First Field Demonstration of Automatic WDM Optical Path Provisioning over Alien Access Links for Data Center Exchange

Toru Mano(1), Thomas Ferreira de Lima(2), Yue-Kai Huang(2), Zehao Wang(3), Wataru Ishida(4), Ezra Ip(2), Andrea D'Amico(5), Seiji Okamoto(1), Takeru Inoue(1), Hideki Nishizawa(1), Vittorio Curri(5), Gil Zussman(6), Daniel Kilper(7), Tingjun Chen(3), Ting Wang(2), Koji Asahi(8), Koichi Takasugi(1)

(1) NTT Network Innovation Labs, Kanagawa Japan, toru.mano@ntt.com (2) NEC Labs America, Princeton, USA, (3) Duke University, Durham, NC, USA, (4) NTT Software Innovation Center, Tokyo, Japan, (5) Politecnico di Torino, Torino, Italy, (6) Columbia University, New York, USA, (7) CONNECT Centre, Trinity College Dublin, Ireland, (8) NEC Corporation, Chiba, Japan.

Abstract *We demonstrated under six minutes automatic provisioning of optical paths over field-deployed alien access links and WDM carrier links using commercial-grade ROADMs, whitebox muxponders, and multi-vendor transceivers. With channel probing, transfer learning, and Gaussian noise model, we achieved an estimation error (Q-factor) below 0.7 dB. ©2023 The Author(s)*

Introduction

With the emergence of technologies like AI and private 5G, the demand for computing resources has rapidly grown, expanding data center (DC) footprints[1]. To provide low-latency edge services, overcome limitations in regional power generation, and increase the robustness to natural disasters[2], new DCs need to be geographically distributed[3], resulting in a rapidly rising market for data center interconnects (DCI)[4]. To satisfy the evolving user and service demands, there have been discussions on providing data center exchange (DCX) services that offer flexible and on-demand interconnections among geographically distributed DCs using WDM optical paths and multi-vendor transceivers[5]. Realizing these DCX services requires the automation of WDM optical path provisioning that can estimate the quality of transmission (QoT) and accordingly configure transceivers servicing carrier links (CLs) and *unknown* user access links, or *alien* access links (AALs)[6].

A few provisioning methods have been proposed under unknown link parameters. One study[7] proposed a channel-probing method and demonstrated excellent QoT estimation accuracy with field fibers in the context of optical spectrum as a service, which promising for DCX in that it connects CLs and AALs whose parameters are unknown. However, this approach did not address the challenges of real time automation. Another study[6] proposed an architecture and protocol that enables the carrier to automatically provision an optical path under unknown AAL parameters. The proposed method quickly provisions an optical path by leveraging an analytical fiber propagation model. However, it was limited to laboratory experiments and single-wavelength transmission.

This paper demonstrates, for the first time, automatic WDM optical path provisioning over field-deployed AALs with multi-vendor transceivers. A channel probing method[7] gauges the QoT for a particular WDM setting. Based on the probed result, the QoTs for various WDM settings are estimated using a transfer-learning technique that predicts complex amplifier gain profiles[8] and an open-source planning tool, GNPy[9], to compute transmission impairments based on an approximate analytical fiber propagation model[10]. A field demonstration emulating DCX was conducted with Open ROADM[11] compliant transceivers of different vendors in combination with commercial-grade reconfigurable optical add-drop multiplexer (ROADM) units. We successfully provisioned WDM optical paths on-demand at the maximum achievable bit rate along with dozens of other wavelengths in under six minutes with less than 0.7 dB Q-factor estimation error, despite unknown AAL parameters.

Field Trial Setup and Experiment Scenario

Figs. 1(a) and (b) show the field trial setup using the COSMOS testbed, a city-scale programmable testbed deployed in Harlem, NYC[12]. The COSMOS testbed provides a programmable optical networking environment, including optical space switches, Lumentum ROADM-20 units, and Manhattan dark fibers. Two dark fiber routes were used; a 32 km loop-back field fiber route between Columbia University and a colocation data center at 32 Avenue of the Americas and an 8 km loop-back field fiber route between Columbia University and the City College of New York. We deploy whitebox muxponders, which comply with Telecom Infra Project's (TIP's) Phoenix requirements[13], and installed NEC's network operating system (NOS) which is based on the TIP Goldstone NOS[14]. These muxponders utilize Open ROADM compliant 400G CFP2-DCO pluggable transceivers from Fujitsu Optical Components and Lumentum.

