Demonstration of In-Service Protocol-independent End-to-End Optical Path Control and Restoration in All-Photonics Network

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Abstract: We propose a control method for in-service end-to-end optical paths, and experimentally demonstrate the simultaneous restoration of Ethernet, CPRI, and HDMI signals, which is the world's first operation of protocol-independent control for end-to-end optical-path.

1. Introduction

A number of services and use cases for cyber-physical systems have been detailed, all of which require the network to transport large amounts of various contents including sensing information from remotely monitored areas with extremely low latency and high reliability. The All-Photonics Network (APN) has been proposed to meet these requirements [1, 2]. In the APN, a dedicated wavelength is assigned to each user terminal (UT); it provides protocol-independent connections to other UTs and cloud servers, namely end-to-end (EtE) optical paths, in a flexible manner. The logical connections originating from the UTs cross the border between access and metro networks without any optical/electrical conversion.

The Photonic Gateway (Ph-GW) has been proposed as the APN access node [3]. The Ph-GW not only transfers client signals between access and metro networks without optical/electrical conversion according to the destination of individual optical path, but also remotely controls UT wavelength via an auxiliary management and control channel (AMCC). Since the AMCC is an independent channel that is superimposed in a lower frequency band in the same wavelength as a client signal, the AMCC enables the Ph-GW to control various types of UTs regardless of their client signal protocols. In [3], a demonstration of EtE optical-path control for autonomous optical-path setup was reported. However, all UTs were Ethernet equipment whereas the AMCC is for remote control. This means that protocol-independent EtE optical-path control has not been demonstrated to date.

Once the EtE optical path is established, path control from the Ph-GW becomes much more difficult. This is because the Ph-GW has to send control signals to the UT even though in-service optical paths are not terminated in the Ph-GW. Ref. [4] proposed a scheme for superimposing an AMCC on an in-service EtE optical path. Using in-line optical modulators, the AMCC is superimposed onto the optical signals that are input from metro networks to the Ph-GW. This indicates that the Ph-GW loses the means of controlling the EtE optical path if no optical lights happen to be input to the Ph-GW due to some failures such as cutting of the optical fibers in the metro network. Without any method for restoring the EtE optical paths, the UTs can never restart communication in this situation.

In this paper, we propose a method for controlling in-service EtE optical paths that provides UTs with various types of optical-path restoration schemes regardless of client signal protocols. Owing to remote UT control using AMCC,

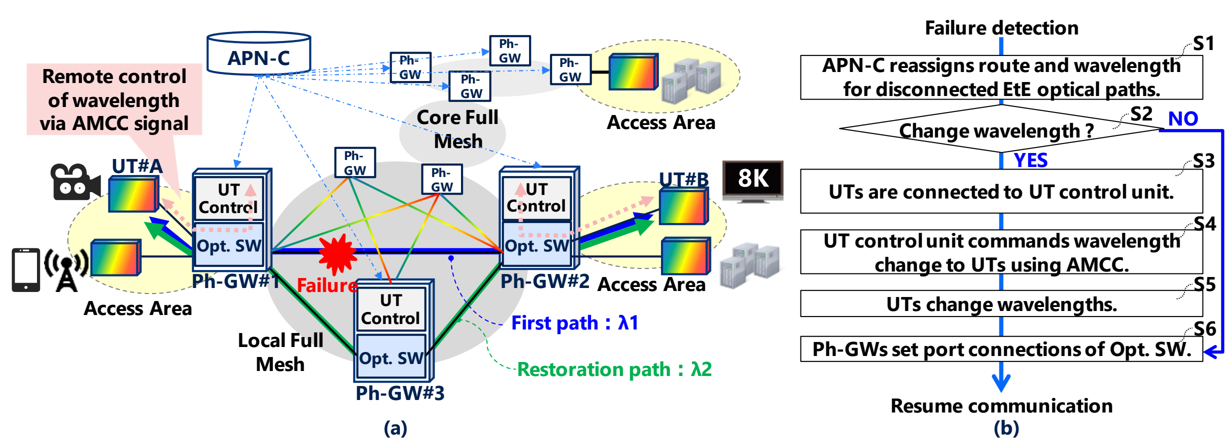

Fig. 1: (a) Restoration architecture in All-Photonics Network, (b) Proposed procedure for EtE optical-path restoration.

which realizes wavelength reallocation, the proposal achieves restoration with a common sequence even when optical-fiber cuts occur simultaneously at multiple points. Its feasibility is confirmed through a system-level demonstration using Ethernet, CPRI and HDMI equipment as the UTs and our Ph-GW prototype consisting of an optical node and a controller.

