Photonic Gateway and Protocol-Independent End-to-End Optical-Connection Provisioning in All-Photonic Metro-Access Converged Network

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***Abstract*—The All-Photonics Metro-Access Converged Network (APN) aims to achieve a flat and simple architecture that even covers access areas and represents the evolution of optical transport. Electrical processing functions such as exchange, multiplexing, and switching are uniformly placed at the border of the network segments, i.e., access, metro, and core networks, in current optical networks. These functions are placed in Data Centric Infrastructure (DCI) and accessed only when needed in the APN. By flexibly providing direct optical connections between user premises and/or DCI according to requests from users and services, the APN creates new types of use cases requiring end-to-end guaranteed wide-bandwidth and/or extremely low latency and jitter along with an information-computing platform. To provide optical paths originating from user terminals that launch client signals using protocols preferable to their applications, we propose a configuration for a novel optical edge node, the Photonic Gateway (GW), and a procedure based on remote control of user terminals to establish end-to-end optical paths that are independent of the client signal protocol. To verify these, we present results of a proof-of-concept experimental demonstration of establishing end-to-end optical paths. An auxiliary management control channel is employed in the protocol-independent access control method. We also describe future challenges facing the Photonic GW that must be addressed.**

***Index Terms*—All-photonics network (APN), optical edge node, optical-path provisioning, remote user terminal (UT) control.**

I. Introduction

WIDE spread digitization of society and industry through IoT and AI technologies and proliferation of remote industries such as telework and telemedicine have accelerated recently. These technologies have not only increased the amount of traffic on the Internet, but also created new types of use-case demands that are different from those for conventional communication services. Considering further advancement of such new services, strict requirements have emerged for guaranteeing wide-bandwidth, extremely low latency, and low jitter for end-to-end telecommunication networks. For example, in a cyber-physical system that is expected to create new values and novel solutions, the network transport infrastructure will require two capabilities in particular [1]. One is to upload a large amount of real-world sensing data to an information-computing platform in real time without any loss or error. The other is to feed back precise control information to the real world in a highly reliable manner with low latency.

Based on this, a new network architecture must be designed and developed to meet the growing demands for guaranteed bandwidth and latency properties the levels for which are far different from those of conventional requirements while still enhancing the throughput and capacity for continued demands. Recently, there has been a push toward a novel networking and computing concept, the Innovative Optical and Wireless Network (IOWN) [2]. The metro-access convergence is a key of IOWN and represents the evolution of optical transport covering even access areas [3]. The All-Photonic Metro-Access Converged Network (APN) provides direct optical connections across access and metro areas to meet the requests from users and services. These requests include the endpoints of the optical connections, *e.g.,* user-terminal locations, necessary bandwidth, and allowable upper limits for latency and jitter. By allocating a wavelength to each user and service, the optical connections are logically isolated from those for other users and services. Data center interconnects, on-demand high-definition video distribution platforms, and live entertainment platforms with interactivity and immersion are some use cases for the APN.

The APN architecture replaces as many electrical components as possible with optical components to satisfy the lowest latency requirements of critical use cases and addresses social issues concerning power consumption. Previously investigated all-photonic technologies mainly intend to replace electric routing with optical burst switching or optical packet switching inside routing nodes interconnected by optical transport networks to resolve bottlenecks in terms of, for example, processing capacity, power, and thermal limit [4], [5]. Meanwhile, the intention

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of the APN is not to evolve the routing node but to evolve simply the optical transport network itself based on wavelength circuits to achieve access and metro convergence for emerging use cases and services.

The APN covers the access area as well as the metro area and provides optical paths originating from user terminals (UTs) to any arbitrary point even beyond the border between the access and metro areas. Note that the terminologies of access and metro in the APN do not imply that optical paths are always separated segment by segment. These terminologies are used only to indicate the regions in the APN. The optical edge node at the border between the access and metro areas remotely controls the endpoints of optical paths, i.e., UTs, and optically multiplexes optical paths from the access area. The APN architecture is considered to extend the metro network to cover the entire access and metro areas. This differentiates the APN from current optical networks, in which optical paths are disjointed and operated independently in each of the network segments, i.e., access, metro, and core networks.

To actualize such an APN and accommodate flexibly various types of users and services, we must establish a novel optical edge node configuration and a procedure based on remote control of user terminals for automatically establishing an optical path that is independent of the client signal protocol. In the APN, the optical path is not set up autonomously in a distributed manner using, for example, message exchange based on the Generalized Multi-protocol Label Switching protocol, but is set up under the control of the central controller. Here, since the optical paths might originate from user premises and UTs launch client signals with various protocols appropriate for their applications in the APN, the procedure for optical-path provisioning in current wavelength-division-multiplexing (WDM) networks based on reconfigurable add/drop multiplexers (ROADMs) and optical cross connects cannot be employed without change. In current WDM networks, the endpoints of optical paths, i.e., transceivers/transponders, are typically inside the telecom carrier buildings and do not need to be controlled remotely.

In this paper, we first present the concept behind the APN transport architecture. Then, we propose a configuration for a novel optical edge node in the APN, which we refer to as a Photonic Gateway (GW). We then present the proposed procedure and experimental feasibility investigation for autonomously and remotely establishing a protocol-independent end-to-end optical path through the Photonic GWs. Finally, we describe future challenges facing the photonic GW that must be addressed.

