Optical Communications and Networks

Dynamic Optical Path Provisioning for Alien Access Links: Architecture, Demonstration, and Challenges

Hideki Nishizawa, Takeo Sasai, Takeru Inoue, Kazuya Anazawa, Toru Mano, Kei Kitamura, Yoshiaki Sone, Tetsuro Inui, and Koichi Takasugi

The authors propose an architecture and protocol for cooperative optical path design between a customer and carrier, utilizing a state-of-the-art technique for estimating link parameters.

ABSTRACT

With the spread of datacenter interconnect (DCI) and private 5G, there is a growing demand for dynamically established connections between customer locations via high-capacity optical links. However, link parameters, such as signal power profile and amplifier gains, are often unknown and have to be measured by experts, which prevents dynamic path provisioning because of time-consuming manual measurements. Several techniques have been proposed for estimating the unknown parameters of such alien access links; however, no work has presented the architecture and protocol driving the estimation techniques to establish an optical path between the customer locations. This study aims to automatically connect customer-owned transceivers via alien access links with maximum data rate. First, we propose an architecture and protocol for cooperative optical path design between a customer and carrier, utilizing a state-of-the-art technique for estimating link parameters. Second, we implement the proposed protocol in a software-defined networking controller and white-box transponders using an open API. The experiments demonstrate that the optical path is dynamically established via alien access links in 137 seconds from the transceiver’s cold start. Finally, we discuss the possible reduction of required OSNR margin with this method and the remaining issues.

INTRODUCTION

Digital coherent optical transmission technology was developed as a long-haul optical transmission technology. In the 2010s, with the advancement of silicon microfabrication technology, optical transmission technology has rapidly become more power efficient and modularized (with prices dropping over 25 percent/year), and is currently implemented in various user cases other than long-haul. The datacenter interconnect (DCI) market is rapidly expanding at a compound annual growth rate (CAGR) of more than 10 percent. In the private 5G network market, where the CAGR is approaching 50 percent, there is a rapidly growing demand for optical networks to connect private 5G radio units that are located far from each other. To satisfy the emerging demands for DCI and private 5G, optical paths need to be occasionally be rebuilt. In addition to DCI and private 5G, in an emergency such as a disaster, the network must be dynamically reestablished by finding an appropriate transceiver configuration for the damaged fiber within a short period. In public networks, if low-margin operation [1] becomes a regular practice for the effective use of optical resources, it is necessary to periodically update the transceiver configuration and routes before the quality of transmission (QoT) degrades. Moreover, it is desirable to directly connect customers with optical paths without optical-electrical-optical conversion whenever possible to reduce the power consumption, transceiver cost, and transmission latency caused by the conversion. Compared with the alien wavelength, which installs customer transceivers at carrier edges, the optical reach is extended to the customer site, providing a greater advantage by removing the OEO conversion at the carrier edges.

In practice, there are several challenges in dynamically setting up an optical path between customers. Optical paths often need to be set up through transmission links whose parameters (e.g., the optical signal power profile along the link and amplifier gains) must be re-measured, or whose components (e.g., fiber types) are unknown. This is because link owners do not always track the up-to-date status of links, and the link status may significantly deviate from installation or previous measurements owing to aging, accidents, and disasters. Therefore, the current link status must be measured by experts; however, it takes at least a few days for a carrier to set up an optical path in current operations. The goal of this work is to automatically configure an optical path with the maximum data rate over a transmission link whose current parameters are unknown. In this study, we define an alien access link (AAL) as an access network whose components, quality, and parameters are unknown, and consider a situation in which customer transceivers are connected to a carrier-managed network with AALs (Fig. 1).

Several studies have been conducted on dynamic path provisioning using AALs. Unprecedented advancements in digital signal processing and machine learning technologies have enabled receivers to estimate the QoT. The following two approaches have been proposed:

• Digital longitudinal monitoring (DLM): Estimates link parameters in a distance-wise and component-wise manner, such as the signal power...
profile, fiber types, and gain spectra of each amplifier [2, 3], which are then used by an optical path design tool [4] to estimate the QoT.