2. Proposed End-to-End optical-path restoration procedure including remote UT control

Figure 1(a) shows the proposed restoration architecture in the APN. The APN controller (APN-C) manages the wavelength resources across the APN, and assigns a wavelength and a route to each optical path so as to meet the bandwidth and latency requirements. The Ph-GWs interconnect access networks and metro networks (shown as Local Full Mesh NW in Fig. 1(a)) transparently without optical/electrical conversion. The Ph-GW mainly consists of function blocks for UT control and optical switching. For remote wavelength control to UTs, the UT control unit exchanges control signals on AMCC with the UTs via the optical switching unit as directed by the APN-C. When the optical fibers between the Ph-GWs are cut, the APN has to reconfigure EtE optical connections so that they take different routes.

Figure 1(b) illustrates the proposed restoration procedure for EtE optical paths. When a fault is detected, the APN-C reassigns the routes and wavelengths for the disconnected EtE optical connections (S1). Based on the reassignment so determined, the APN-C confirms whether wavelength change is necessary or not for individual UTs (S2). When a new wavelength is assigned, the Ph-GW connects to the UT and the UT control unit by changing port connections inside the optical SW (S3). Then, the UT control unit issues a wavelength change command to the UT using AMCC (S4), and the UT changes its transmitter wavelength (S5). Finally, the Ph-GWs on the new route set port connections inside their optical SWs (S6). If originally used wavelength is assigned again at S1, the APN-C judges that wavelength change is not necessary for the UT at S2. Then, steps from S3 to S5 are skipped. Here, wavelength reallocation to the UTs enables the re-assignment of routes to the EtE optical connections flexibly and promptly regardless of the scale of the failure. Since the AMCC is independent from client signal protocols, this restoration method can be employed to any protocols. Wavelength collision between the existing optical paths and the reconfigured optical paths can be easily avoided by considering wavelength usage by the existing optical paths on the living routes. This eliminates the cost of reserving redundant paths for all the optical paths in advance and reduces the number of fibers, namely capital expenditure, necessary to serve high reliability EtE path connections. In addition, wavelength reallocation minimizes the impact of multiple failures due to a catastrophic disaster [5]. Therefore, the proposed method is applicable to various restoration scenarios including simultaneous multiple failures with a common sequence.

3. Experimental Setup and Results

(a) Experimental Setup

Figure 2 illustrates the experimental setup for verifying the feasibility of the proposed procedure. Three Ph-GWs were connected in a ring topology. These Ph-GWs were controlled by a single APN-C implemented on an Ubuntu server as a C language program. Each Ph-GW was composed of a 32x32 optical SW based on piezoelectric element, arrayed waveguide gratings (AWGs) for multiplexing or demultiplexing with 100-GHz spacing, and a whitebox switch (WB-SW) serving as a UT control unit. The port connections inside the optical SW were controlled by the APN-C. A C-band tunable transceiver with AMCC function (AMCC TRx) was inserted into the WB-SW. This AMCC TRx launches control signals to the UTs over the AMCC for remote wavelength control using the management port of the optical SW. The in-line power monitor installed in Ph-GW #1 detected optical fiber disconnection. When the measured

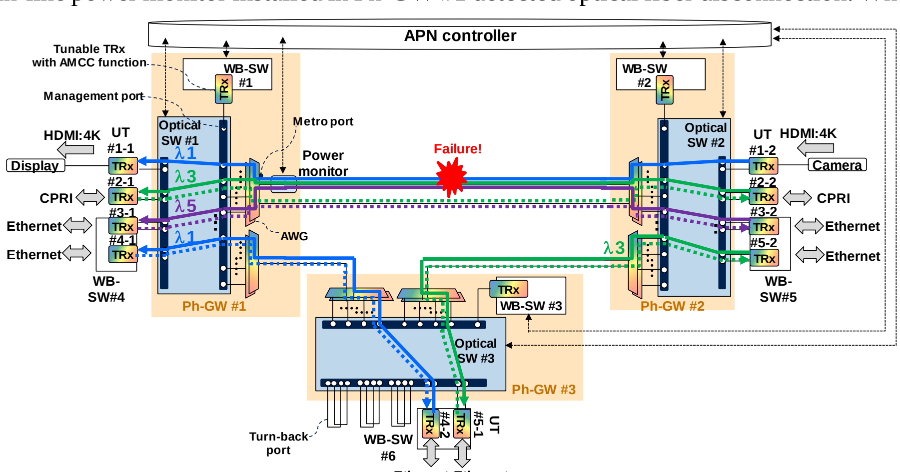

Fig. 2: Experimental setup.

value was below the threshold, the power monitor notified APN-C of the disconnection event between Ph-GW #1 and Ph-GW #2. The threshold value and the sampling interval for monitoring were set at -20 dBm and 62.5 ms, respectively. Triggered by this notification, the APN-C commenced the proposed sequence. The APN-C re-assigned wavelengths at random to the cut EtE optical connections.