We built a transmission system similar to the DCX environment that consists of two user sites (`site1` and `site2`), two AALs (`AAL1` and `AAL2`), and two CLs (`short` and `detour`) (Fig. 1(b)). Both user sites have a muxponder that connects to an

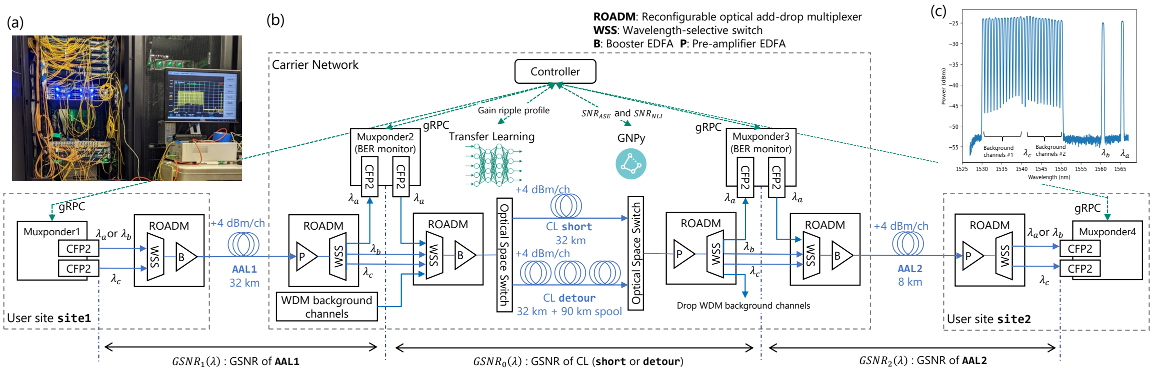

Fig. 1: (a) Equipment in COSMOS testbed. (b) Field trial setup. (c) WDM spectrum setup.

AAL. The first AAL, `AAL1`, consists of a ROADM and 32 km field fiber and connects to a CL. The second AAL, `AAL2`, consists of a ROADM and 8 km field fiber. The `short` and `detour` CLs have different length and losses for different link conditions, with a total of 25 WDM background channels inserted to emulate existing in-service channels (Fig. 1(c)). Two muxponders are placed at the boundaries between AAL and CL for pre-FEC BER probing measurements.

Our aim is to automatically provision the optical path between the user sites with the requested capacity without human intervention within 10 minutes[6] under the following five assumptions. (1) The AAL link parameters are unknown (fiber type, length, loss, dispersion, etc.). The carrier knows the CL's link parameters. (2) The user knows the transceiver characteristics: the implemented operational modes and back-to-back (B2B) BER-OSNR curves, but the carrier does not. (3) The user and carrier are allowed to probe the links, using only the dedicated edge channel, to avoid interference with existing in-service channels. In this study, the dedicated probe channel is 191.5 THz, λ_a, at the edge of the C-band. (4) CL route and available channels are given in advance. In this study, the route is either `short` or `detour`. The available channels are 192.1 THz, λ_b, and 194.6 THz, λ_c. The first channel, λ_b, is located outside of the background channels, while the second one, λ_c, is situated inside for different channel conditions (Fig. 1(c)). (5) The user and carrier have a pre-established secure channel to exchange control information.

Automatic Provisioning Method

We implemented the controller for automatic WDM path provisioning (Fig. 1(b)). This controller interacts with the muxponders in user sites and carrier boundaries through the pre-established secure channel using gRPC. Although we used multi-vendor transceivers, the controller can interact with them in a vendor-agnostic manner thanks to the Transponder Abstraction Interface[15]. This controller receives a path request, gathers transceiver characteristics, measures the

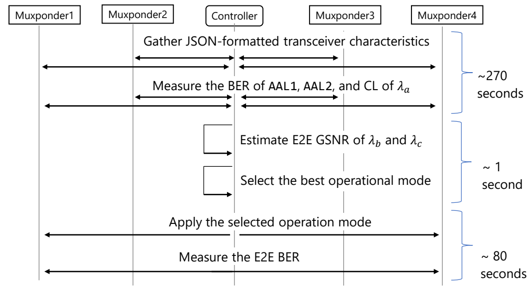

Fig. 2: Automatic provisioning overview and elapsed time.