- Black-box approach: A characterized probing light with a fixed modulation format and symbol rate is inserted into the network, and the forward error correction (FEC) BER estimation of the receiver is used to estimate the end-to-end (E2E) QoT [5–7]. Once the QoT is estimated using these approaches, the optimal configuration can be set for the transceiver using an open API, such as the transponder abstraction interface (TAI) defined in the Telecom Infra Project (TIP). If necessary, the line system can be controlled using the OpenROADM YANG model or a similar model. Optical signals from AALs are likely to be alien wavelengths, which have been extensively researched [8]. Research is underway to establish optical paths beyond administrative boundaries, such as between customers and carriers (GMPLS [9] and alien wavelength [10]). Therefore, although these elemental technologies exist, the architectures and protocols required for the use cases described at the beginning of this article have not been studied.

The contributions of this article are as follows:

- We compare the two QoT estimation approaches, assuming that the transmission link between the carrier and customer is unknown. Upon clarifying the advantages and disadvantages of the two approaches, the remainder of this article focuses on the DLM approach because of its distance-based resolution, which is indispensable for fault diagnosis. Moreover, we discuss the potential of the DLM approach in reducing the required functions, for example, a DLM estimator, on a customer or carrier. The protocol is designed to exchange only disclosed information between a customer and carrier.

- Using the TAI of TIP, we implement the proposed protocol in a proprietary software-defined networking (SDN) controller and white-box transponder. We demonstrate that the optical path can be configured from a cold start without a significant temporal overhead. Moreover, we discuss the potential of the DLM approach in reducing the required functions (OSNR, BER, etc.) for maximum temporal overhead. Finally, the remaining research issues are discussed in detail, including those specific to practical applications.

### Network Model and Requirements

This work is based on the following simple network model (configuration and assumptions). We assume the configuration displayed in Fig. 1, in which the path traverses the customer transceiver, AAL, carrier-managed network, AAL, and the customer transceiver. Customer transceivers and the carrier line system may be produced by different vendors. The following assumptions were made in this study:

- **AALs:** For simplicity, only a single wavelength channel is used in this study (however, most of the arguments in this article are valid even if WDM is assumed). We assume that neither the customer nor the carrier knows the link parameters regardless of the owner.

### Optical Path Design Over AAL: A Review of Existing Approaches

This section presents two existing approaches that can be used for optical path design over AALs and discusses the corresponding advantages and disadvantages.

#### DLM: Optical Path Design Based on Link Parameter Estimation of AALs

The DLM technique [2] was used to estimate the parameters of AALs. The DLM estimates the physical characteristics distributed in the fiber-longitudinal direction by solely processing the received (Rx) signals without using traditional hardware testing instruments (OTDR, OSA, etc.). For instance, the

---

**FIGURE 1.** Alien access links directly connecting consumers.

(amplifier, filter, etc.) can be installed. The carrier knows the link parameters, whereas the customers do not.

- **Customer transceivers:** We assume coherent transceivers. Only the customers know the transceiver characteristics, that is, the OSNR at the transceiver output (TxOSNR), back-to-back bit error rate (BER) vs. OSNR, and the implemented functions. The route and wavelength used are given in advance; however, the method for selecting them is beyond the scope of this study. A secure channel is pre-constructed between the customers and carrier, through which the control information can be exchanged. Authentication is outside the scope of this study.

Here, we define the requirements for optical path configuration as follows: The transmitting customer sends an optical-path setup request to the customer. Our goal is to maximize the performance of the optical path through an AAL. Performance is defined as the bit rate per optical frequency range. The allowable BER was assumed to be the standard threshold, that is, $1 \times 10^{-12}$. The carrier and customers cooperatively configure an optimal optical path by calculating the link OSNR degradation caused by amplified spontaneous emission noise (OSNR,ase) and fiber non-linear noise (OSNR_nli). The customers configure the transceiver parameters (output power, bit rate, modulation format, FEC, etc.) for maximum link performance while considering the receiver sensibility. The configuration process is performed automatically, without human intervention, and should take at most 10 min to complete.
estimation of the fiber longitudinal power profile (PP), gain spectra of optical amplifiers (OAs), and frequency responses of optical filters have been successfully demonstrated. Unlike hardware-based testing, DLM is capable of “multi-span” measurement, which enables rapid and cost-efficient AAL monitoring. Additionally, DLM visualizes the entire line system, making it possible to optimize and identify/localize soft failures caused by link components, such as fibers, amplifiers, and filters. In this study, we focus on PP estimation (PPE).