Each UT was equipped with the same AMCC TRx used in the Ph-GW. At the initial setup, UT #1-2 transmitted an HDMI signal to UT #1-1 on 1554.940 nm (λ_1). The HDMI signal was an uncompressed 4K video stream (RGB 4:4:4 8 bit) at 30 fps; its bandwidth was 8.91 Gbps. UT pair #2-1/#2-2 (λ_3 = 1553.328 nm) and pairs of UTs #3-1/#3-2 (λ_5 = 1551.720 nm), #4-1/#4-2 (λ_1 = 1554.940 nm), #5-1/#5-2 (λ_3 = 1553.328 nm) transmit and receive CPRI option 7 signal at 9.83 Gbps and Ethernet signals at 10.0 Gbps, respectively.

(b) Experimental Results

Figure 3(a) shows an event log during the restoration procedure recorded at the APN-C. This clearly shows that the restoration control was autonomously performed under the control of APN-C in accordance with the proposed sequence in Fig. 1(b). Figs. 3(b), (c) and (d) show the optical spectra before reconfiguration monitored at the points between Ph-GW #1 and #2, Ph-GW #1 and #3, and Ph-GW #3 and #2, respectively. Figs. 3(e), (f) and (g) show those after reconfiguration at the same points. At the initial setup, the optical spectra from UTs #1-2 (λ_1 = 1554.940 nm), #2-2 (λ_3 = 1553.328 nm) and #3-2 (λ_5 = 1551.720 nm) are observed at the metro port as shown in Fig. 3(b). As shown in Figs. 3(f) and (g), we can see that the optical paths has been restored and new wavelengths have been added to avoid the spectra of UT #4-2 and #5-2, which were originally present in Figs. 3(b) and (c), respectively. At this time, the same wavelength as that before the reconfiguration was re-assigned to UT pair #3-1/#3-2.

Figures 3(h), (i) and (j) show the transition of the received power of UT #1-1 (HDMI signal) and UT #2-1 (CPRI signal) and throughput of Ethernet signal received at UT #3-1, respectively. The reconfigurations for pairs of UTs #1-1/#1-2 and #2-1/#2-2 with wavelength reallocations were conducted sequentially. We also confirmed that the throughput of pairs of UTs #4-1/#4-2 and #5-1/#5-2 did not decrease. These results demonstrate that our proposed procedure realized remote control of TRx wavelength in UT even in the case of failure involving multi-protocol client signals.

4. Conclusion

We proposed a control method for in-service EtE optical paths carrying various client signals. The proposal enables several types of restoration schemes, in which the UT wavelength is reallocated as needed. An experiment using Ethernet, CPRI, and HDMI equipment successfully demonstrated the world's first operation of protocol-independent control for EtE optical paths in the APN.

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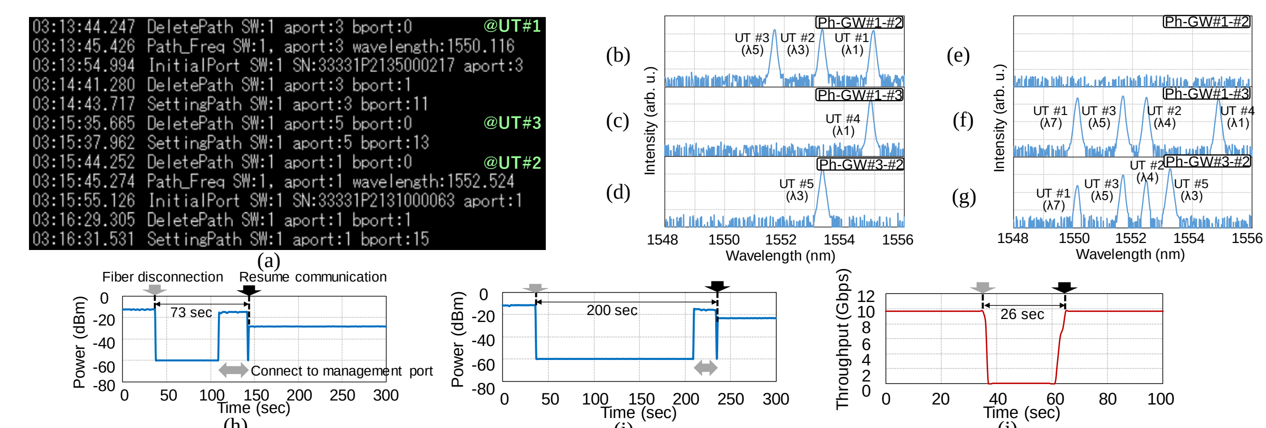

Fig. 3: Experimental results (a) Event log during restoration procedure, (b),(c),(d) Optical spectra before reconfiguration, (e),(f),(g) Optical spectra after reconfiguration, (h) Received power of HDMI signal, (i) Received power of CPRI signal, (j) Throughput of Ethernet signal