A part of the Photonic GW concept was originally presented in [6]. In this paper, we extend the content in [6] to present a comprehensive concept of the Photonic GW. The main points representing this extension are as follows. First, as background for the need for the new edge node, i.e., the Photonic GW, we comprehensively explain the aims, concepts, and main features of the APN in Section II. Second, the novelty of the Photonic GW is clarified in Section IV-A in a description of the novel features of the Photonic GW compared to conventional ROADMs. Third, in addition to the five functions required for the Photonic GW described in Section IV-A, we newly present a configuration example of the Photonic GW in Section IV-B.

II. APN Architecture

A conventional wide-area telecommunications network generally has an architecture that connects its network domains hierarchically. When transferring traffic from access to metro networks, optical signals are once converted to electrical signals at the border between the network domains. Electrical aggregation or multiplexing is then applied enabling an optical path with a higher bandwidth in the upper network domain to accommodate traffic from a larger number of users and services. While capital expenditure (CAPEX) is reduced by sharing equipment and optical paths among many users and services owing to this architecture, the effective bandwidth per user and service is limited. As a result, a long delay occurs when transmitting high-capacity data, *e.g.,* 8K/16K high-definition video and 360° virtual-reality video, mainly due to the need for encoding and decoding. In addition, queue processing of packets and frames induces delay and jitter at the electrical aggregation and multiplexing points.

The APN aims to achieve a flat and simple architecture across access and metro for emerging use cases and services and eliminates the need for electrical termination of the optical path at the border between the conventional network domains. The APN directly connects elements of Data Centric Infrastructure (DCI), which is a distributed computing infrastructure spanning clouds, edges, and end-user premises rather than replacing the current optical network that connects mainly L2/L3 switches/routers [7]. Owing to end-to-end and full-mesh wavelength paths dedicated to each user and service, the APN provides optical connections independent of a specific signal protocol with a guaranteed bandwidth and extremely low latency and jitter.

Since the APN covers the access area, an end-end connection in the APN provides a wavelength path originating from a UT. The UT itself must ensure the fulfillment of requirements for optical connections longer than those in conventional networks. While this aspect can increase the UT cost, eliminating the need for optical transponders between the UTs lowers the overall cost of the transmission equipment per user. In the APN architecture, it can be regarded that the line interface of the transponder, which is in the building of the carrier in the conventional ROADM-based network, is extended to the user premises. This eliminates the need for the equipment and modules for short-distance transmission between the UT and the transponder required in the conventional ROADM-based network.

The APN also allows electrical termination of the wavelength path at arbitrary points for some processing in the network function and service function layers. This electrical termination could also be applied to regenerate optical signals using a repeater with 3R functions, i.e., reshaping, retiming, and regeneration, when the level of transmission quality cannot be met between the requested endpoints without any regeneration. This architecture makes the APN suitable as an optical transport infrastructure despite diverse and strict requests.

Fig. 1 shows the concept behind the APN architecture [8]. The APN comprises optical nodes, which we refer to as the Photonic GW. The Photonic GW is an edge node at the border between the access and metro areas, and accommodates various types of UTs.

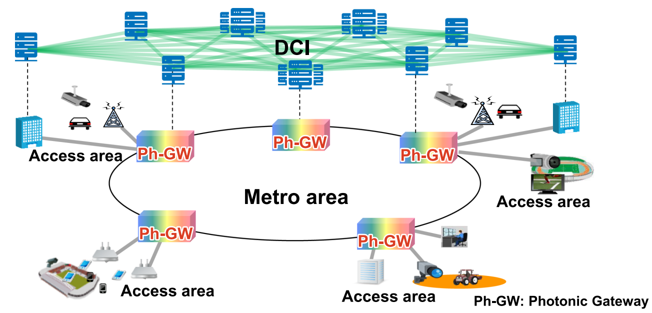

Fig. 1. Concept of All-Photonics Metro-Access Converged Network.

In other words, the Photonic GW is the entrance to the full-mesh network from the viewpoint of the UT. Inside the Photonic GW, no electrical processing such as exchange, multiplexing, or switching is performed. The Photonic GW forwards the optical paths to the neighboring node without optical/electrical conversion and enables the termination of optical paths by dropping the optical paths once outside the optical nodes when necessary for some processes.

Summarizing the above descriptions, the main APN features are given below.

1) The APN enables direct optical connection between arbitrary points without any electrical processing.
2) The APN guarantees wide-bandwidth, low-delay, and low-jitter quality communications by allocating dedicated wavelengths to users and services.
3) The APN provides a variety of services by flexibly combining necessary processes on the network function layer and/or service function layer at the points appropriate for individual services.
4) The APN provides users with a communications environment where users do not need to be concerned with, for example, service types and signal protocols.

III. Related Work

The APN intends to achieve convergence of access and metro for emerging use cases and services. The aim is to provide wide-bandwidth, low-latency, and low-jitter connectivity between any endpoints, *e.g.*, user premises and DCI, to actualize an evolved distributed computing infrastructure across clouds, edges, and end-user premises.