Figure 2 illustrates the common configuration of the DLM. The key to PPE is fiber nonlinearity (self-phase modulation); the PP is obtained by estimating the distance-wise nonlinear phase rotation owing to its proportionality. An arbitrary signal emitted from the transmitter (Tx) propagates an AAL, and the received signal is then sent to the SDN controller, in which distance-wise nonlinearity is estimated via the DSP. Note that no special training or pilot signal is required for the Tx signal because it can be recovered at the receiver or SDN controller. To estimate the fiber nonlinearity caused in the link, transmission impairments, except for nonlinearity, are compensated. The demodulated signals and Tx signal recovered from the symbol decision (decoding and mapping, if possible) and Nyquist filtering are fed into the DLM algorithms. The distance-wise nonlinear phase rotation is obtained by performing least-squares [2] or cross-correlation [11].

In this approach, the optical path is established in the following steps:
1. The Tx customer requests the carrier to establish an optical path.
2. The customer sends its transceiver characteristics to the carrier via a secure channel.
3. The customer and carrier synchronously estimate AAL parameters.
4. The customer or carrier selects the transceiver mode using the estimated link parameters.
5. The customer configures the transceiver with the selected mode.

The advantage of this approach is that the main factors that degrade the line system (OSNR_ase, OSNR_nli) can be calculated. However, this approach presents the following two problems:
1. To calculate the OSNR value at the receiver end, the TxOSNR value is needed in addition to the line system’s estimated OSNR value;
2. The analysis of the received BER requires the receiver’s back-to-back characteristics, such as BER vs. OSNR, in addition to the line system QoT.

As described later, the proposed architecture and protocol enable carriers and customers to collaboratively exchange the TxOSNR and back-to-back characteristics; accordingly, the two problems can be resolved. Thus, the combination of the DLM and the proposed architecture and protocol enables accurate path design and reduces redundant margins, as described in a later section. However, because DLM uses fiber nonlinearity to estimate the above characteristics, their accuracy degrades at a practical launch power [2, 11].

**Black-Box Approach: Optical Path Design Based on E2E QoT Estimation with Receiver Pre-FEC BER**

The black-box approach selects the optimal transceiver configurations by E2E QoT estimation with a probing light without estimating the parameters of the AAL [5–7]. In this approach, the optical path is set up only by the customers, without any involvement from the carrier, except for the preparation of an empty channel. The black-box approach follows the steps outlined below:
1. The Tx customer requests the carrier to prepare an empty channel.
2. The carrier prepares the channel and notifies the customer of its wavelength.
3. The customer configures transceivers with the wavelength.
4. The customer selects the transceiver mode using the estimated conditions.
5. The customer configures the transceiver with the selected mode.

The advantage of the black-box approach is that the customer can solely implement the optical path, thus simplifying the system and eliminating the need to work with the carrier. However, the QoT cannot be decomposed into elements, such as OSNR_ase and OSNR_nli, because the link parameters of the line systems cannot be obtained; therefore, it is not possible to optimize the optical path or isolate the fault/locating of these elements. This fundamental problem in service operations is difficult to solve through architectural and protocol improvements.

Thus, the remainder of this article focuses on the DLM approach. We utilize the GNPy open design tool for optical path design [4] with QoT at exchanged transceiver parameters via the protocol described next, known carrier link parameters, and estimated access link parameters. GNPy assumes a Gaussian noise approximation that enables optical path design over a wide range of distances, from long-haul to metro, quickly and with sufficient accuracy. Reference [12] demonstrated QoT maximization with GNPy by collecting open-line system (OLS) parameters, and we focused on partially unknown OLS parameters.

