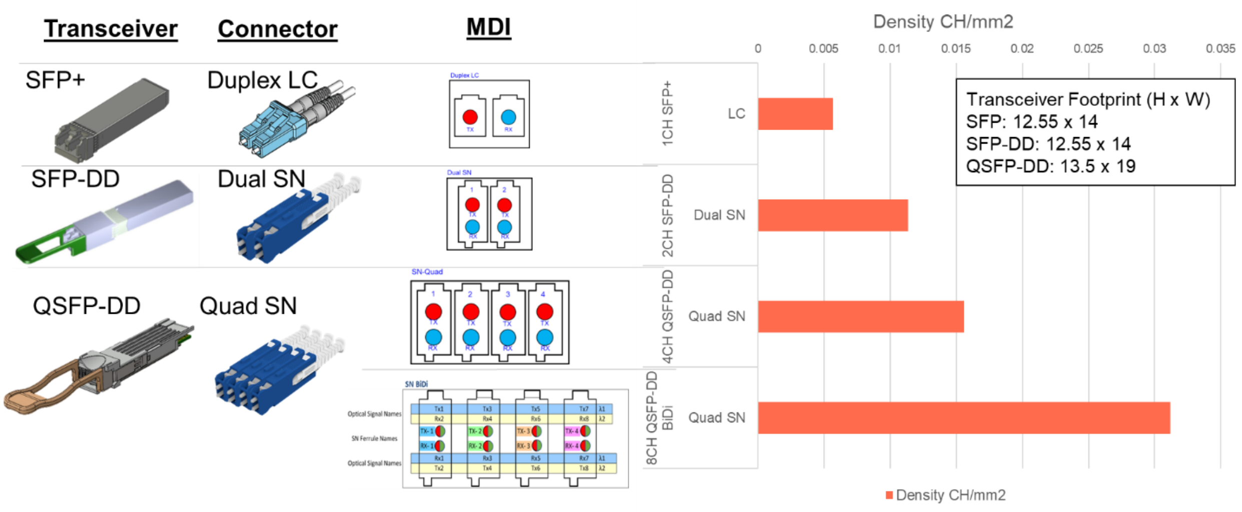


Figure B.3-8: Comparison Chart of Transceiver Density among Different Transceiver and Connector Types

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

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 has been some report of a few hundreds of kilometer-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 part 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.

E.g., 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	•Lens-system supports arbitrary core arrangement with low loss and low crosstalk •Device size tends to be large (*5)	•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)	•Thin cladding SMFs are buddled 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)	•Laser inscription realizes arbitrary core arrangement and small device •Relatively large insertion loss (*9) •Polymer waveguides using the Mosquito Method (*17)	•Enables mass-production with low loss •Laminated structure requires precise positioning, and hard to realize three layers or more (*10)
	Compatibility with bidirectional technology	Shown on some paper *14, 15, 16. 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

*1 O. Shimakawa, et. Al.,"Pluggable Fan-out realizing Physical-contact and low coupling loss for Multi-core fiber", in Proc. OFC/NFOEC Technical digest, OM3I.2 (2013)

*2 O. Shimakawa, et. Al., "Compact Multi-core Fiber Fan-out with GRIN-Lens and Micro-lens Array", in Proc. OFC, M3K.1 (2014)

*3 H. Uemura, et Al., “Fused taper type fan-in/fan-out device for multicore EDF,” in Proc. OECC/PS, 2013, pp. 1-2.

*4 V. I. Kopp, et Al., “Ultra-low-loss MCF fanouts for submarine SDM applications,” in Proc. OFC 2022, Th1E.2

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*11 K. Kawasaki, T. Sugimori, K. Watanabe, T. Saito, and R. Sugizaki, "Four-fiber Fan-out for MCF with square lattice structure," 2017 Optical Fiber Communications Conference and Exhibition (OFC), 2017, pp. 1-3.

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*13 K. Watanabe, T. Saito, and M. Shiino, "Development of fiber bundle type fan-out for 19-core multicore fiber," 2014 OptoElectronics and Communication Conference and Australian Conference on Optical Fibre Technology, 2014, pp. 44-46.

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*15 A. Sano, H. Takara, T. Kobayashi, and Y. Miyamoto, "Crosstalk-Managed High Capacity Long Haul Multicore Fiber Transmission With Propagation-Direction Interleaving," in Journal of Lightwave Technology, vol. 32, no. 16, pp. 2771-2779, 15 Aug.15, 2014, doi: 10.1109/JLT.2014.2320826.

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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, ROADM, 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)	~ 3.8×10^{-10} (1550 nm) (*3)	~ 2.3×10^{-10} (1550 nm) (*3)	~ 3.8×10^{-10} (1550 nm) (*3)	~ 3.8×10^{-10} (1550 nm) (*3)	~ 3.8×10^{-10} (1550 nm) (*3)	~ 3.8×10^{-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 $n_2 = 3.0\times10^{-20}$ (m^2/W) and $A_{eff} = 80\times10^{-12}$ (m^2) for G.652 and $n_2 = 2.3\times10^{-20}$ (m^2/W) and $A_{eff} = 113\times10^{-12}$ (m^2) for G.654.					

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

This Annex describes implementation examples of APN-I, APN-G, and APN-T for the purpose of ensuring that Open APN hardware is implementable based on current technologies. Note that it is not the intention 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 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 Open ROADM MSA [Open ROADM 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 Ugi) in the figure) corresponds to (i.e., shall comply to) Multi-wave interface (MW interface) defined in the Open ROADM MSA [Open ROADM 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.

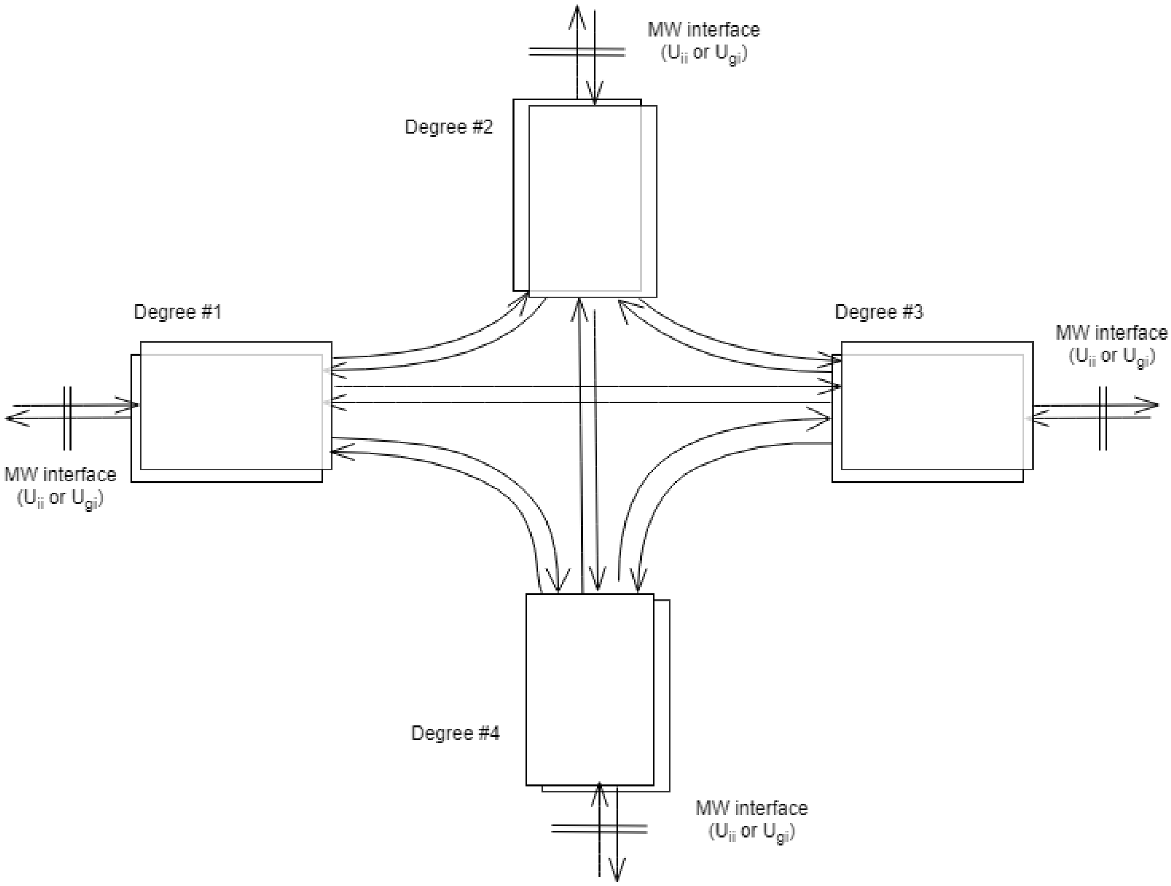


Figure C.1-1: Implementation Example of APN-I

C.2. APN-G

Figure C.1-2 shows an implementation example of APN-G that has two Shared Risk Groups (SRGs) and two Degrees [Open ROADM Network White Paper][Open ROADM 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 MxN WSSs [G.672][WSS], a pair of Multi-Cast Switches (MCSs) [G.672][MCS ROADM], or a pair of Optical Cross Connects (OXCs) with wavelength multi/demultiplexers [G.672][OXC ROADM], typically. The SRG is identical to the one defined in the Open ROADM MSA [Open ROADM Device White Paper]. The components of the Degree can be the same as that of APN-I. The SRG in Figure C.1-2 corresponds to a 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.