First, let us focus on the main objectives and approaches to access-metro convergence. There have been many research projects that target access-metro convergence such as PIEMAN, (Photonic Integrated Extended Metro and Access Network) [9], SARDANA (Scalable Advanced Ring-based passive Dense Access Network Architecture) [10], and DISCUS [11]. In general, access-metro convergence intends to reduce infrastructure CAPEX, operational expenditure, and power consumption for mainly residential and mobile services by eliminating the need for electrical processing, *e.g.*, aggregation, multiplexing, and routing, at the border between the access and metro areas and by consolidating nodes. A typical approach for this is to increase the power budget of the access system, for example, by employing optical amplification technologies. The coverage area of the optical access system is extended to cover the entire access and metro areas. The network architectures in [9], [10], [11] are basically based on time-division multiplexed Passive Optical Network (TDM-PON) where a single Optical Line Terminal (OLT) serially hosts multiple Optical Network Units (ONUs). The physical interface and signal protocol should be uniform among ONUs.

The APN approach to access-metro convergence is the opposite. The APN architecture integrates access and metro by extending the endpoint of the optical path even to user premises. In current segment-based networks, the optical paths that provide direct optical connectivity across the WDM-based metro network are terminated at the end of the metro area. Therefore, the APN approach to access-metro convergence is considered to be expansion of the metro network to cover the entire access and metro areas, which is quite different from the approaches in previous studies. WDM networks are inherently transparent to the client signal protocol because optical paths are separated by wavelength channels. The physical interface and signal protocol should be common within a pair of UTs communicating with each other, but do not need to be common between a pair of UTs and another pair of UTs. The converged access and metro actualized by the APN enables wavelength channels with various client signal protocols to be multiplexed without change.

The scalability of the metro in the APN can be increased by simply adding more optical fibers within the metro section when the number of optical paths required for the section exceeds the maximum number of wavelengths that can be accommodated. In addition, how to scale out node configurations in the APN is described in Section IV-B. Here, it must be noted that the number of connections required for APNs is orders of magnitude less than that of the networks in [9], [10], [11]. As mentioned above, the APN primarily aims to actualize an evolved distributed computing infrastructure across access and metro, while access and metro convergence in [9], [10], [11] is primarily aimed at increasing the efficiency of residential and mobile infrastructure.

Second, let us focus on the control scheme and procedure for establishing end-to-end optical paths. In traditional WDM transport networks across metro and core, optical paths are configured statically. Optical paths are designed offline by expert engineers using specialized tools. Operation to reconfigure optical paths on-the-fly after once setting is not assumed. In addition, transmission parameters, *e.g.*, baud rate, modulation format, and output power from transmitters, are uniformly set so that transmission quality better than the threshold is achieved in the longest route.

Recently, there has been a resurgence of industrial interest in dynamic optical networking for metro and core networks rather than for access networks. One of the aims of this dynamic optical networking is to provide flexibly optical paths on demand. The Open Optical & Packet Transport (OOPT) project group of the Telecom Infra Project (TIP) [12], which facilitates disaggregation and openness of carrier transport networks on the basis of software defined networking (SDN) architecture, has accelerated this trend by developing Gaussian noise simulation in Python (GNPy) to predict the quality of communication (QoT) online for path computation [13], [14].

To achieve this dynamic optical-path provisioning, two methods must be established. The first one is path computation in a virtual or controller domain. The path computation derives optimal transmission parameters and a route for each optical path, for example, using GNPy. At this stage, the optimal values of the gain of the cascaded optical amplifiers should be carefully recalculated so that addition or deletion of optical paths and changes in output power from transmitters do not affect the transmission quality of other existing optical paths [15], [16], [17], [18]. In the second method, an SDN controller generates optical paths in a real or physical domain according to the results of the path computation. This method includes setting the optical node configuration, *e.g.*, port connection and wavelength routing, and controlling the wavelength to the transponders/transceivers terminating the optical path.

This paper focuses on how to establish the second method for the APN, which covers access and metro. Methods to establish an end-to-end optical path transparent to the client signal protocol have been an actively investigated research topic especially targeting metro/core networks.

However, some challenges still remain for the APN, which extends the current metro networks to cover the entire access and metro areas as described above. Simply applying conventional ROADMs to the APN access nodes and employing conventional schemes for optical-path control will not satisfy the requirements. Since endpoints of optical paths in the APN are located at user premises instead of in telecom carrier buildings, control signals to UTs should be transmitted remotely in-band to avoid the need for dedicated physical media, *e.g.*, fiber, and to simplify the UT configuration as described in Section IV-A. Here, UTs launch client signals unchanged using protocols suitable for their applications. Therefore, these lead to one of the challenges and novelties of the APN, how to control remotely UTs in-band with transparency to the client signal protocol and establish end-to-end optical connections.