**Proposed Architecture and Protocol**

The architecture and protocol are designed to resolve the problems discussed previously. The left-hand side of Fig. 3 illustrates the proposed architecture. To minimize the accuracy degradation in long-distance estimation, we divide the long E2E path into customer and carrier sections. An optical switch is placed at the carrier edge to divert the customer-side path to the measurement receiver of the carrier, which estimates the AAL parameters using signals from the customer transceiver. Customer transceivers and measurement receivers can communicate using predetermined standardized
interoperable modes [6]. The controller is mounted on the carrier and has a consistency check function and EtE path design function. The former selects common modes from the mode catalogs of the transceivers at user sites A and B. The latter inputs the link parameters estimated by the DLM and transceiver information into the optical path design tool, and designs the EtE optical path. The optical switch then reconnects the customer-side paths to establish the EtE path.

The information required to design the EtE optical path includes the link parameters in the access and carrier sections and the capability of customer transceivers. Here, carrier-link parameters are generally not disclosed to customers, whereas the configurable modes of the customer transceiver should be accessible from the carrier because it is necessary to manage the quality and safety of the network. Moreover, the proposed system allows for a connection between the transceivers of different vendors. Since configurable modes generally vary by vendor, generation, and version, the carrier requires a mechanism to automatically collect transceiver capability information and perform consistency checks.

Figure 3 depicts the overall architecture and protocol of the DLM approach. All components are handled by the carrier controller through a secure channel. Transceivers at user sites A and B are connected to optical switches at the carrier via AALs A and B, respectively. Both switches are connected through the carrier link and can switch the signal from the AAL to either the carrier link or the measurement receiver. The mode catalog (bitrate, modulation format, FEC type, etc.) is generated and sent to the carrier controller (see the upper right of Fig. 3). The controller compares the mode catalogs received from the transceivers to create a list of common modes (see the middle right of Fig. 3). If no interconnectable mode exists, an error is returned to the transceivers. The controller obtains a list of optical path routes from the carrier link in advance and connects transceivers at user sites to the measurement receivers at the carrier edges using switches. Subsequently, DLM is performed to estimate the link parameters of the AALs. All estimated link parameters are collected by the controller, which then calculates the EtE QoT, e.g., generalized SNR (GSNR), for each possible optical path route using an optical path design tool. The controller determines the optimal optical path route and transmission mode by referring to the optical path common mode list. If no interoperable mode exists, the controller returns an error to the transceiver. Finally, the path was established by connecting the AALs via the carrier link using switches.

**Evaluation of Proposed Scheme**

**Experimental Test**

We experimentally evaluated the proposed scheme and demonstrated that the optical path could be set up automatically within 137 s. First, the PP of the AAL was measured using DLM, and the GSNR was estimated by inputting the obtained physical layer parameters into GNPy. Figure 4 displays the experimental setup and the estimated PP. Two white-box transponders were placed at user sites A and B and connected through AAL A, the carrier link, and AAL B. These white-box transponders include the Cassini with Goldstone network operation system (NOS), which is openly specified by the TIP. NOS has a TAI library defined as a C header file, which disaggregates hardware and software in the control of coherent transceivers. Coherent modules from two different vendors were used and vendor dependencies were absorbed by the TAI library. This enabled transceivers from different vendors to be controlled in a unified manner.

The transmission section consists of AALs A and B, which connect the carrier and user and the carrier link. AAL A includes 50-km standard single-mode fibers (SMFs) and an erbium-doped fiber amplifier (EDFA). The AAL A parameters are shown in the lower part of Fig. 4. The carrier segment and AAL B consisted of short optical fibers (0.5 m each).

The optical switch can switch the signal from the AAL to the measurement equipment and the carrier link. We used the OpenROADM YANG model as a reference and developed a common-control interface for abstracting multivendor switches.

The controller has a proprietary implementation. It is connected to white-box transponders
and optical switches via control lines, and collects capability and QoT data from transceivers and measurement equipment. The controller utilizes GNPy to estimate the EtE QoT and determine the optimal configuration with the parameters of all links. Following that, the controller provides instructions for opening the optical path.