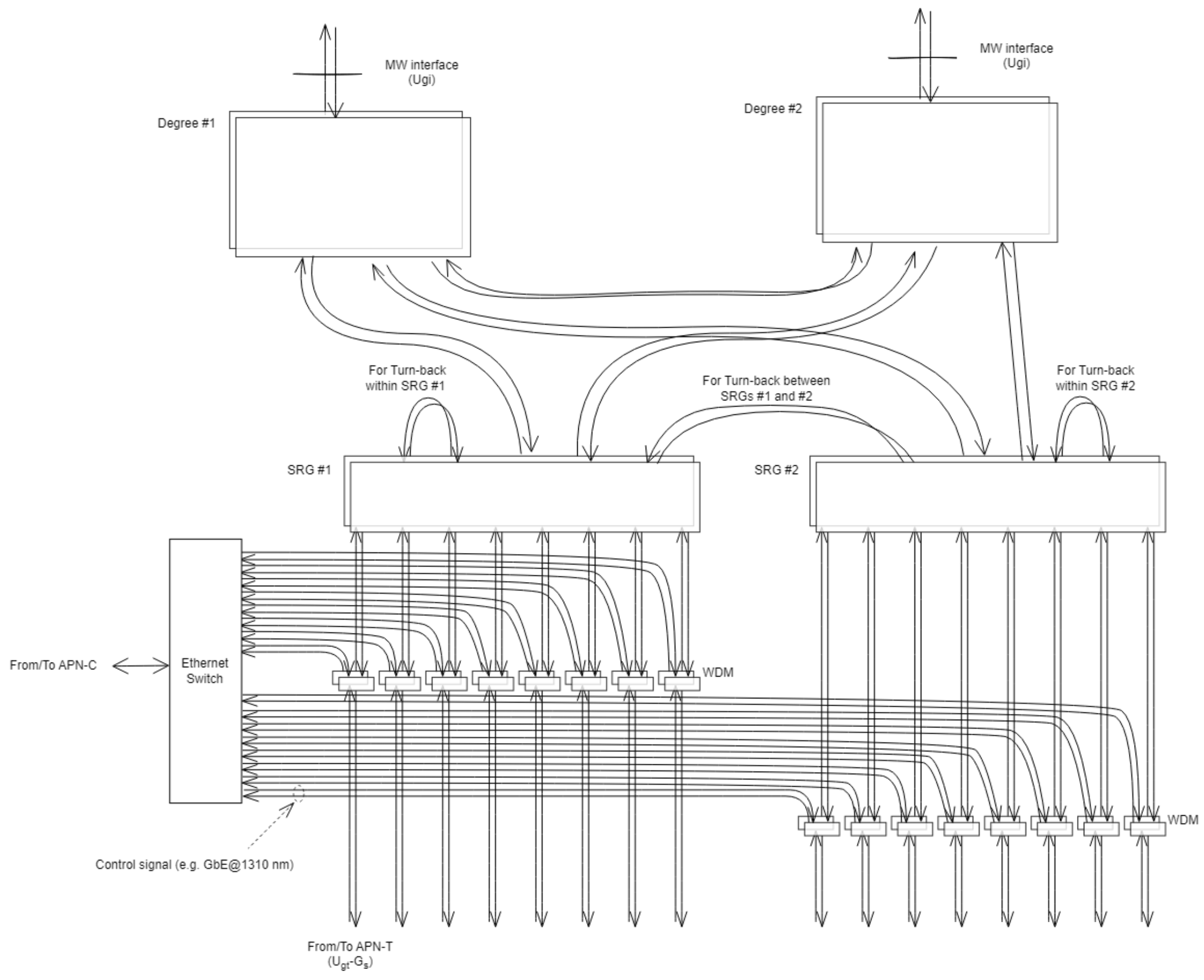


Figure C.1-2: Implementation Example of APN-G (1)

Figure C.1-3 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.)

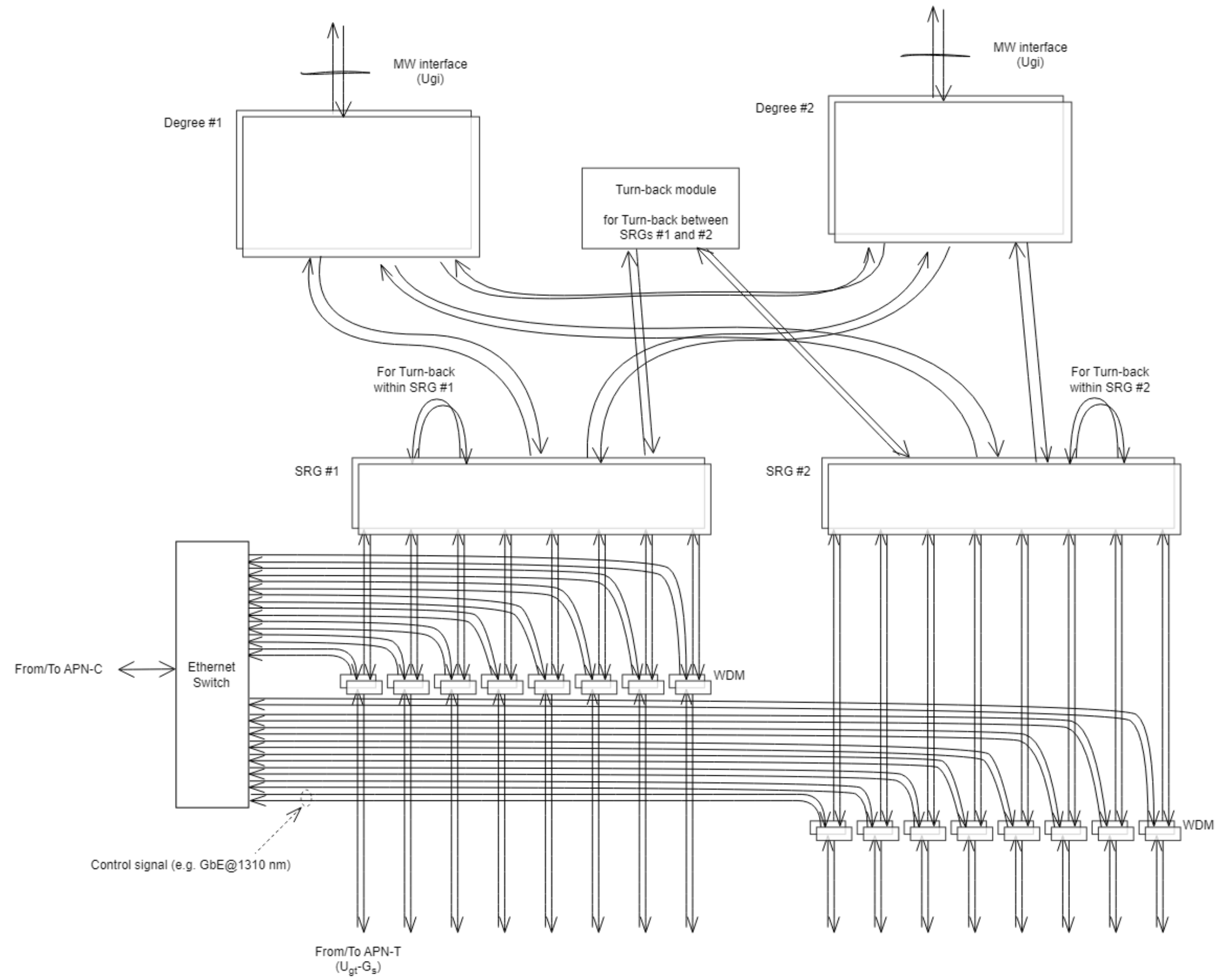


Figure C.1-3: Implementation Example of APN-G (2)

C.3. APN-T

Figure C.1-4 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 Open ROADM MSA [G.972]; “W interface” in the figure corresponds to (i.e. shall comply to) the Single-wave (W) interface defined in the Open ROADM MSA [Open ROADM Device White Paper][Open ROADM 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 signals and the control signals 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 needed 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 boarder in Figure C.1-4. In this example, it is expected that the APN-T function will be integrated into a single module in the future.

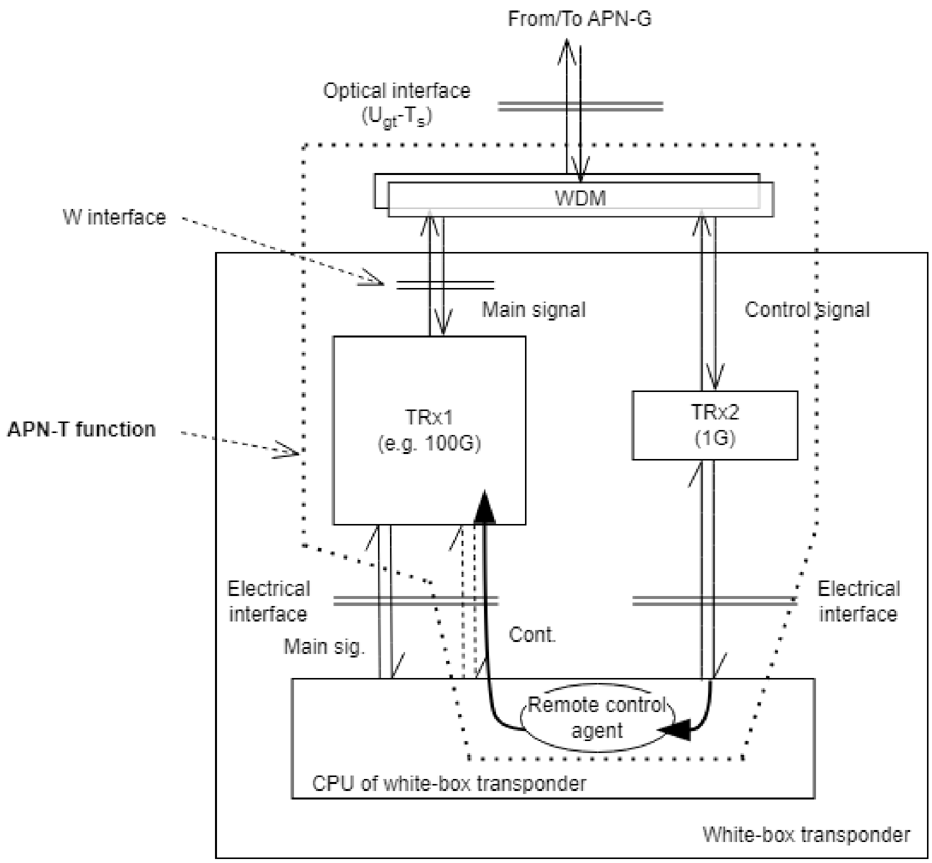


Figure C.1-4: Implementation Example of APN-T for the Digital-coherent Optical Interfaces

While this example shows the configuration that the main and the control signals are on the same access fiber, it is possible another configuration with the control-signal channel on another physical route. For example, if there is an IP network for control and management of the white-box transponder, APN-T also can 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 to ITU-T G.698.2 for the 10G optical interface.