BER of each link via the probe channel λ_a, estimates end-to-end (E2E) GSNR of available channels λ_b and λ_c, and selects and applies the best operational mode to the muxponders (Fig. 2).

First, upon receipt of a path request consisting of two endpoints and transmission capacity, e.g., `site1` and `site2` with 400G, the controller gathers JSON-formatted transceiver characteristics. These JSON files contain implemented operational modes and B2B BER-OSNR curves.

Then, the controller interacts with the four muxponders to measure the BER of the two AALs (`AAL1` and `AAL2`) and the CL (`short` or `detour`) using the probe channel λ_a. We configure the ROADMs in advance so that the probe signal was added and dropped at the boundaries of each link. Together with B2B BER-OSNR curves, the controller converts the measured BER to the GSNR of AALs and CL for the probe channel λ_a.

Next, the controller estimates E2E GSNR of available channels λ_b and λ_c. We employ the additive white Gaussian noise channel model[10], so the E2E GSNR $\mathrm{GSNR_{E2E}}$ of an arbitrary channel ζ can be represented by each link's GSNR as $\mathrm{GSNR_{E2E}}(\zeta)^{-1} = \sum_{i=0}^{2} \mathrm{GSNR}_i(\zeta)^{-1}$ where GSNR_0, GSNR_1, GSNR_2 are GSNR of CL, `AAL1`, `AAL2`, respectively. We can approximate $\mathrm{GSNR}_1(\zeta)$ and $\mathrm{GSNR}_2(\zeta)$ with the probed ones, $\mathrm{GSNR}_1(\lambda_a)$ and $\mathrm{GSNR}_2(\lambda_a)$, because the AALs have a limited number of channels and are relatively short. Conversely, the CL has dozens of WDM channels and is relatively long in the `detour` route. So we need to estimate GSNR by combining the QoT estimation and EDFA profile estimation methods, described as follows. Assuming the simple

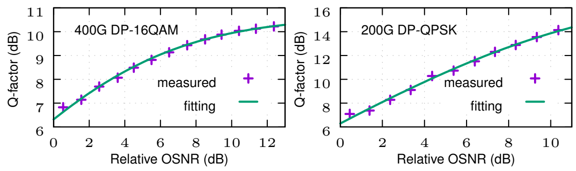

Fig. 3: Measured and fitting curves of B2B BER-OSNR.

ROADM filtering penalty model[10], the GSNR of CL can be represented as $\mathrm{GSNR}_0(\zeta)^{-1} = F \cdot \left(\mathrm{SNR}_{\mathrm{ASE}}(\zeta)^{-1} + \mathrm{SNR}_{\mathrm{NLI}}(\zeta)^{-1}\right)$ where F is the ROADM filtering penalty, $\mathrm{SNR}_{\mathrm{ASE}}$ and $\mathrm{SNR}_{\mathrm{NLI}}$ are the SNR values for ASE and NLI noises, respectively. Both $\mathrm{SNR}_{\mathrm{ASE}}$ and $\mathrm{SNR}_{\mathrm{NLI}}$ can be estimated via a QoT estimation tool like GNPy[9]. Thus, we can estimate $\mathrm{GSNR}_0(\zeta)$ as

$$\mathrm{GSNR}_0(\lambda_a) \cdot \frac{\mathrm{SNR}_{\mathrm{ASE}}(\lambda_a)^{-1} + \mathrm{SNR}_{\mathrm{NLI}}(\lambda_a)^{-1}}{\mathrm{SNR}_{\mathrm{ASE}}(\zeta)^{-1} + \mathrm{SNR}_{\mathrm{NLI}}(\zeta)^{-1}}$$

from the measured $\mathrm{GSNR}_0(\lambda_a)$ and estimated $\mathrm{SNR}_{\mathrm{ASE}}$ and $\mathrm{SNR}_{\mathrm{NLI}}$ by using GNPy. Note that since the EDFA gain profile, which affects $\mathrm{SNR}_{\mathrm{ASE}}$ and $\mathrm{SNR}_{\mathrm{NLI}}$, depends on the WDM configuration, we estimated the gain ripple profile using a pre-trained model by the transfer learning[8] and input it to GNPy in the estimation process. The GNPy estimation used the following parameters: fiber loss is 0.22 dB/km; chromatic dispersion is 16.7 ps/nm/km; fiber nonlinearity is 1.27 W^{-1}/km; link losses of the `short` and `detour` are respectively 13.3 dB and 36.4 dB; noise figures of the booster and pre-amplifier are respectively 5.9 dB and 7.6 dB. The link losses were measured directly and other parameter values were taken from data sheets.

