Development of Disaggregated Optical Systems and its implementation with Optical Network Digital Twin technology

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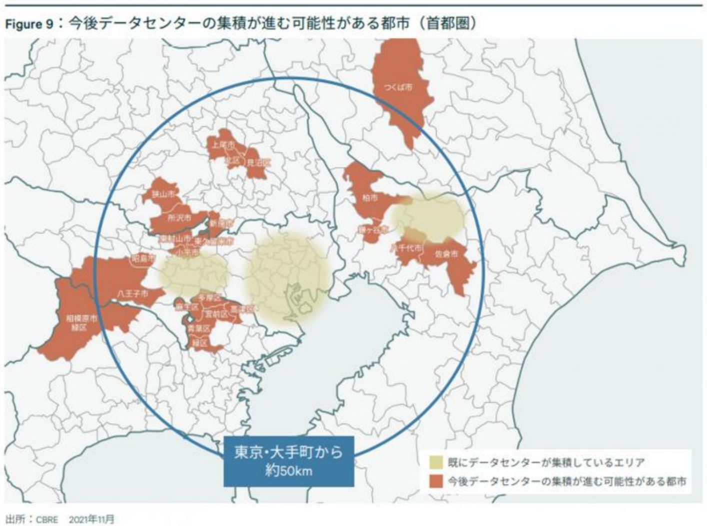
Outline

- Emerging DCI
- Leveraging the Optical Network Digital Twin for Distributed Data Centers
- Requirements, Challenges and field validation: Transponder, Controller, Line system
- Next Challenge: Multiple LLM-based Agent
- Conclusion

Background: Emerging DCI

- CAGR=13~14% (other WDM = 2%)



Metropolitan areas where data center concentration may increase (Source: CBRE)

- To provide AI and cloud services with low latency, demand for data centers near users is increasing.
- To ensure data security and privacy, data is being placed in geographically specified regions.
- Due to regional power supply limitations and insufficient locations, the expansion of data centers and the networks connecting them is accelerating.

Background:
The Evolution of Digitalization and Standardization

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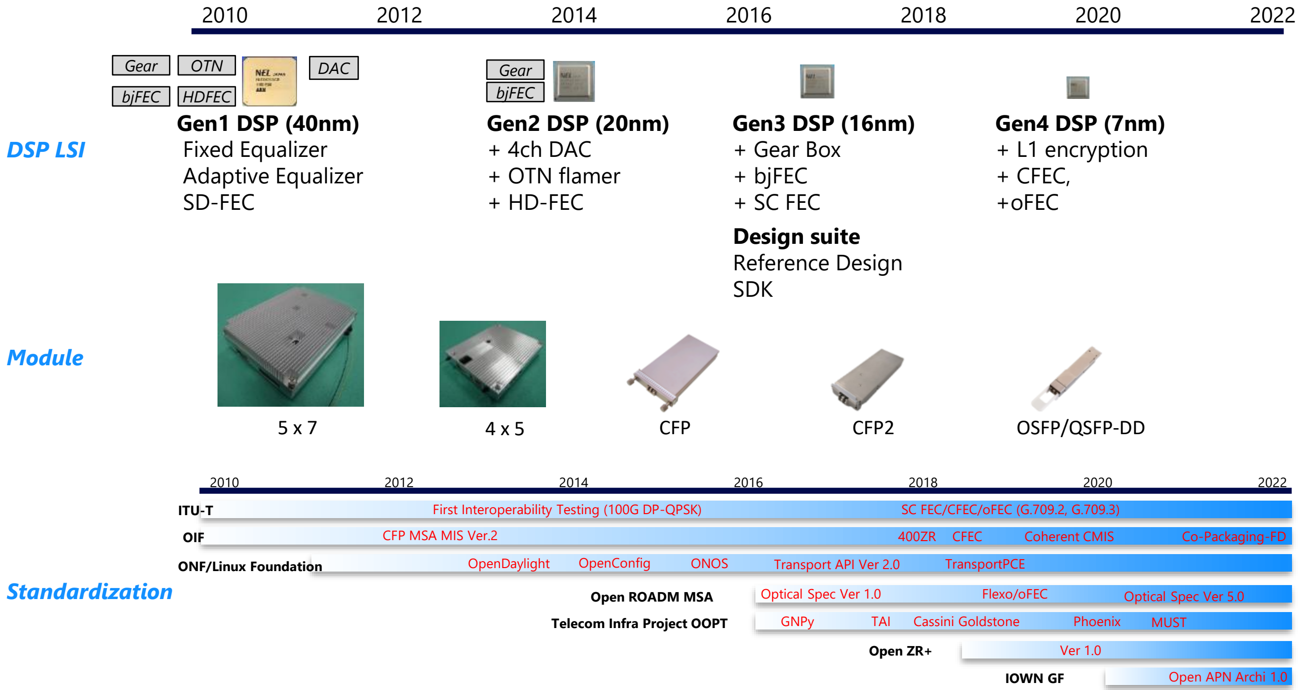
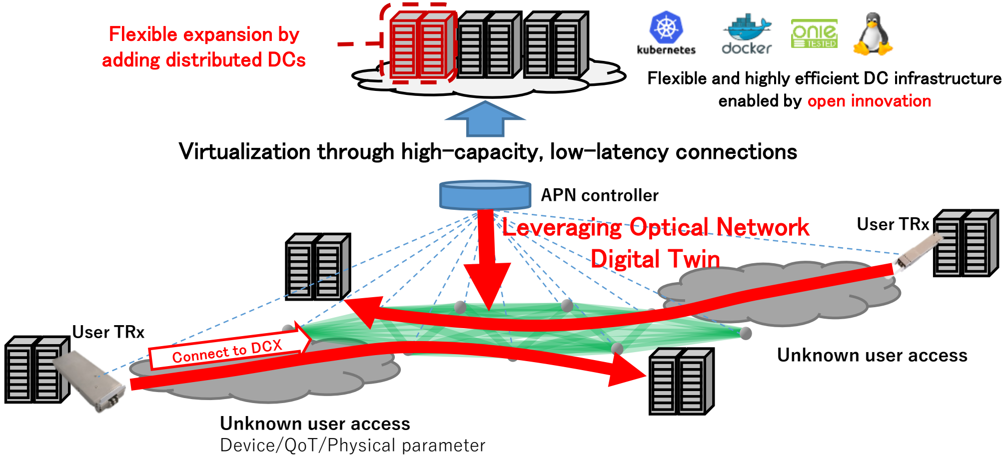
With digital technologies, beyond longer reach and lower power, open interfaces and SDN have advanced—expanding adoption from carriers to DC and cloud operators.