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.

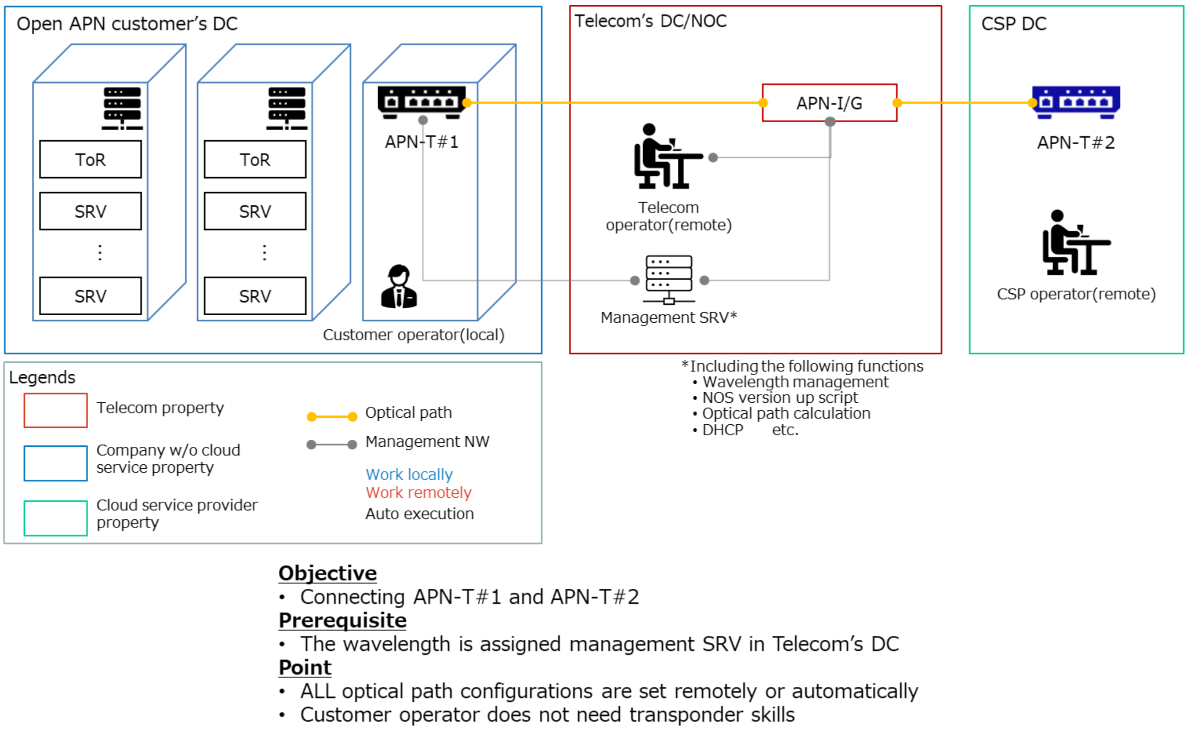


Figure D.1-1: Plug and Play Data Center Use Case

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.

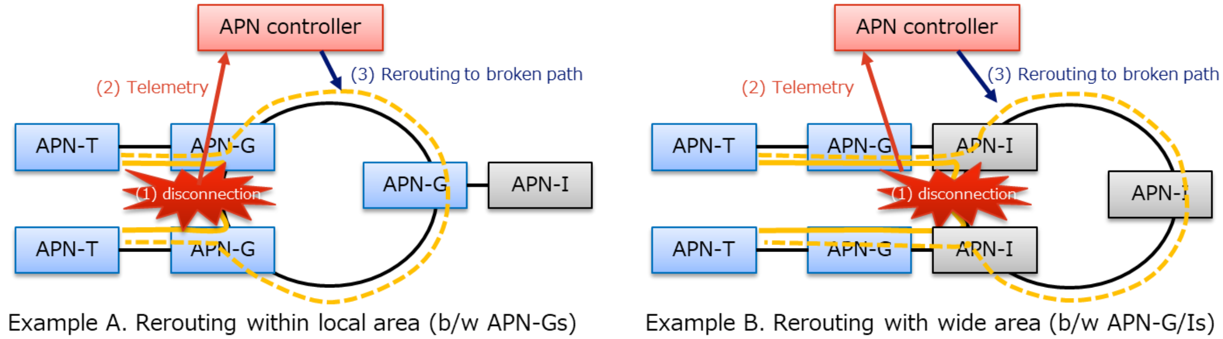


Figure D.2-1: Real-time Control for Resilient Network

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). 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):

- real-time 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 location,
- 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].

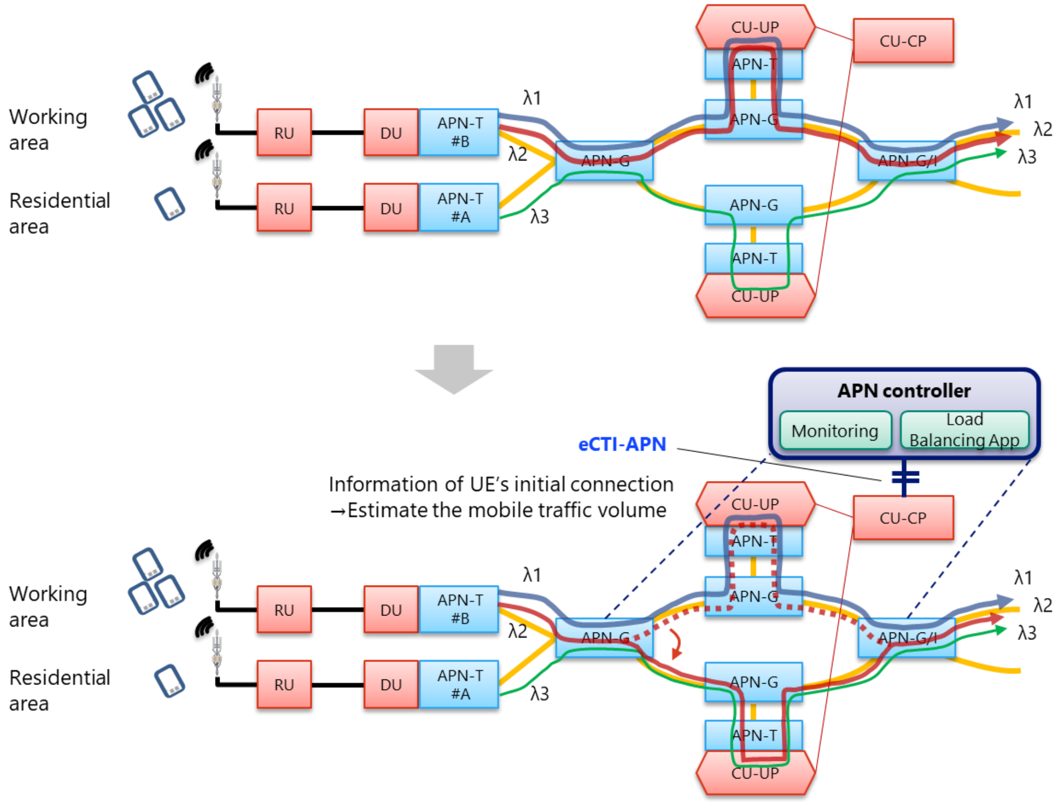


Figure D.3-1: Dynamic Optical Path Switch according to User Mobility

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 real-time 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.

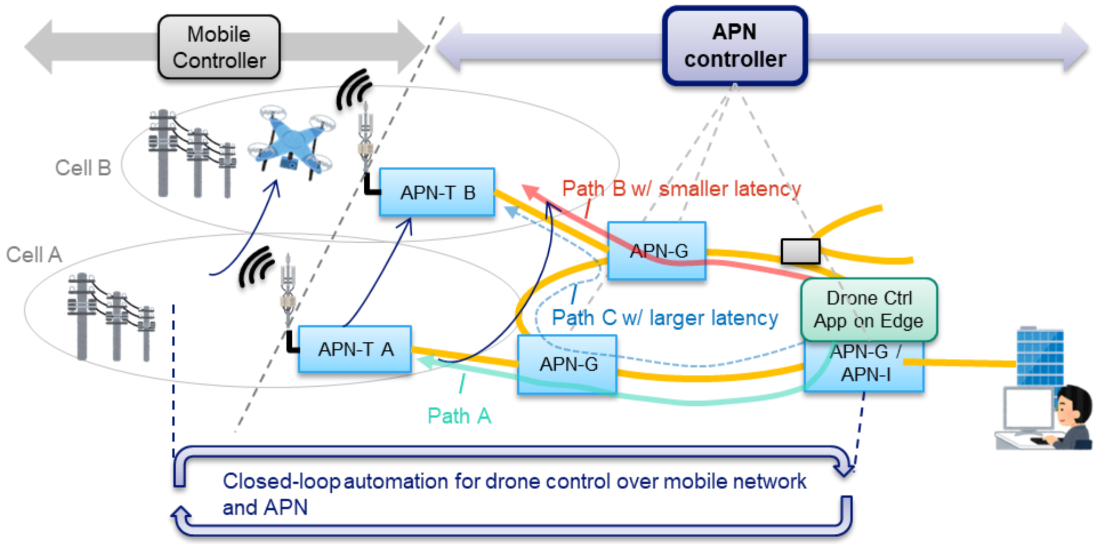


Figure D.4-1: Real-time Optical Path Control for Stringent SLA

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).