IV. Photonic GW

A. Photonic-GW Functions

The Photonic GW is an optical node that is placed at each entrance to a full-mesh network and is connected to various types of UTs. The Photonic GW operates by following directions from the APN controller. The Photonic GW remotely controls the UTs and transfers optical paths originating from the UTs in accordance with the termination point of the individual optical path. Fig. 2 illustrates five basic functions proposed for the Photonic GW. *Remote wavelength control* of a UT wavelength is necessary to establish a direct optical connection according to the wavelength assignment by the APN controller. *Multiplexing/demultiplexing* enables the sharing of optical media among several optical paths through the APN. Note that power consumption of the APN is much lower than that for conventional hierarchal networks based on electrical aggregation since no electrical processes are performed at the border between the access and metro areas. *Pass/block* enables direct optical connection between access and metro only when its wavelength corresponds to the assigned wavelength. UTs located at the user premises might emit at wavelengths different from those assigned remotely by the APN controller. In this case, the optical signals with improper wavelengths are shut down to avoid collision with other optical signals with an appropriate wavelength. *Turn back* enables direct optical connection within access areas. With these last two functions, end-to-end optical connection between UTs is flexibly established, which provides guaranteed wide-bandwidth and/or extremely low latency and jitter. Meanwhile, *add/drop* enables the optical path to be dropped, which allows some processing functionality on the network function layer or service function layer at the edge of the APN.

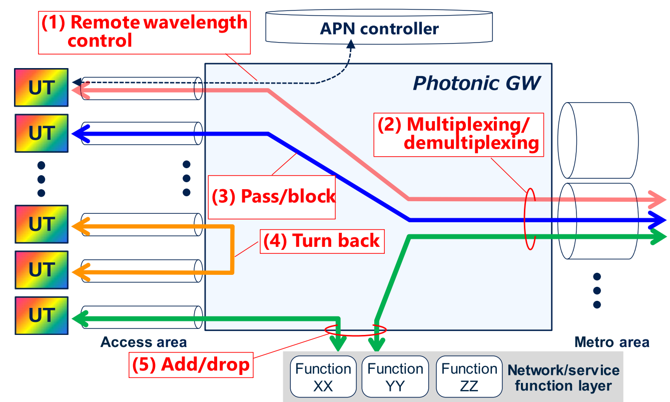

Fig. 2. Basic functions of Photonic Gateway.

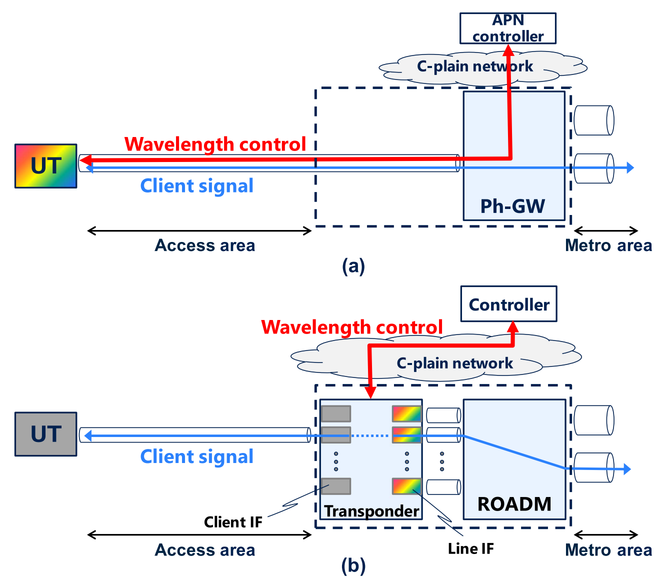

Fig. 3. Wavelength control scheme in (a) APN and (b) conventional ROADM-based network.

The Photonic GW is considered as an optical node the functionality of which evolved from that of the add/drop block comprising conventional ROADMs [19], [20], [21]. The following describes the main differences between the Photonic GW and conventional ROADMs.

First, the Photonic GW provides remote control channels to the APN controller as shown in Fig. 3(a) so that the APN controller can communicate with the UTs and control them. This

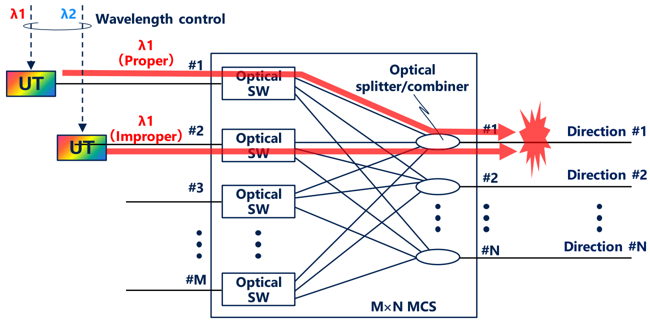

Fig. 4. Wavelength collision in M × N MCS when UT emits improper wavelength.

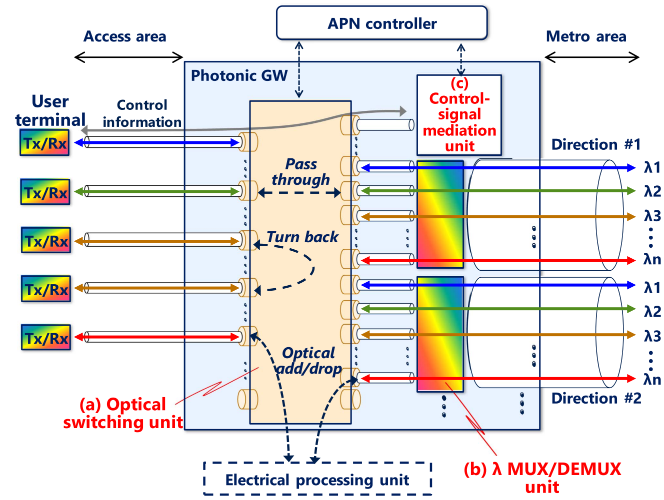

Fig. 5. Configuration example of main function blocks in Photonic Gateway.

is a necessary function since endpoints of optical paths in the APN are located at user premises instead of in telecom carrier buildings. Conventional ROADMs cannot provide remote control channels. This is because endpoints of optical paths, i.e., transceivers/transponders, are located in telecom carrier buildings and directly controlled by controllers in current ROADM-based networks as shown in Fig. 3(b). Therefore, ROADMs do not need to provide remote control channels between the controller and endpoint terminals.