Then, after estimating $\mathrm{GSNR}_{\mathrm{E2E}}(\lambda_b)$ and $\mathrm{GSNR}_{\mathrm{E2E}}(\lambda_c)$, the controller seeks the path configurations that uses the fewest channels that satisfy the following two conditions. (i) Total capacity of the paths matches the user request, e.g., 400G. (ii) All paths have at least 3 dB GSNR margin to the FEC limit, e.g., 2.0×10^{-2} BER for oFEC. This GSNR margin is calculated based on the B2B BER-OSNR curve of the receiver.

Finally, the controller applies the selected mode to the muxponders and measures the BER to ensure that the secured margin is at least 3 dB.

Results

We first measured the B2B BER-OSNR and computed the fitting curves[16] for the BER-GSNR conversion and GSNR margin calculations. Fig. 3 shows the results of the receiver at `site2`. The other results are similar and were omitted. The fitting curves agree well with the measured points, and the fitting error in Q-factor is around 0.1 dB.

We set the user-requested capacity to 400G for `short` and `detour` routes. Tab. 1 shows the measured BER and converted GSNR (dB) for AALs and CL. Combining these measured GSNR values and GNPy and transfer learning, our controller estimated E2E GSNR and provisioned the optical paths (Tab. 2). As for the `short` route, our controller successfully selected the single 400G DP-16QAM path using λ_b with a 5.2 dB secured GSNR margin. As for the `detour` route, our controller also successfully selected the two 200G DP-QPSK paths using λ_b and λ_c since 400G DP-16QAM is not error-free due to the low E2E GSNR. The secured margins for these two paths were 5.1 dB and 4.9 dB. In all cases, the differences between the estimated and measured Q-factor (BER) were less than 0.7 dB.

Tab. 1: Measured BER (GSNR in dB)

Route	AAL1	CL	AAL2
short	1.24e-3(23.3)	1.03e-3(23.9)	5.64e-4(27.2)
detour	1.14e-3(23.6)	1.75e-3(12.4)	1.21e-3(23.0)

Tab. 2: Estimated $\mathrm{GSNR}_{\mathrm{E2E}}$, selected mode, secured margin, estimated Q-factor, and measured Q-factor

Route	Ch	GSNR	Mode	Margin	Est. Q	Mes. Q
short	λ_b	19.7 dB	400G	5.2 dB	8.76 dB	9.40 dB
detour	λ_b	11.7 dB	200G	5.1 dB	10.6 dB	11.2 dB
detour	λ_c	11.6 dB	200G	4.9 dB	10.5 dB	10.9 dB

The total provisioning time was 351 seconds, broken down as follows. Link BER measurements took 270 seconds, E2E GSNR estimation and mode selection took under one second, and E2E configuration and BER measurement took 80 seconds (Fig 2). Most of the time is spent on changing the transceiver configurations during the BER measurements. We administratively halted the transceiver for every configuration to ensure a stable transition, each requiring around a minute. Using the dedicated probe channel contributes to fast provisioning because the BER measurements dominate the provisioning time. If we measured the BER of all available channels, the provisioning time would increase as the number of channels increases. Our approach keeps the BER measurement time constant even if the number of available channels increases, because the GSNRs of multiple channels are estimated from the probe channel measurement.

Conclusion

We have provided the first demonstration of automatic provisioning of optical paths over field-deployed AALs and WDM CLs using commercial-grade ROADMs, whitebox muxponders, and multi-vendor transceivers. The achieved performance (under six minutes with less than 0.7 dB QoT estimation error) represents a fundamental milestone towards the creation of automated DCX services.

Acknowledgements

We thank Rob Lane and the CRF team (Columbia), Lumentum, FOC, and the TIP OOPT group for their support. This work was supported by NSF grants CNS-1827923, OAC-2029295, CNS-2112562, CNS-2128638, EEC-2133516, CNS-2148128, CNS-2211944, and SFI under Grant No. 13/RC/2077 P2.

References

[1] Y. Lu and H. Gu, "Flexible and scalable optical interconnects for data centers: Trends and challenges", *IEEE Communications Magazine*, vol. 57, no. 10, pp. 27–33, 2019. DOI: 10.1109/MCOM.001.1900326.