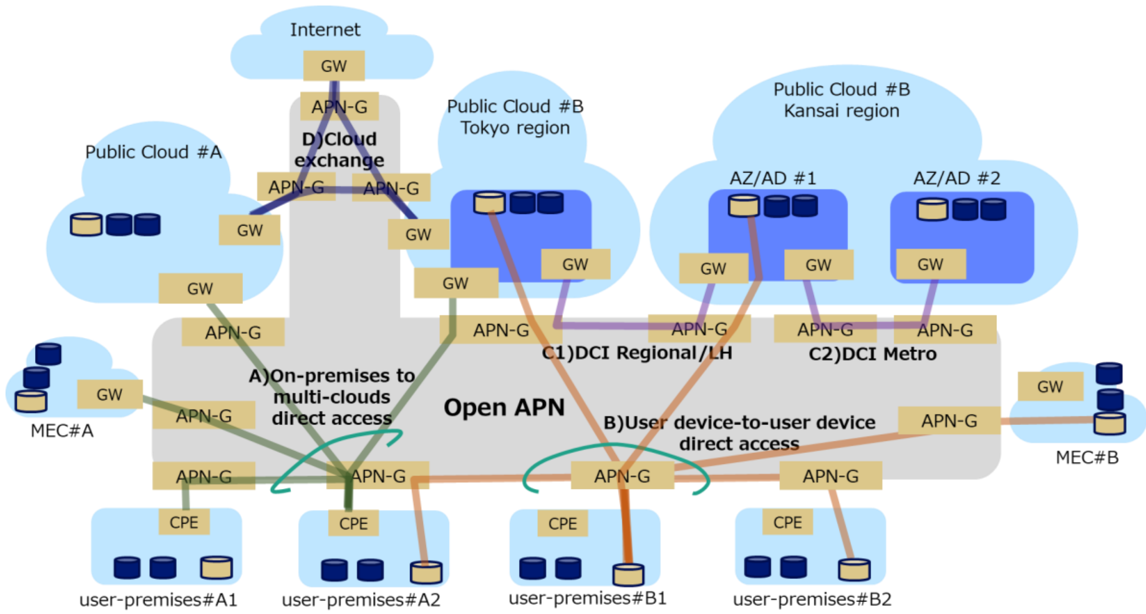


Figure D.5-1: Data Center Interconnect and Cloud Access Services

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.

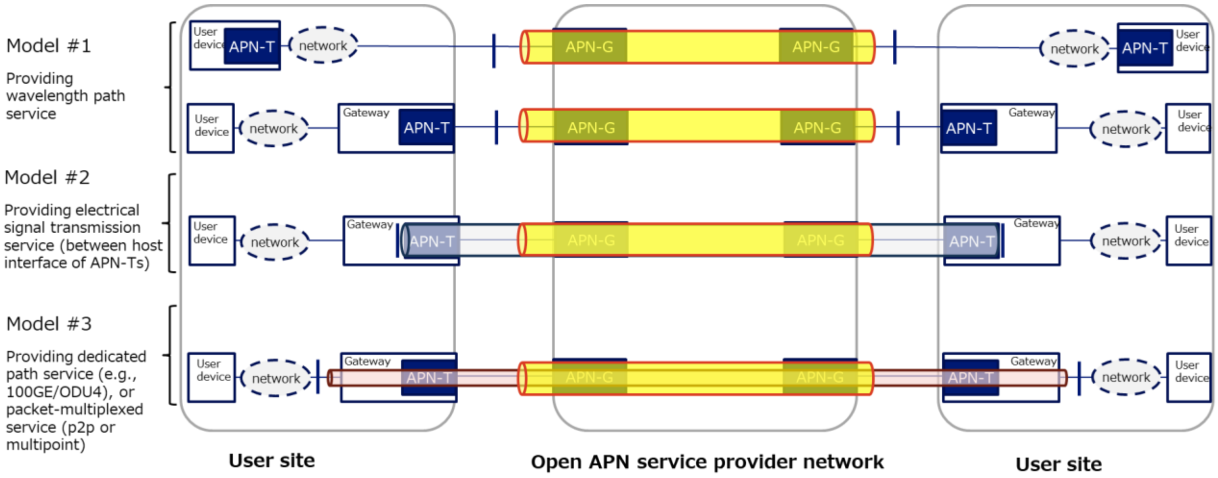


Figure E.1-1: Summary of Service Model Details Utilizing Open APN

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, while Model#3 typically provides mux/demux of 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 Network Media Channel (NMC) or Media Channel (MC) connectivity service (NOTE) to a user. APN-Ts should follow the optical signals being specified.

NOTE: NMC/MC are TAPI terminologies, continuous spectrum bandwidth to carry optical signals generated by an APN-T. 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 transponder, muxponder, and switchponder with pluggable transceivers (APN-T).

NOTE: The service interface specification depends on the type of APN-T. As an example, in the case of CFP2-DCO, the service interface could be specified by OIF IA [OIF-CFP2-DCO].

- 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) to a user, supported over wavelength path(s). An example of a gateway is a muxponder.

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

The other is where an Open APN service provider offers a user packet-multiplexed service. Packet-multiplexed service is supported over optical wavelength path(s), with packet optical integration/cooperation. An example of gateway is switchponder [Open ROADM Device White Paper].

NOTE: 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 control and management scope of the APN-C.

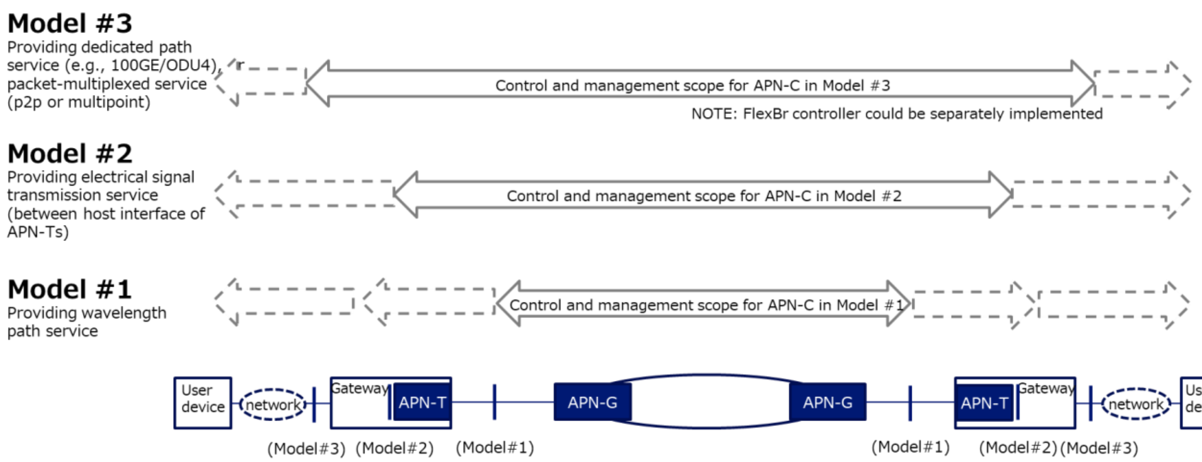


Figure E.2-1: Summary of Control and Management Scope of APN-C

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 3.2.1. 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 address 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 gateway client interfaces.

Furthermore, the APN-C may maintain or may be privileged to control and manage the user network at a granular level, down to user devices for assuring 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, as well as 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, for assuring QoT of end-to-end communications. FlexBr controller is a logical entity controlling such gateways. In this implementation, multiple controllers or a single controller may be used to control the gateway and APN-G/I.

E.3. Detailed Sequences

Figure E.3-1 shows detailed sequences of (1) the registration of a user network device, described in Section 3.2.4. 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.

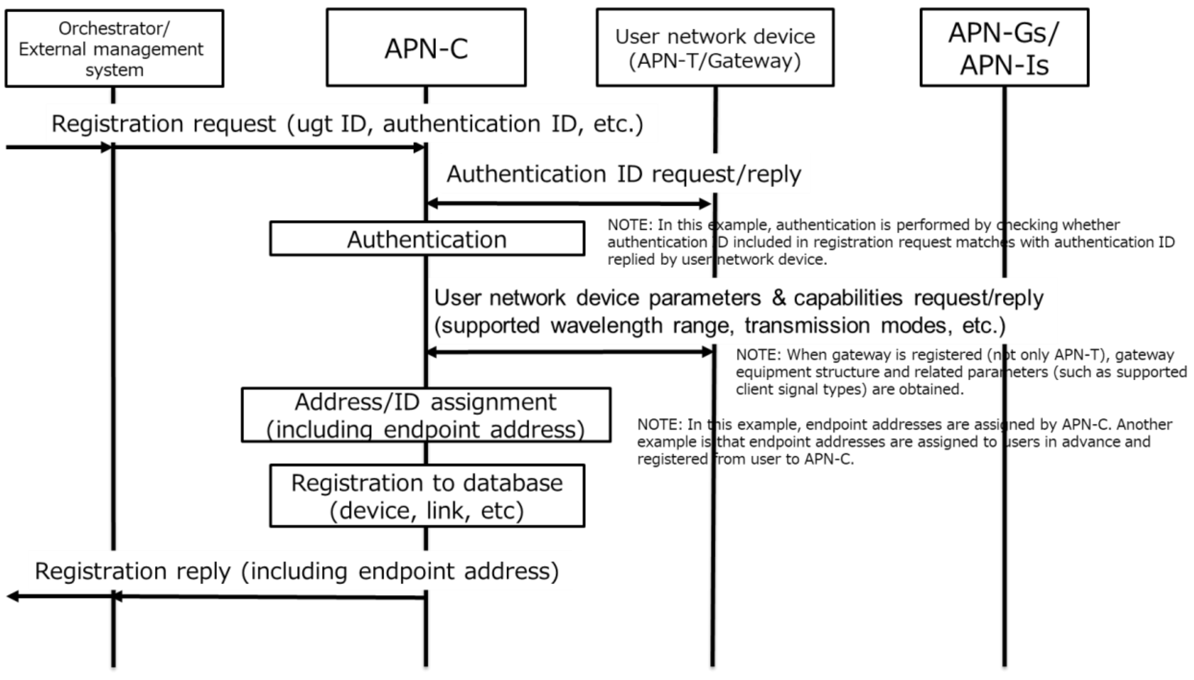


Figure E.3-1: Detailed Sequences for Registration of User Network Device

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 3.2.4.