First, the PP of AAL A is estimated by the DLM by connecting the optical switch, as indicated by (1) in Fig. 4, which is used to estimate the fiber loss/OA gain for the input to GNPy. In this experiment, an offline experimental system was adopted to perform DLM; however, in the future, it will be possible to perform DLM using only a commercially available transceiver. The transmitter was installed on the carrier side, and when the DLM started, the signal was sent to AAL A via an optical switch to monitor the AAL. We used the same offline system used in [2]. The captured waveform on the customer side was sent to a network controller (PC), and demodulation and PPE were applied. For PPE, we used gradient learning of the split-step Fourier method (SSFM) for the Manakov equation [2]. The DLM output of AAL A is illustrated at the bottom of Fig. 4. The vertical axis represents the true optical power (dBm). The estimated PP closely matches the true profile. The fiber loss coefficients, fiber input power, and intermediate amplifier gain were estimated from the PP obtained by linear fitting. While the true values were 0.186 dB/km for the fiber loss coefficients, 5.0 dBm for the fiber input power, and 9.42 dB for the amplifier gain, the estimated values were 0.175 dB/km (1st span) and 0.212 dB/km (2nd span) for the fiber loss coefficients, 4.47 dBm (1st span) and 4.54 dBm (2nd span) for the fiber input power, and 8.83 dB for the amplifier gain. For the carrier link, it is assumed that the link parameter is known, because it is managed by the carrier. For simplicity, only AAL A is used for the DLM estimation; however, the same method can be used to estimate the transmission quality of the carrier link. Additionally, for the transceiver performance parameters (TxOSNR, BER vs. OSNR), we assume that their values are known because they can be obtained from the controller using the architecture and protocol described earlier.

Upon completing the DLM for the AAL, the switch is changed to (2), and the link parameters of AAL A, AAL B, and the carrier link are input to GNPy. The GSNR of the EtE transmission quality was estimated. The transceiver used in this experiment supports a 100 Gb/s dual-polarization (DP) QPSK 32GBd and 200 Gb/s DP-16QAM 32GBd. In this experiment, the GSNR total was sufficiently large to achieve error-free operation even at 200 Gb/s; therefore, the 200 Gb/s mode with a high bit rate per optical frequency bandwidth was automatically selected as the optimal configuration. Using either the true or estimated values of the link parameters, we set the transceiver to the same configuration, 200 Gb/s DP-16QAM 32GBd. It means that our approach is sufficiently accurate to optimally establish the optical path. An optical link was established between the transceivers at user sites A and B to verify error-free operations.

Table 1 summarizes the time required to set up the optical path. The DLM preprocessing is the demodulation process for generating inputs to the DLM, as shown in Fig. 2. The DLM time is the time taken from the start to the end of iterative learning of the SSFM. The total link parameter estimation time is 36 + 27 = 63 s to design the optical path using GNPy for approximately 73 s to boot the transceiver from the initial state. The optical path was automatically constructed for approximately 137 s.

**Potential of Reduction in Required Margin**

This subsection discusses the extent to which the proposed approach can reduce the OSNR margin. Because OSNR estimation inevitably has an error without knowledge of the link parameters, the optical path must be designed for the worst-case estimation. The maximum difference between the true and estimated values is referred to as the margin. If the proposed approach accurately estimates the link status, the margin can be reduced, enabling us to improve spectrum efficiency.

The required OSNR margin consists of the OSNR_ase and OSNR_nli margins. The former is the margin for power losses caused by aging OA, connector losses, fusion splicing losses, etc. The latter is the margin of nonlinear noise. In this section, we discuss the former power loss margin that can be reduced using the proposed scheme. Here, we define the required OSNR margin as the amount of OSNR degradation at the Rx when additional 2-dB losses occur in all spans. The assumptions of the power profile are presented in the upper part of Fig. 5. The fiber input power was uniformly set to 0 dBm for all the links. The span loss was assumed to be 16 dB under normal conditions (0.2 dB/km, equivalent to 80 km standard); however, the loss can have a +2 dB error depending on the optical fiber conditions. The
The required OSNR margins, as a function of the total span number, are illustrated in the lower part of Fig. 5. Here, the Tx OSNR is the OSNR at the output of the coherent transceiver. In a longer-distance regime, the effect of the in-line amplifier becomes dominant. In this regime, an additional span loss of 2 dB always causes an OSNR degradation of approximately 2 dB. In the case of short spans, TxOSNR is the dominant factor for the received OSNR, so the effect of the additional 2-dB span loss is smaller. However, when a high TxOSNR is assumed, the effect of ASE noise in the in-line amplifier becomes dominant and the required OSNR margin approaches 2 dB. This 2 dB margin can be eliminated if the DLM has infinite accuracy. Note that the accuracy of DLM at this time is rather limited; however, the theoretical work of DLM [13] indicates that the accuracy and spatial resolution of DLM is potentially high to fit the theoretical power profile. The above required OSNR margins can be reduced in the future when the DLM can achieve an accuracy comparable to that of OTDRs.