Second, the Photonic GW prevents optical signals with an improper wavelength from interfering with optical signals launched from other UTs due to the pass/block function. There are some structures for the add/drop block in ROADMs. One currently widely implemented structure in industry uses M × N multicast switches (MCSs) with M inputs and N outputs [22]. An M × N MCS comprises M sets of 1 × N optical switches and N sets of M × 1 optical splitters/combiners. Since optical signals from transceivers/transponders are passively multiplexed in this MCS, ROADMs based on MCSs cannot prevent optical signals with an improper wavelength from interfering with optical signals launched from other transceivers/transponders as shown in Fig. 4.

Third, direct optical connections between UTs connected to the same Photonic GW can be set due to the turn-back function. Direct optical connections between transceivers/transponders connected to the same ROADM cannot be set.

B. Photonic-GW Configuration

Fig. 5 shows a configuration example of the main function blocks for the Photonic GW to implement the five basic functions. The Photonic GW includes (a) an optical switching unit, (b) a wavelength multiplexing/demultiplexing (λ MUX/DEMUX) unit, and (c) a control-signal mediation unit.

The optical switching unit transfers optical signals input from the access and metro to the appropriate ports according to the destination of each optical path without optical/electrical conversion. This actualizes three functions. The first is the pass/block function (function (3) in Fig. 2), which directly connects the access and the metro only for a specific optical path. The second is the turn back function (function (4) in Fig. 2), which directly connects the UTs distributed in the access area covered by the same Photonic GW. The third is the add-drop function (function (5) in Fig. 2) for the electrical processing unit.

The λ MUX/DEMUX unit bundles the optical paths that are in the same direction using WDM, and outputs them to the metro through the same port of the Photonic GW. In addition, the λ MUX/DEMUX unit separates the optical signals from the metro into the wavelength unit. This means that the λ MUX/DEMUX unit forwards the respective wavelength paths to different ports of the optical switching unit. In this way, function (2) in Fig. 2 is achieved.

The control-signal mediation unit exchanges control information with the UTs when the UTs initially connect. This control information includes wavelength setting instructions for the UTs, which actualizes function (1) in Fig. 2. Note that the control-signal mediation unit does not need to be connected to all UTs at the same time for initial optical-path provisioning. This is because the UT only needs to be connected to the control-signal mediation unit before establishing the optical path originating from the UT itself. Therefore, the control-signal mediation unit is not equipped with as many ports as the number of the UTs.

The Photonic GW has colorless, directionless and contentionless (CDC) functions similar to conventional ROADMs [19], [20]. The CDC functions actualize non-blocking switching and adding/dropping of wavelengths. The Photonic GW enables the forwarding of optical signals with the same wavelength launched from multiple UTs to the metro without contention. Optical signals from UTs assigned with the same wavelength are output in different directions for each UT. In addition, the Photonic GW enables the forwarding of optical signals with the same wavelength from multiple directions on the metro side to different UTs. Owing to these functions, a UT can be assigned the same wavelength as that already used by other UTs. Therefore, the maximum number of UTs connected to the Photonic GW can be increased without increasing the number of wavelengths by enlarging the scale of the Photonic GW according to the growth in demand for end-to-end optical connections. The scale of the Photonic GW includes the number of ports of the

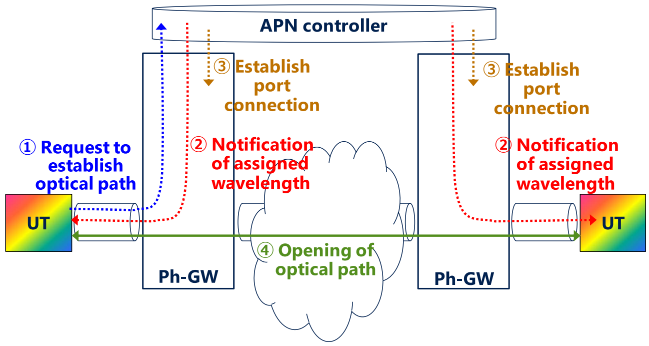

Fig. 6. Workflow for establishing end-to-end optical path.

optical switching unit and the number of directions on the metro side. The number of ports in the optical switching unit can be increased in a scalable manner by arranging the units in parallel. At this time, bridging the units achieves turn back functionality that directly connects a UT connected to one optical switching unit with another UT connected to a different switching unit.

C. Protocol-Independent Access Control Method

As the optical transport infrastructure for various users and services, the APN should promptly provide various types of UTs with optical connections according to their requests. Therefore, establishing an access control method that automatically configures a new optical path between the UTs as soon as an unregistered UT is physically connected to the APN is inevitable. Needless to say, this new optical-path configuration must not cause any disruptions to the existing optical paths.