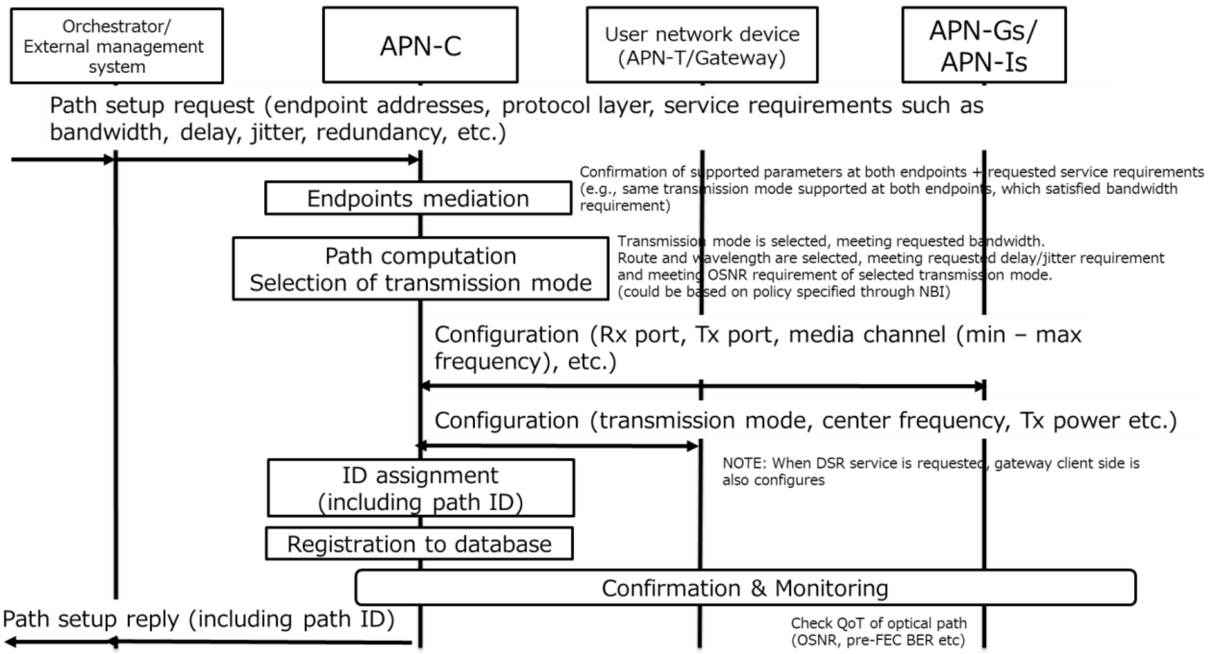


Figure E.3-2: Detailed Sequences for Optical Wavelength Path Setup

TAPI [TAPI] is a good candidate for APN-C NBI. Open ROADM [Open ROADM] and OpenConfig [OpenConfig] are good candidates for APN-C SBI (Open ROADM 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.

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 manage 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.

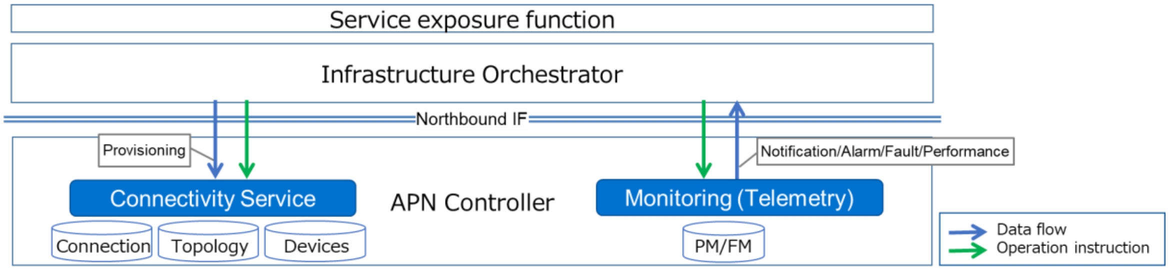


Figure E.4-1: Infrastructure Orchestrator Functional Diagram

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.

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.

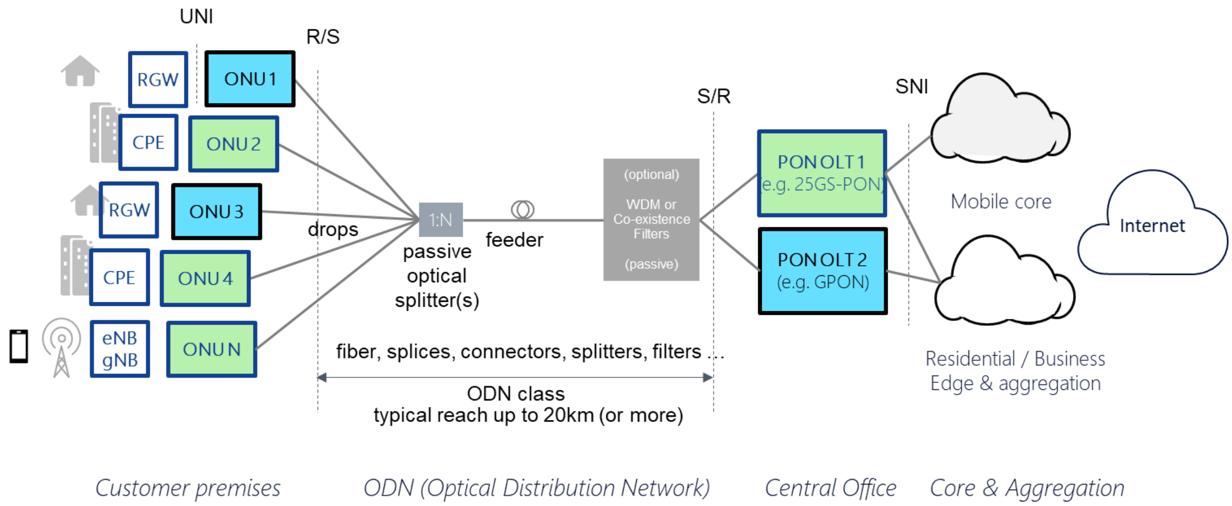


Figure F.1-1: A Passive Optical Network System Composed of OLT, ONUs, and Point-multipoint Fiber Infrastructure

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).

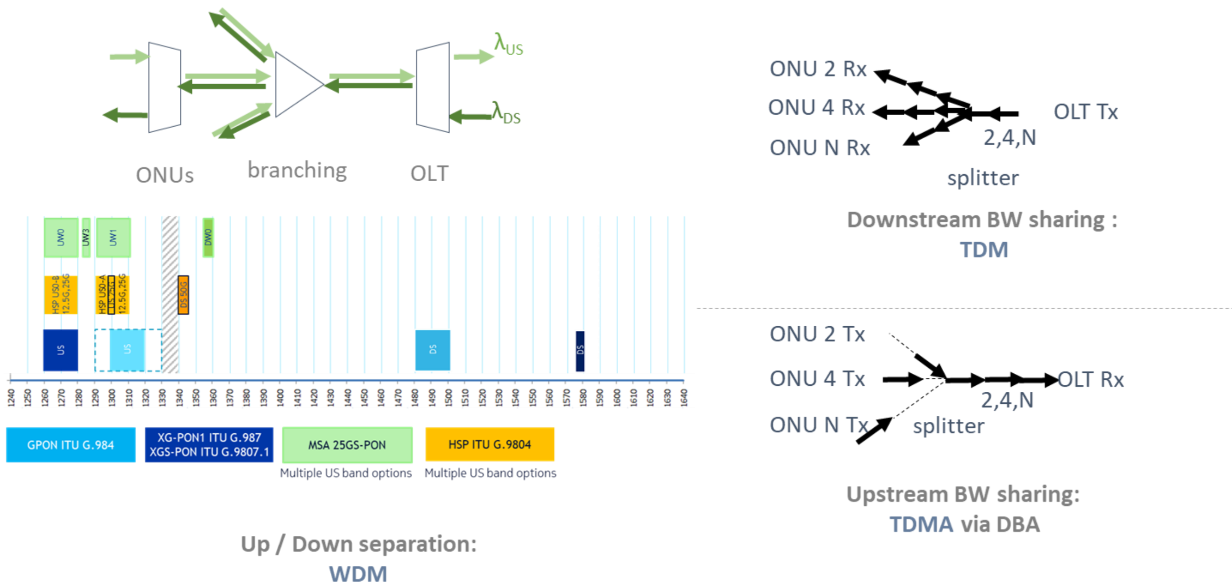


Figure F.1-2: TDM PON: Up- and Downstream Separation by WDM, Up- and Downstream Bandwidth Sharing by TDM(A)

The second is WDM PON, using a dedicated wavelength pair (upstream + downstream) per ONU (See FigureF.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).

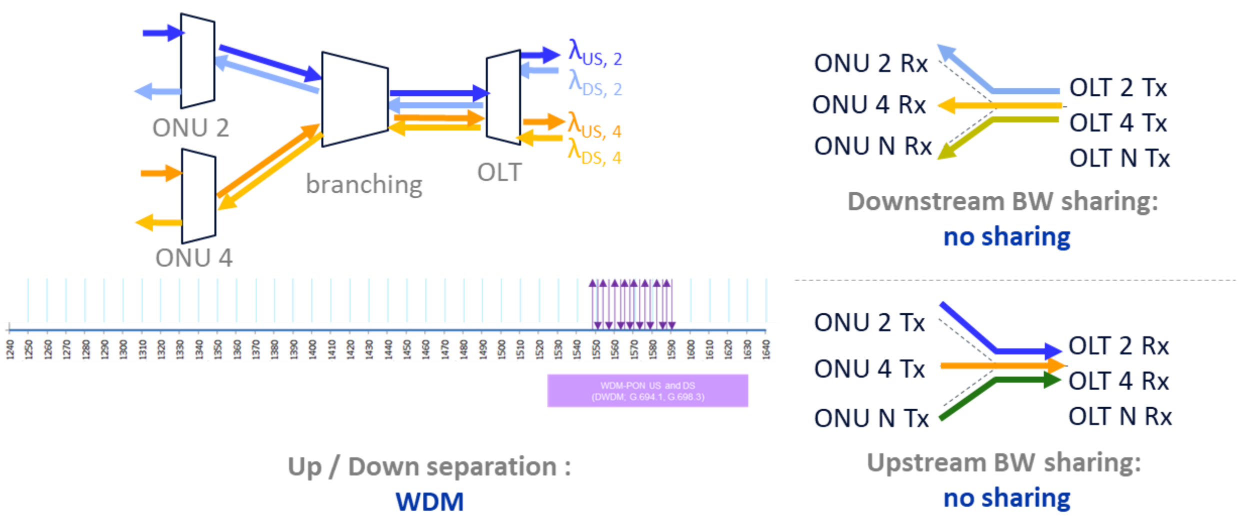


Figure F.1-3: WDM PON: Up- and Downstream Separation by WDM, without Up- and Downstream Bandwidth Sharing

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).