REMAINING RESEARCH ISSUES

While the DLM approach offers various advantages, the challenge is to develop low-cost measurement equipment and optical switches in the carrier network. In our experiment, a single wavelength was used for simplicity; however, it is necessary to examine the effects of the wavelength dependence of OAs and fiber nonlinear effects when deploying DLM in WDM. It is also necessary to solve problems related to accommodation design, such as available wavelength assignment in the carrier link and optical path route design, which are discussed at the IOWN Global Forum [14].

The number of transceiver modes has increased as DSP LSIs have evolved. There is an urgent need for a method to efficiently select the optimal mode without measuring the QoT characteristics of each mode [4]. A method of selecting the optimal format without trying all of them, which is only a selection of the modulation format, was studied in [6]. The method requires the BER-OSNR characteristics of the customer’s transceiver; however, there is no open API to obtain them. If the transceiver characteristics can be obtained, it will be possible to estimate the OSNR more accurately based on the individual differences of transceivers, which is expected to reduce the margins or improve the spectrum efficiency.

Regarding the confidentiality of the link parameters between the customer and carrier, in this study, we assumed that the carrier obtains the estimated link parameters; however, the customer may not allow the carrier to obtain the parameters. In virtual networks, cryptographic techniques, such as secure multiparty computation, have been proposed to set up virtual paths without disclosing information [15]. A similar approach can be used in optical transmission networks to select the optimal transceiver mode without revealing the link parameters of the optical path.

As described in the beginning, optical path setting requests may be concentrated on carriers as the frequency of optical transmission network usage and number of optical lines increase. Such concentrated requests are often observed in mobile networks where admission control has been introduced. However, as observed in our experiments, optical path setting requires more time than mobile terminal registration, so it cannot be used as is for optical path setting. In particular, at the time of a large-scale failure due to a disaster, not only do all terminals request reconnection again upon recovery, but the estimation process cannot be omitted because the link parameters of the optical path may have changed due to the disaster. Thus, there is a need for a new admission control that is optimized for optical path settings.

CONCLUSION

We propose an architecture and protocol for cooperative optical path design between carriers and customers. The protocol utilizes DLM, a technique for estimating optical link parameters, to automatically configure the optical path with a maximum data rate between customer-owned transceivers connected via AALs, whose link parameters are unknown, and carrier-managed networks. The DLM enables the estimation of OSNR_ase and OSNR_nli and reduces the required margin for receiver-end OSNR degradation by up to 2 dB for each span, assuming a 2 dB increase in span loss. Our experiments verified that the proposed architecture and protocol enabled the customer to optimize and establish an E2E optical path that included AALs in approximately 137 s.