Fig. 6 shows the workflow to establish an end-to-end optical path. First, the UT sends a request to the APN controller via the Photonic GW to establish an optical path. Second, the APN controller determines the wavelength assignment to the UT, and notifies the UT of the assigned wavelength via the Photonic GW. The APN controller is an element that functions as a wavelength-resource administrator and as route designer for the optical path throughout the APN. Third, port connections inside the Photonic GWs are automatically set. This remote establishment of an optical path originating from the UT is achieved only when the five basic functions of the Photonic GW are used. After wavelength assignment, the photonic GW implements remote wavelength control over the UTs. The optical switches (SWs) in the Photonic GWs then reconfigure the port connections in accordance with the route assignment, which actualizes the pass, turn back, and add/drop functions. Multiplexing/demultiplexing allows a new optical path to extend beyond the border between the access and metro area domains without collision with the existing optical paths.

Here, this access control method should be independent of the client signal protocol. This is because the client signals from various types of UTs are transmitted unchanged without being capsulized into a common frame type, *e.g.*, Ethernet frame, in the APN. The use of an auxiliary management control channel (AMCC) is effective in achieving a protocol-independent access control method [23], [24], [25], [26]. Since the AMCC for the control signals is superimposed on the lower frequency band in the same wavelength as the client signals, control signals and client signals can be isolated from each other. Therefore, the AMCC enables the Photonic GW to control directly various types of UTs that launch client signals with protocols appropriate for their applications.

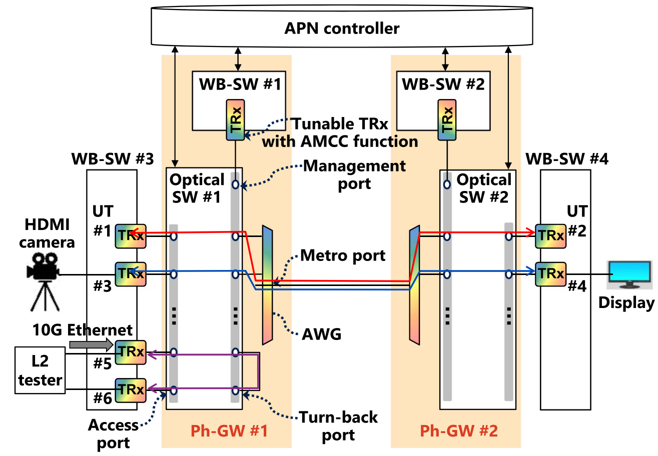

Fig. 7. Experimental configuration.

V. Demonstration of Establishing Autonomous End-to-End Optical Path

A. Experimental Configuration

We conducted an experiment using the configuration shown in Fig. 7. The aim of this experiment is to prove the feasibility of the proposal for the basic Photonic GW configuration and autonomous procedure for end-to-end optical-path provisioning. While the scale of the experimental configuration is relatively small, this experimental configuration is suitable to achieve the above aim. Since the new optical-path configuration does not cause any disruption to the existing optical paths, it is not necessary to set a large number of existing optical paths in advance to confirm the validity of the proposed procedure. In addition, the maximum number of UTs connected to the Photonic GW can be easily scaled without increasing the number of wavelengths by enlarging the scale of the Photonic GW, i.e., the number of ports of the optical switching unit and the number of directions on the metro side.

Two Photonic GWs are connected via an optical fiber and controlled by a single APN controller, which is implemented on an Ubuntu server in C language. The wavelength-allocation algorithm is implemented in the APN controller so that the longest wavelength among unused wavelengths on the route is assigned to a new optical path.

To provide the five Photonic GW functions described in the previous section, each Photonic GW prototype comprises a 32 $\times$ 32 optical SW based on a microelectromechanical system, an arrayed waveguide grating (AWG) with 100-GHz spacing, and a white box switch (WB-SW). The APN controller sets the port connections of the optical SW for the pass, turn back,

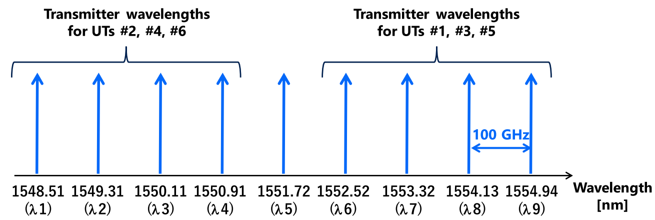

Fig. 8. Range of wavelengths allocated to UTs.

and add/drop functions. The input ports of the optical SW have optical power monitors. For MUX/DEMUX, the AWG is placed next to the optical SW. This AWG actualizes the pass/block function and MUX/DEMUX function. The AWG blocks optical signals that have an improper wavelength before they are multiplexed with optical signals launched from other UTs. A C-band 10-Gbit/s optical tunable transceiver (TRx) with AMCC functions is inserted into the WB-SW. This AMCC TRx is connected to the management port of the optical SW and launches control signals into the AMCC for remote wavelength control.