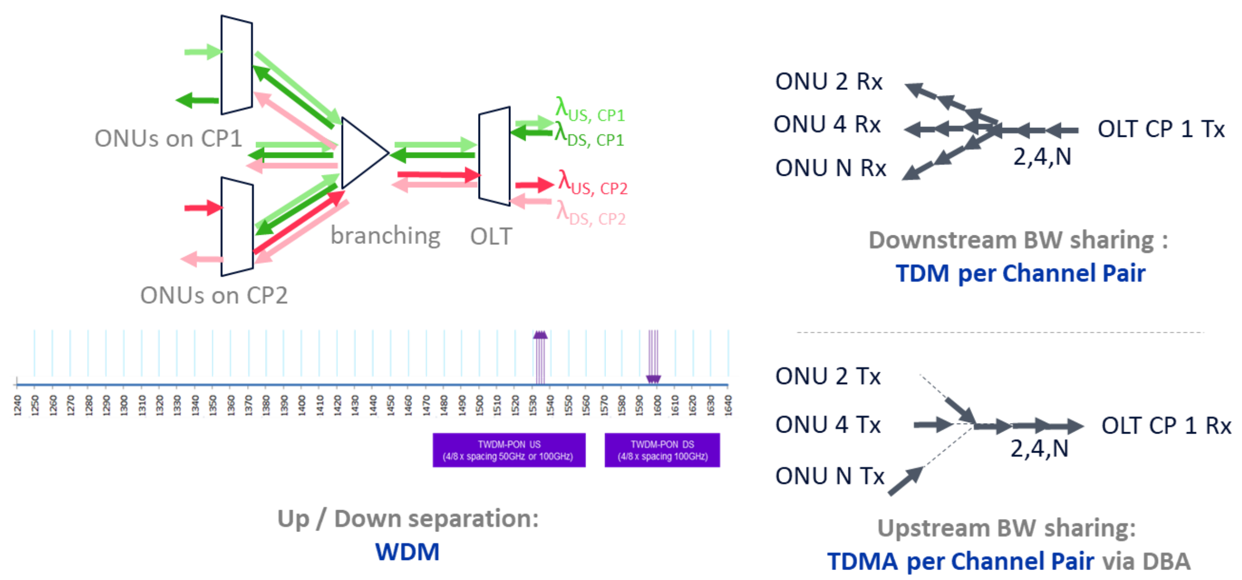


Figure F.1-4: TWDM PON: Up- and Downstream Separation by WDM, Up- and Downstream Bandwidth Sharing by TDM(A) per Channel Pair

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.

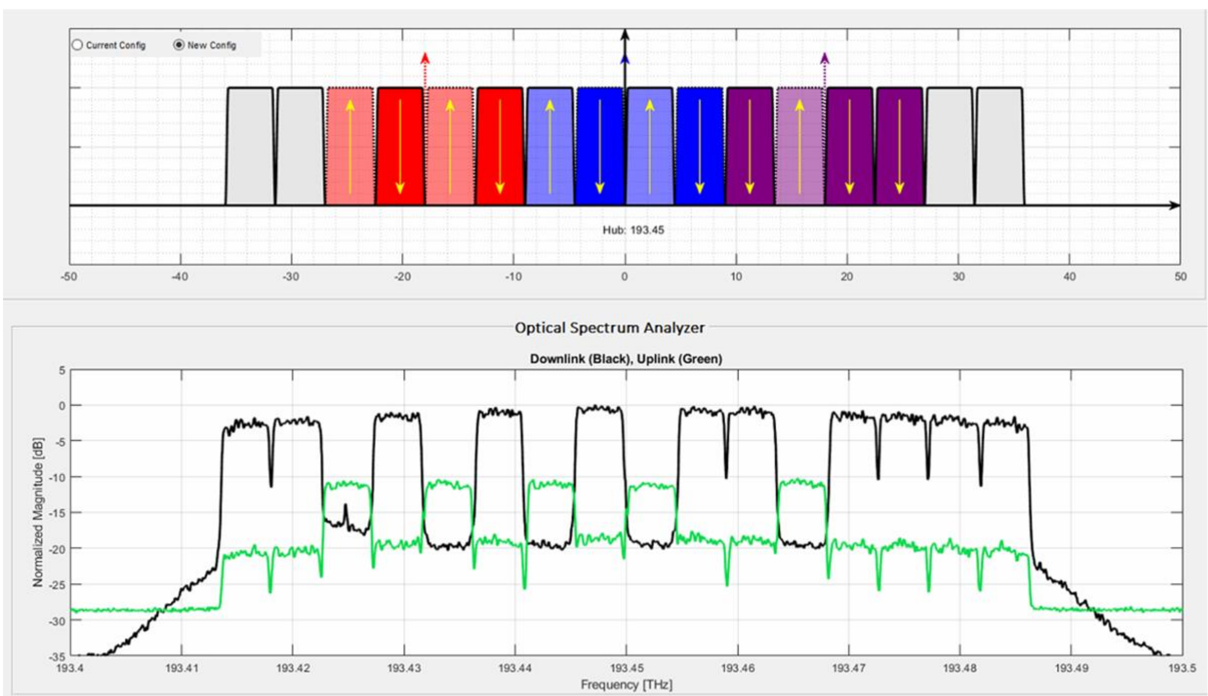


Figure F.1-5: SCM; Up- and Downstream Allocated from Several Subcarriers

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).

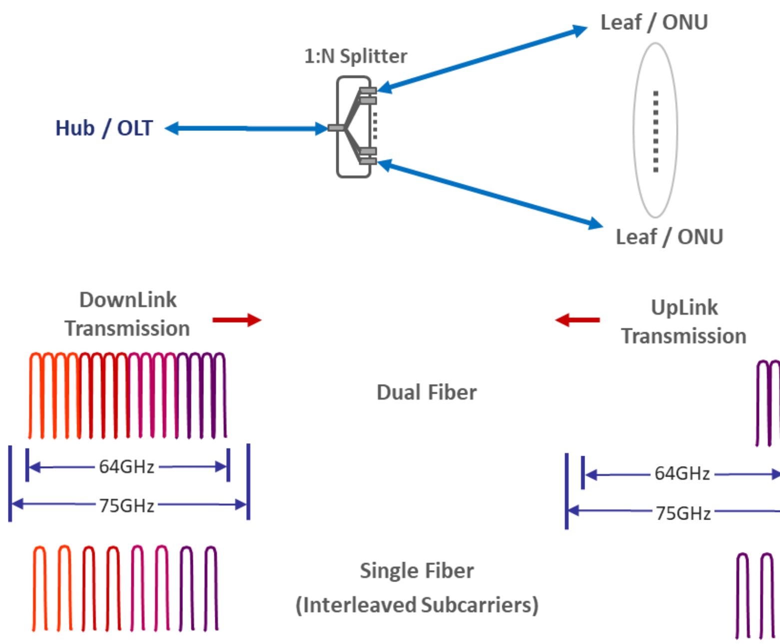


Figure F.1-6: Subcarrier Implementation Methods for Point-to-multipoint

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).

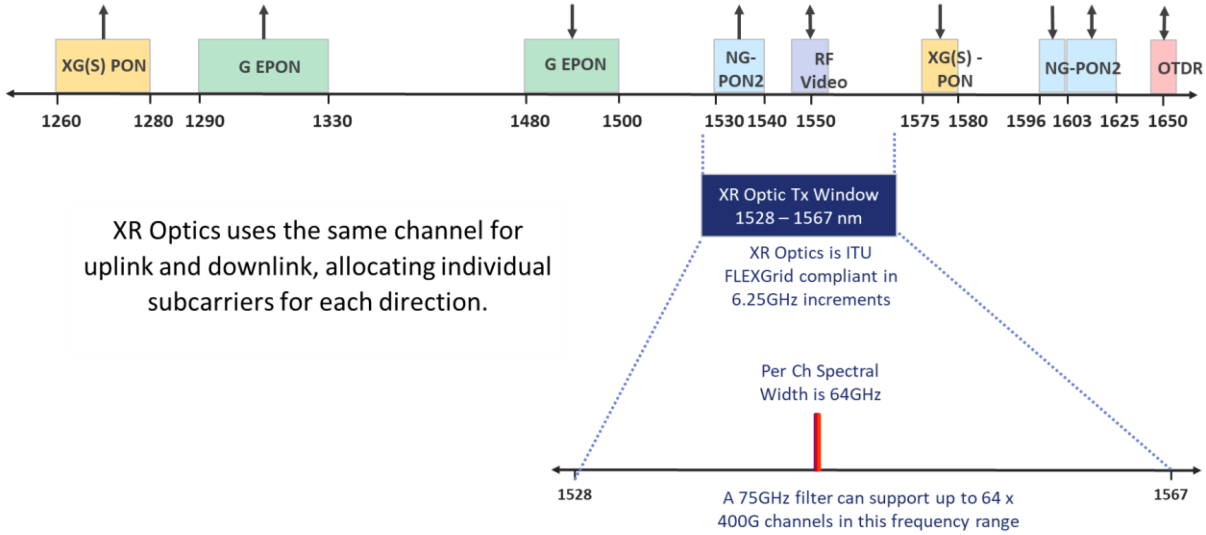


Figure F.1-7: Relative PON Wavelength Chart

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);

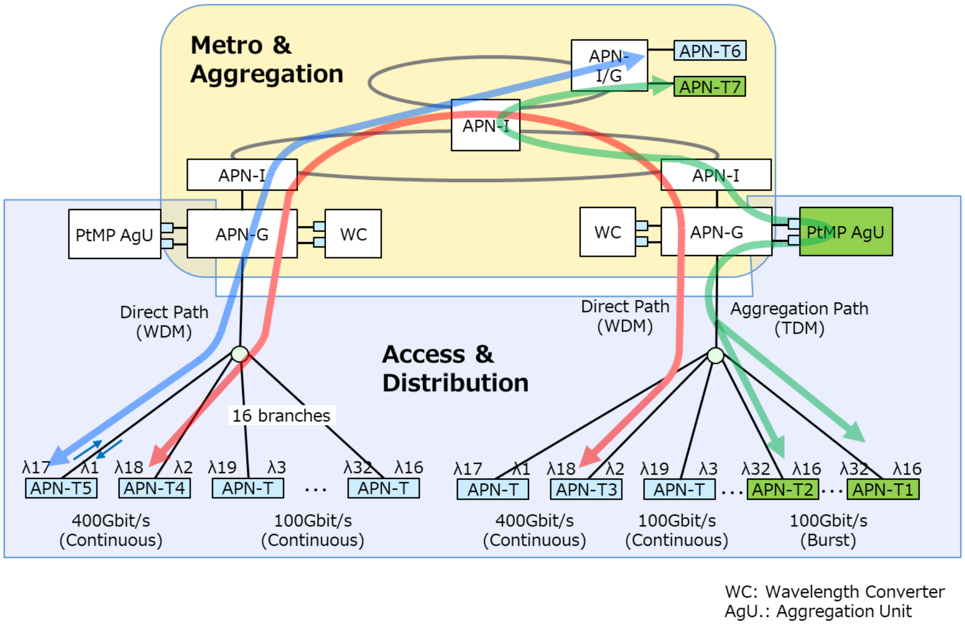


Figure F.2-1: Fiber Topology Example

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 tocan 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).