REFERENCES

[1] M. Filer et al., “Low-Margin Optical Networking at Cloud Scale,” J. Optical Commun. and Net., vol. 11, issue 10, 2019, pp. C94–C108.
[2] T. Sasai et al., “Digital Longitudinal Monitoring of Optical Fiber Communication Link,” J. Lightwave Tech., vol. 33, no. 8, Apr. 2022.
[3] T. Tanimura et al., “Concept and Implementation Study of Advanced DSP-Based Fiber-Longitudinal Optical Power Profile Monitoring toward Optical Network Tomography,” J. Opt. Commun. and Net., vol. 13, no. 10, Oct. 2021.
[4] V. Curri, “GNPy Model of the Physical Layer for Open and Disaggregated Optical Networking,” J. Opt. Commun. and Net., vol. 14, issue 6, 2022, pp. C92–C104.
[5] K. Kaewal et al., “QoT Assessment of the Optical Spectrum as A Service in Disaggregated Network Scenarios,” J. Opt. Commun. and Net., vol. 13, no. 10, Oct. 2021.
[6] K. Anazawa et al., “Automatic Modulation-Format Selection with White-Box Transponders: Design and Field Trial,” OECC 2021, paper JS2A14.
[7] A. Gouin et al., “Real-Time Optical Transponder Prototype with Autonegotiation Protocol for Software Defined Networks,” J. Opt. Commun. and Net., vol. 13, no. 9, Sept. 2021.
[8] L. Alahdab et al., “Alien Wavelengths over Optical Transport Networks,” J. Opt. Commun. and Net., vol. 10, no. 11 Nov. 2018.
[9] L. Liu et al., “Field and lab trials of PCE-based OSNR-Aware Dynamic Restoration in Multi-Domain GMPLS-Enabled Transparent WSON,” Proc. Netw. Perform. Conf., vol. 19, no. 27 Dec. 2011.
[10] A. M. Fagertun and B. Skjoldstrup, “Flexible Transport Network Expansion via Open WDM Interface,” Int’l Conf. Computing, Networking and Commun., Optical and Grid Networking Symp., 2013.
[11] T. Tanamura et al., “Fiber-Longitudinal Anomaly Position Identification over Multi-Span Transmission Link Out of Receiver-End Signals,” J. Lightwave Tech., vol. 38, issue 9, 2020, pp. 2726–33.
[12] T. Sasaki et al., “Closed-Form Expressions for Fiber-Nonlinearity-Based Longitudinal Power Profile Estimation Methods,” Proc. Eur. Conf. Opt. Commun., Basel, Switzerland, Sept. 2022, Paper Tu1D.6.
[13] G. Borraccini, “Using QoT for Open Line Controlling and Modulation Format Deployment: An Experimental Proof of Concept,” ECOC 2020.
[14] IOWN Global Forum Technical Paper, “Open ALL-Photonic Network Functional Architecture 1.0,” Jan. 2022.
[15] T. Mano et al., “Efficient Virtual Network Optimization Across Multiple Domains Without Revealing Private Information,” IEEE Trans. Network and Service Management, vol. 13, issue 3, Sept. 2016.

BIographies
Hideki Nishizawa (hideki.nishizawa.zw@hco.ntt.co.jp) received B.E. and M.E. degrees in physics from Chiba University, Chiba, Japan, in 1994 and 1996, respectively. In 1996, he joined NTT Laboratories, Japan, where he has been engaged in research on open and disaggregated optical systems.
Takero Inoue received B.E. and M.E. degrees in electrical engineering from the University of Tokyo, Japan, in 2014 and 2016, respectively. In 2016, he joined NTT Laboratories, Japan, where he has been engaged in research on optical fiber link.
Takeru Inoue received his Ph.D. in information science from Kyoto University, Japan, in 2006. He joined NTT Laboratories in 2000 and currently serves as a Distinguished Researcher.
Kazuya Anazawa received his B.E. and M.E. degrees from the University of Aizu in 2016 and 2018, respectively. He joined NTT Laboratories in 2018. His current research interests are autonomous control of optical transport networks.
Toru Mano received B.E. and M.E. degrees from the University of Tokyo in 2009 and 2011, respectively. He joined NTT Labs in 2011. He received the Ph.D. degree in computer science and information technology from the Hokkaido University in 2020. His research interests are network architectures, network optimization, software-defined networking.
Kei Kitamura received B.E., M.E. degrees in information and communication engineering from the University of Electro-Communications, Tokyo, Japan, in 2008 and 2010, respectively. In 2010, he joined NTT Laboratories and has been engaged in research on network interfaces and large-capacity transmission systems.
Yoshio Sone received his M.E. degree in electronics engineering from Tohoku University, Miyagi, in 2003. In 2003, he joined NTT Laboratories to focus his research on network engineering technologies for optical transport networks.
Tetsuro Inui received his B.E. degree in electric engineering from Waseda University, Tokyo, Japan in 1995 and M.E. degree in electronic engineering from the University of Tokyo, in 1998. In 1998, he joined NTT Laboratories, Japan, where he has been engaged in research on high-speed optical transport systems and optical transport network architecture.
Koichi Takasugi received the B.E. degree in computer science from Tokyo Institute of Technology in 1995, the M.E. degree from Japan Advanced Institute of Science and Technology in 1997 and Ph.D. in engineering from Waseda University in 2004. In 1997, he joined NTT Laboratories, Japan, where he has been engaged in research on wireless and optical transport networks.