In Fig. 7, WB-SW #3 functions as UTs #1, #3, #5, and #6 while WB-SW #4 functions as UTs #2 and #4. Each UT is equipped with a 10-Gbit/s tunable TRx with AMCC functions, which is the same tunable TRx as that used in the Photonic GW. The transmitter wavelength is controlled in accordance with the wavelength-control signal in the AMCC from the Photonic GW. UTs #1, #3, and #5 are assigned wavelengths from 1552.52 nm (λ_6) to 1554.94 nm (λ_9) and UTs #2, #4, and #6 are assigned wavelengths from 1548.51 nm (λ_1) to 1550.91 nm (λ_4), as the transmitter wavelength as shown in Fig. 8.

When a new UT is connected to the APN transport network, the optical SW in the Photonic GW detects it using the optical power monitor and notifies the APN controller that a new UT is connected. Then, to register and activate the new UT, the APN controller commands the optical SW to configure a port connection to enable the APN controller to communicate with the new UT through the management port. The APN controller and the new UT communicate with each other through the AMCC. Using the AMCC, the new UT requests the APN controller to provide an optical path. To fulfill this request, the APN controller assigns a route and wavelength to the optical path originating from the UT. After wavelength assignment, remote wavelength control is performed using the AMCC. The optical SW then reconfigures the port connection in accordance with the route assignment, which actualizes the pass, turn back, and add/drop functions.

This experimental configuration does not employ optical amplifiers, which are actually required in wide-area metro-access converged networks. The reason for this is because in this investigation we prioritize overcoming technical challenges specific to the APN. We consider those challenges common to general WDM transport networks as future work. Deploying or deleting wavelengths dynamically without degrading other existing optical paths, which is one of the major challenges common to real WDM networks, has gradually become realistic

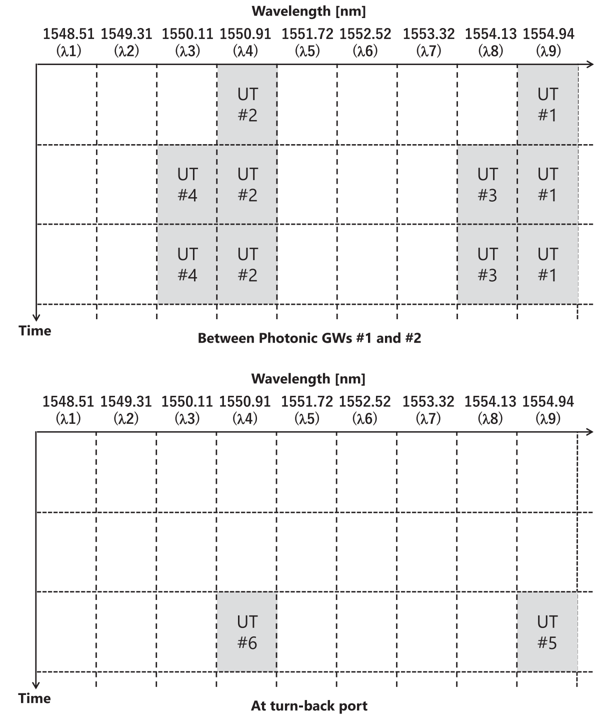

Fig. 9. Scenario for wavelength allocation.

[15]. The APN has to overcome technical challenges arising from covering access as well as metro areas unlike conventional WDM transport networks. More specifically, this involves how to control remotely UTs in-band with transparency with respect to the client signal protocol and to establish end-to-end optical connections. Therefore, this experiment focuses on demonstrating the feasibility of this procedure.

B. Experimental Results

We established a new optical path under the assumption that there already exists an end-to-end optical path between UTs #1 and #2, as shown in Fig. 7. We added other end-to-end optical paths between UTs #3 and #4 and between UTs #5 and #6 in order. The end-to-end optical paths between UTs #3 and #4 and between UTs #5 and #6 were established with the pass and turn-back functions of the Photonic GW, respectively. Fig. 9 shows the anticipated wavelength allocation in the above scenario.

Fig. 10(a) shows optical spectra that were observed during the experiment. Initially, the output light from UT #3, the initial wavelength of which is 1552.52 nm (λ_6), is observed at the management port in Photonic GW #1 when UTs #3 and #4 are connected. This proves that optical power detection at optical SW #1 properly induces port-connection configuration for communication between the APN controller and UT #3. The optical spectra from UTs #1 and #2, the wavelengths of which are 1554.94 nm (λ_9) and 1550.91 nm (λ_4), respectively, are observed at the metro port. After the optical paths for UTs #3 and #4 are opened, the optical spectrum at 1552.52 nm (λ_6) disappears at the management port in Photonic GW #1. At the same time, new

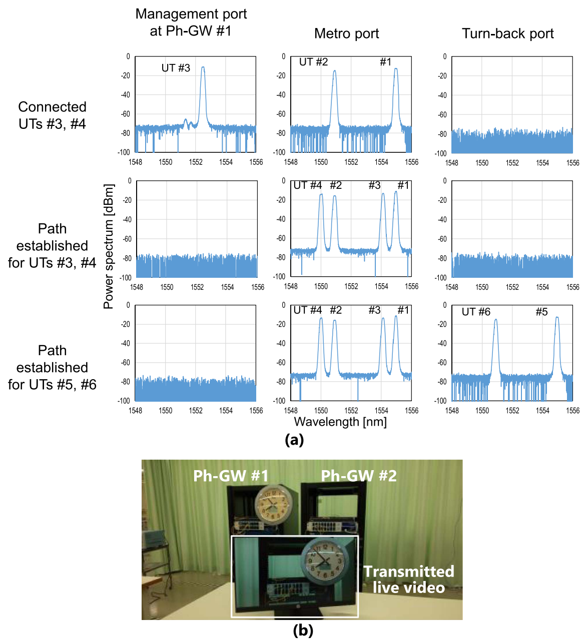

Fig. 10. (a) Optical spectra when establishing optical path and (b) transmitted live video from HDMI camera.