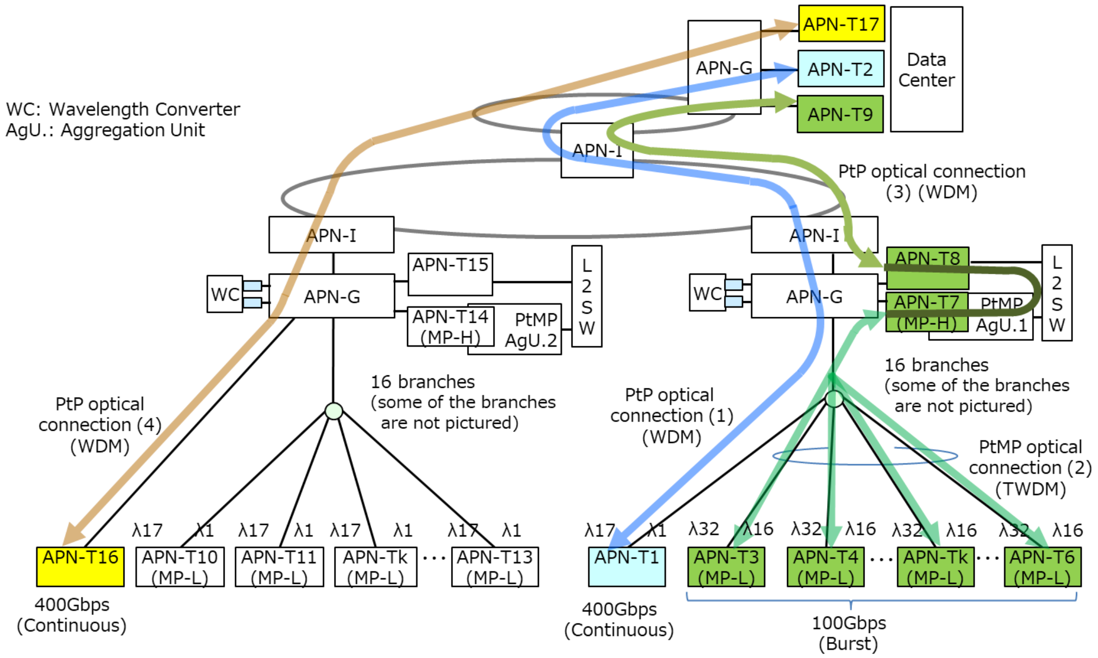


Figure F.3-1: An Example of Configuration Image of WDM PtP and PtMP Co-existence System

However, for the practical implementation, there are several issues to be clarified or resolved as shown in Table F.3-1.

Table F.3-1: Issues for PtP PtMP co-existing system

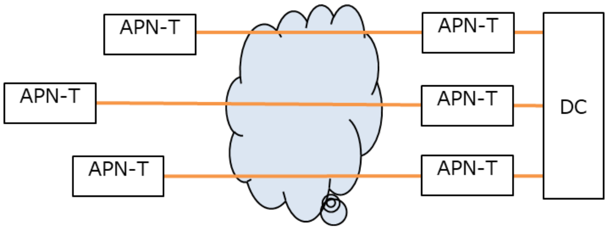
No.	ISSUE	DESCRIPTION
i.1	Difference of wavelengths used in conventional PtP and PtMP systems	PtP uses C+L band while PtMP uses O band. (Current FTTx system using O band)
i.2	Crosstalk, linearity, and transition response of amplifier for both PtP and PtMP signals	When burst signals are transmitted to distant APN-T(MP-H), amplifiers are required (current FTTx system has distance limitation of 20 km/40 km). In addition, current PtMP uses burst signals and PtMP signals through a splitter with large power splitting loss.
i.3	Directions of optical signals	PtP uses unidirectional fiber while PtMP uses bidirectional fiber
i.4	Implementation of PtP / PtMP selectable and high-speed APN-Ts	Variable line rate and burst transmission are required with practical cost
i.5	Controller which can manage suitable PtP / PtMP modes and line rate of APN-Ts based on the traffic rate or applications.	Not only management of APN-Ts for suitable mode selection but also traffic estimation or other technologies are required

F.4. The Number of APN-Ts and Energy Consumption

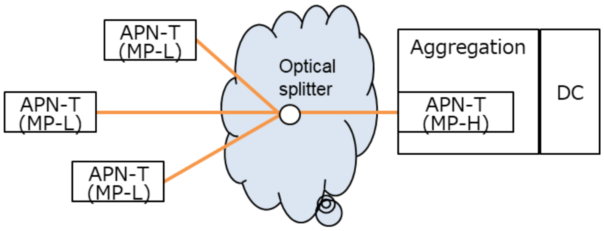
Figure F.4-1 (1) shows an example configuration of an Open APN with PtP. When the number of users is N, 2N transceivers are required. If the line rate of APN-T is B_P, the total throughput is B_P x N for each direction.

In case of PtMP, an APN-T(MP-H) located on an aggregation unit is connected to APN-T(MP-L)s via an optical splitter as shown in Figure F.4-1 (2). The number of transceivers is N+1. In the PtMP, an optical fiber connected to APN-T(MP-H) is shared by all APN-T(MP-L)s using TDM technology with burst transmission or some other technologies.

Therefore, when the line rate of APN-T(MP-L) is B_{MPL}, the total throughput is still B_{MPL} for each direction no matter the number APN-T(MP-L)s increases. If B_{MPL} and B_P are the same, the throughput of Open APN with PtMP is 1/N of PtP. The required time for transmission using PtMP is N times compared to PtP for the same volume of data.



(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].

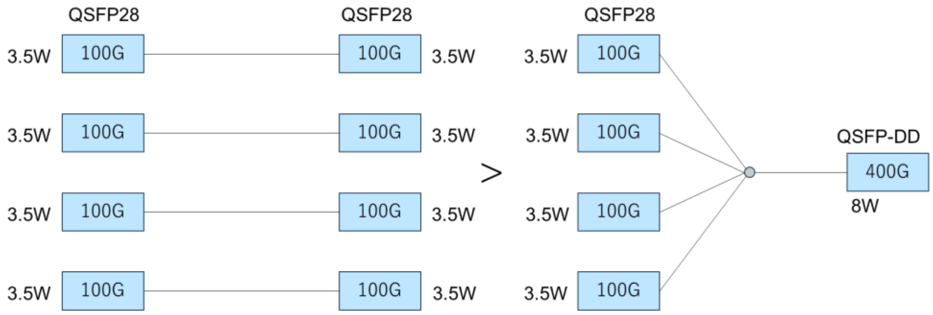


Figure F.4-2: Compares Estimated Energy Consumption between PtP and PtMP Configuration Focusing the Number of APN-Ts

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 the 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 the 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 ultra-high-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.

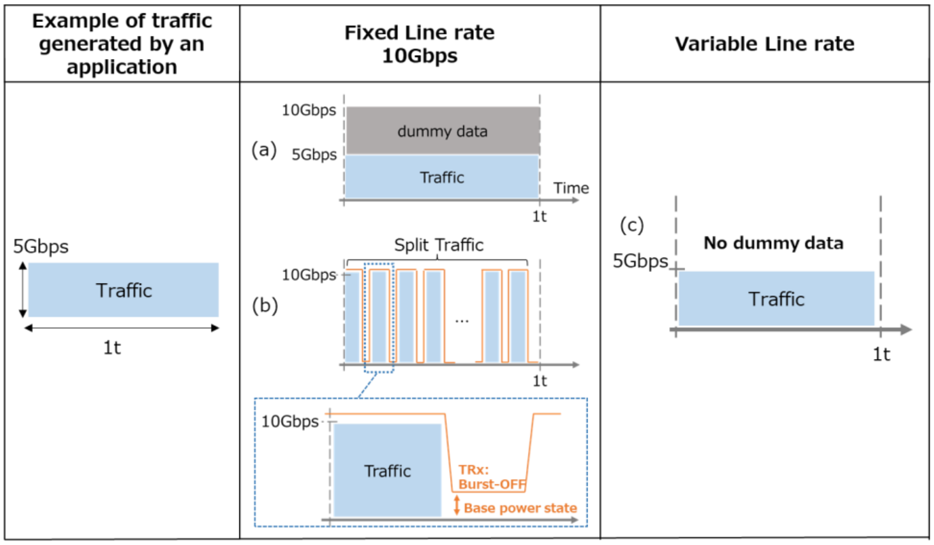


Figure G.3-1: The Relationship between Application Traffic, Fixed Line Rate, and Variable Line Rate

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.