[2] NTT East Corporation. (2012). Recovering from the great east japan earthquake, [Online]. Available: https://www.ntt-east.co.jp/info/detail/pdf/shinsai_fukkyu_e.pdf (visited on 04/20/2023).

[3] V. Dukic, G. Khanna, C. Gkantsidis, T. Karagiannis, F. Parmigiani, A. Singla, M. Filer, J. L. Cox, A. Ptasznik, N. Harland, W. Saunders, and C. Belady, "Beyond the mega-data center: Networking multi-data center regions", in *Proceedings of the ACM SIGCOMM*, 2020, pp. 765–781. DOI: 10.1145/3387514.3406220.

[4] C. Xie and B. Zhang, "Scaling optical interconnects for hyperscale data center networks", *Proceedings of the IEEE*, vol. 110, no. 11, pp. 1699–1713, 2022. DOI: 10.1109/JPROC.2022.3178977.

[5] IOWN Global Forum. (2023). IOWN global forum, [Online]. Available: https://iowngf.org/ (visited on 04/20/2023).

[6] H. Nishizawa, T. Sasai, T. Inoue, K. Anazawa, T. Mano, K. Kitamura, Y. Sone, T. Inui, and K. Takasugi, "Dynamic optical path provisioning for alien access links: Architecture, demonstration, and challenges", *IEEE Communications Magazine*, pp. 1–7, 2023. DOI: 10.1109/MCOM.006.2200567.

[7] K. Kaeval, T. Fehenberger, J. Zou, S. L. Jansen, K. Grobe, H. Griesser, J.-P. Elbers, M. Tikas, and G. Jervan, "Qot assessment of the optical spectrum as a service in disaggregated network scenarios", *Journal of Optical Communications and Networking*, vol. 13, no. 10, E1–E12, Oct. 2021. DOI: 10.1364/JOCN.423530.

[8] Z. Wang, D. Kilper, and T. Chen, "Transfer learning-based roadm edfa wavelength dependent gain prediction using minimized data collection", in *Proceedings of the Optical Fiber Communication Conference (OFC)*, Optica Publishing Group, 2023, Th2A.1.

[9] Telecom Infra Project. (2023). GNPy: Optical route planning and DWDM network optimization github site, [Online]. Available: https://github.com/Telecominfraproject/oopt-gnpy (visited on 04/20/2023).

[10] V. Curri, "Gnpy model of the physical layer for open and disaggregated optical networking [invited]", *Journal of Optical Communications and Networking*, vol. 14, no. 6, pp. C92–C104, 2022. DOI: 10.1364/JOCN.452868.

[11] OpenROADM. (Aug. 2022). OpenROADM MSA specification ver 5.1, [Online]. Available: https://openroadm.org/ (visited on 05/01/2023).

[12] T. Chen, J. Yu, A. Minakhmetov, C. Gutterman, M. Sherman, S. Zhu, S. Santaniello, A. Biswas, I. Seskar, G. Zussman, and D. Kilper, "A software-defined programmable testbed for beyond 5g optical-wireless experimentation at city-scale", *IEEE Network*, vol. 36, no. 2, pp. 90–99, 2022. DOI: 10.1109/MNET.006.2100605.

[13] Telecom Infra Project. (Dec. 2021). First demonstration of TIP Phoenix at NTT R&D Forum, [Online]. Available: https://telecominfraproject.com/first-demo-tip-phoenix-ntt-rd-forum/ (visited on 05/01/2023).

[14] Telecom Infra Project. (2023). Goldstone: Transponder abstraction interface, [Online]. Available: https://github.com/oopt-goldstone/goldstone-mgmt (visited on 05/01/2023).

[15] Telecom Infra Project. (2023). TAI: Transponder abstraction interface, [Online]. Available: https://github.com/Telecominfraproject/oopt-tai (visited on 04/27/2023).

[16] T. Mano, A. D'Amico, E. Virgillito, G. Borraccini, Y.-K. Huang, K. Anazawa, H. Nishizawa, T. Wang, K. Asahi, and V. Curri, "Modeling transceiver ber-osnr characteristic for qot estimation in short-reach systems", in *Proceedings of the International Conference on Optical Network Design and Modeling (ONDM)*, to appear, 2023.