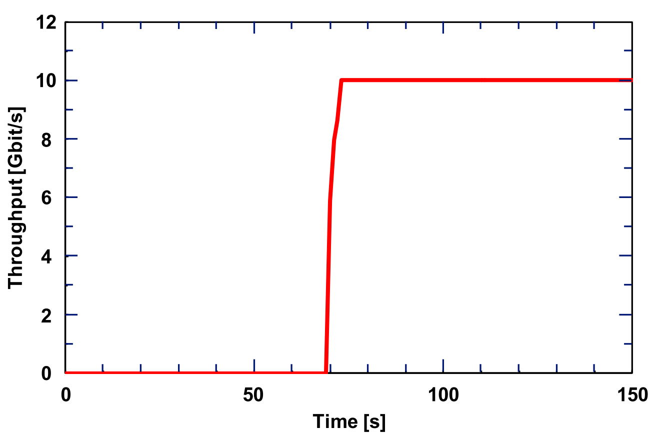

Fig. 11. Throughput between UTs #5 and #6.

optical spectra from UTs #3 and #4, the wavelengths of which are 1554.13 nm (λ_8) and 1550.11 nm (λ_3), respectively, appear at the metro port. This verifies that the route and wavelength assignments are successfully performed. The wavelength pair of 1554.13 nm (λ_8) and 1550.11 nm (λ_3), which is the longest wavelength pair among the unused wavelength pairs on the route between Photonic GWs #1 and #2, is assigned using the AMCC. After the optical paths for UTs #5 and #6 are opened, new optical spectra appear at the turn-back port. Since there are no unused wavelength pairs, the longest wavelength pair of 1554.94 nm (λ_9) and 1550.91 nm (λ_4) is assigned. The video from an HDMI camera is input to UT #3. The video signal is an uncompressed 4K video stream (RGB 4:4:48 bit) at 30 fps with a bit rate of 8.91 Gbit/s. Live video around Photonic GW #1 is clearly viewable after the transmission from UT #3 to UT #4 as shown in Fig. 10(b). A 10-G Ethernet signal is input to UT #5 at the input data rate of 10 Gbit/s. Fig. 11 shows the transition of received data rates of UT #6 before and after the optical-path is opened. These two results also confirm the successful opening of the optical path.

VI. Future Challenges

While establishing an end-to-end optical path, the Photonic GW must also continue exchanging control signals with UTs for status monitoring and remote control purposes regardless of the in-service optical-path status. However, the Photonic GW loses the means to exchange control signals with a UT once the end-to-end optical path is open because the path passes through the Photonic GW without optical/electrical conversion [27], [28]. Therefore, a control and management scheme for in-service end-to-end user connections via Photonic GWs should be established.

As the edge node of an APN transport network through which various innovative services are provided, the Photonic GW must be highly scalable. To actualize this scalability flexibly, a disaggregated node architecture that works under the control of the APN controller through open interfaces should be studied.

VII. Conclusion

We introduced an APN architecture and a new optical edge node called a Photonic GW that comprises the APN. The APN aims to achieve a flat and simple architecture across access and metro areas that is highly flexible and scalable to provide various users and services with optical connections that satisfy their respective requirements. With its ability to provide end-to-end and full-mesh wavelength paths dedicated to each user and service, the APN is suitable as the optical transport infrastructure for future service use cases that demand guaranteed wide bandwidth, extremely low latency, and low jitter the levels of which are far beyond those of present use cases. In addition, due to its transparency to client signal protocols, the APN accommodates various types of UTs that launch unchanged client signals with protocols suitable to their applications.

We proposed five main functions of the Photonic GW and protocol-independent access control with AMCC. The main functions are remote wavelength control of UTs, multiplexing/demultiplexing, pass/block, turn back, and add/drop. Since the Photonic GW is the entrance to the full-mesh network from the viewpoint of the UT, we focused on establishing autonomous end-to-end optical paths as a part of the protocol-independent access control. Using a Photonic GW prototype comprising a 32×32 optical SW for pass, turn back, and add/drop functionalities, a 100-GHz AWG for multiplexing/demultiplexing, and a WB-SW for mediation of remote wavelength-control signals, we conducted experimental demonstrations. The video stream from an HDMI camera was used as the client signal. We confirmed that the direct optical connection between a UT connected to a Photonic GW and a UT connected to another Photonic GW can be set with the pass function. We also confirmed that the direct optical connection between UTs connected to the same Photonic GW can be set with the turn-back function. These experimental demonstrations proved the feasibility of the Photonic GW configuration and procedure for establishing end-to-end optical paths.

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