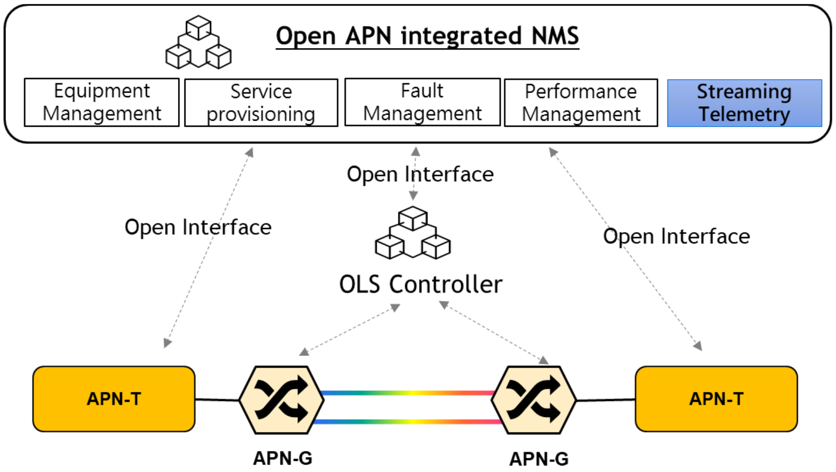


Figure H-1: An Evaluation Setup for Streaming Telemetry Function

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.

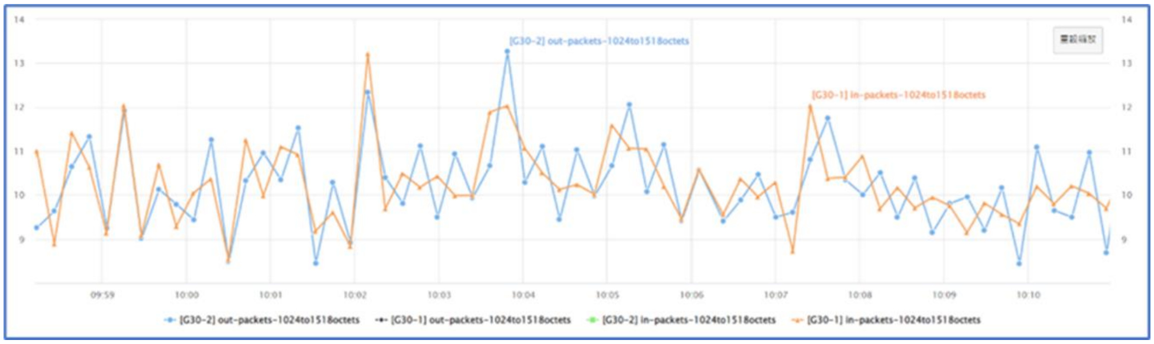


Figure H-2: A Traffic Monitoring with Streaming Telemetry (10 second period)

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.

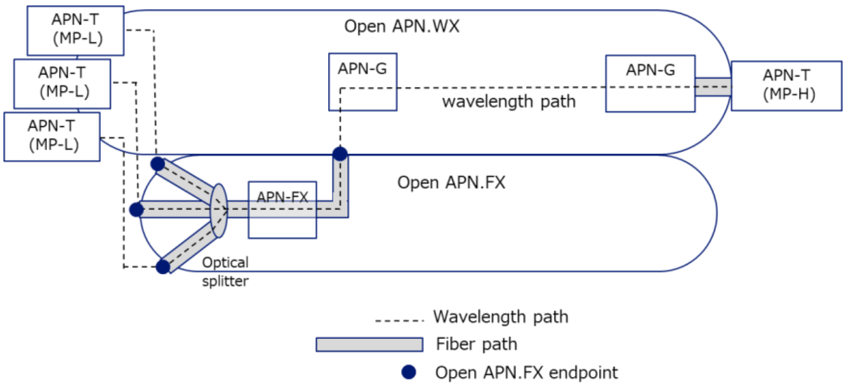


Figure I.1-1: An Example of PtMP Wavelength Path Implementation with PtMP Fiber Path

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(MP-T)s. How to implement APN-G (and APN-I if needed) to allow the wavelength split/combine requires further study.

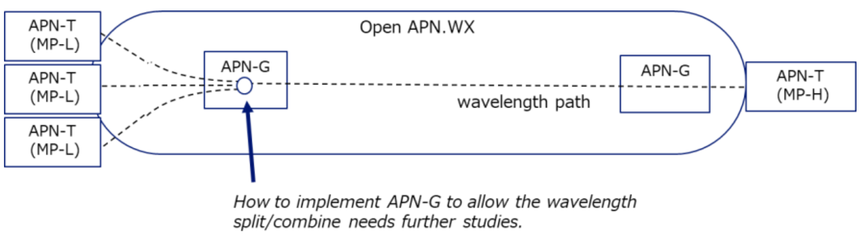


Figure I.1-2: An Example of PtMP Wavelength Path within Open APN.WX

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

The use of PtMP fiber path allows to share 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.

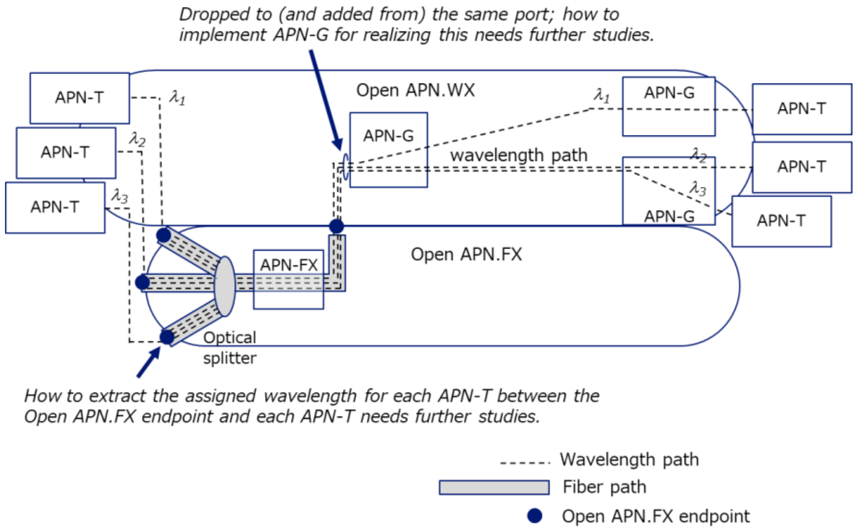


Figure I.1-3: An Example of Access Line Sharing for Multiple PtP Wavelength Path

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

The PtMP fiber path can be used for providing a shared access service based on a non-DWDM optical access system.

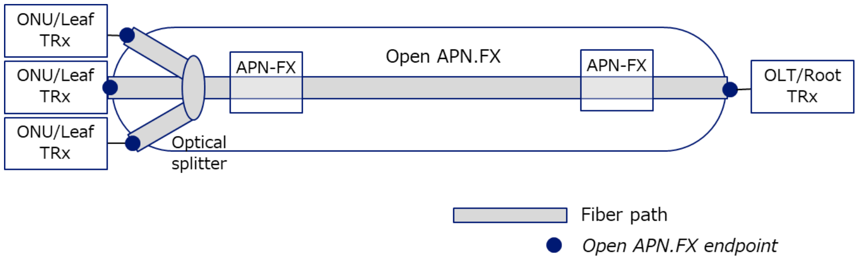


Figure I.1-4: An Example of PtMP Fiber Path Service for Non-DWDM Optical Access

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, which allows service providers to use optical access infrastructure for multiple services such as Open APN wavelength path, mobile fronthaul, fiber sensing, and PON-based fiber broadband.

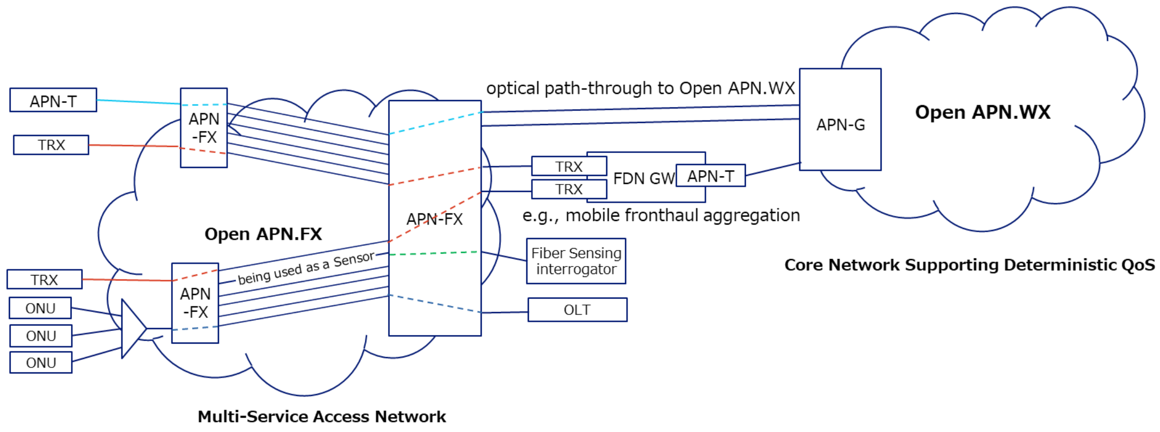


Figure I.1-5: An Example for Multiple Service Provision

Open APN.FX can be used as a network inside 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.

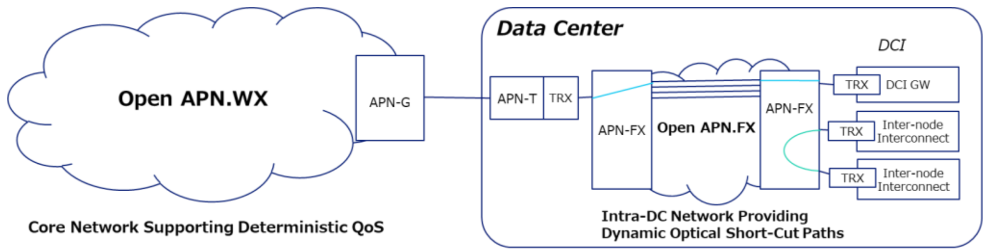


Figure I.1-6: Open APN.FX as Intra-DC Network

I.2. Service Types Supported by Each Release

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

	RELEASE 1	RELEASE 2	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		✔	

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

References

NO.	REFERENCE	CHAPTER/SECTION
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[IOWN GF CPS]	IOWN Global Forum, "Cyber-Physical System Use Case Release-1", 2021, https://iowngf.org/use-cases/	1.1
[IOWN GF AIC]	IOWN Global Forum, "AI-Integrated Communications Use Case Release-1", 2021, https://iowngf.org/use-cases/	1.1
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History

Revision	Release Date	Summary of Changes
1.0	January 27, 2022	Initial Release
2.0	October 19, 2023	- Service: In addion 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.