Leveraging the Optical Network Digital Twin for Distributed Data Centers

- Two key technological innovations: digital coherent and virtualization.
- Growing expectations for All-Photonics Network-as-a-Service (APNaaS) enabling a virtual large-scale DC across distributed metropolitan data centers.



H. Nishizawa, K. Anazawa, and T. Inui et al., "Leveraging Digital Twin Technologies: All-Photonics Networks-as-a-Service for Data Center Xchange in the Era of AI [Invited Tutorial]," arXiv preprint arXiv:2601.10153, Jan. 2026.

Requirements / Challenges

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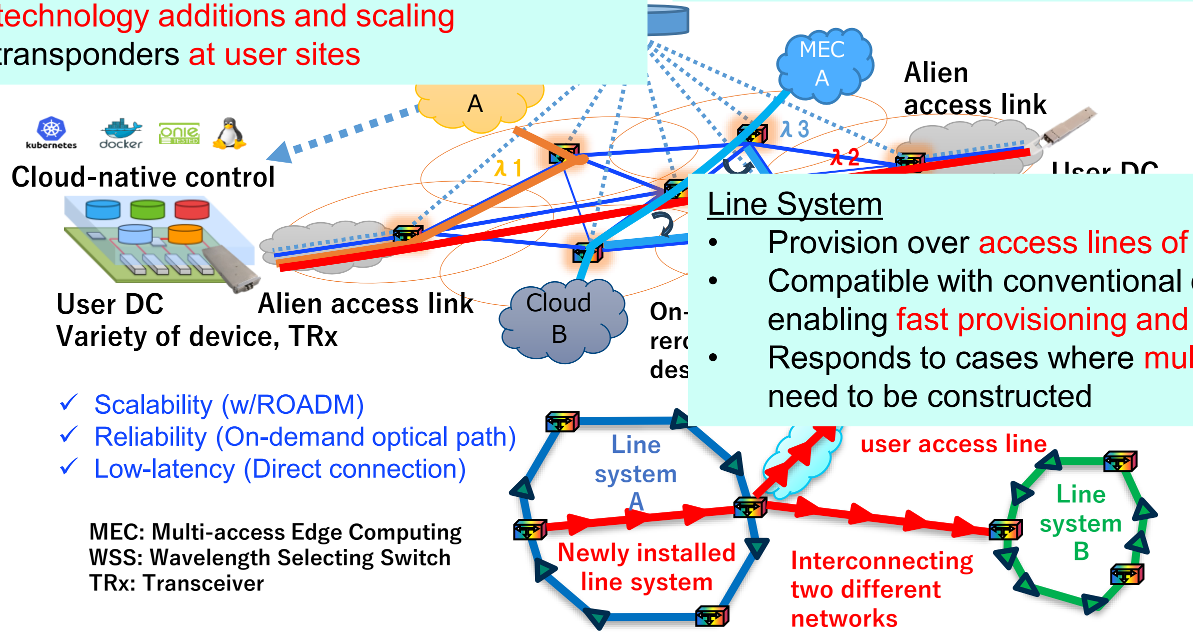
Controller
- Provisioning and rerouting based on user TRx characteristics
- Supports diverse topologies among arbitrary multi-points
- Automatic selection of the optimal mode based on distance and QoT

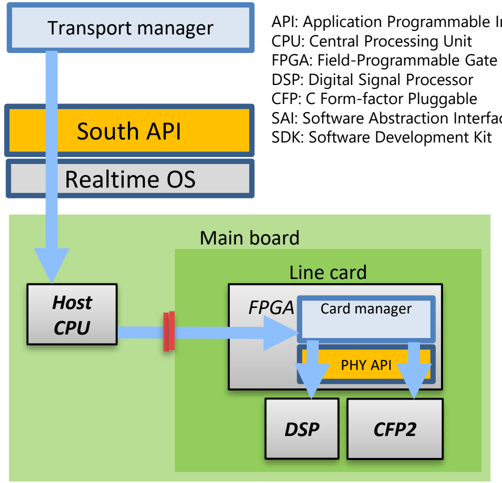
Transponder
- Operation of transponders equipped with different hardware components
- Adaptation to various NOS and Apps, enabling operator-driven future technology additions and scaling
- Operation of transponders at user sites



Line System
- Provision over access lines of unknown quality
- Compatible with conventional operation methods while enabling fast provisioning and fault localization
- Responds to cases where multi-vendor line systems need to be constructed

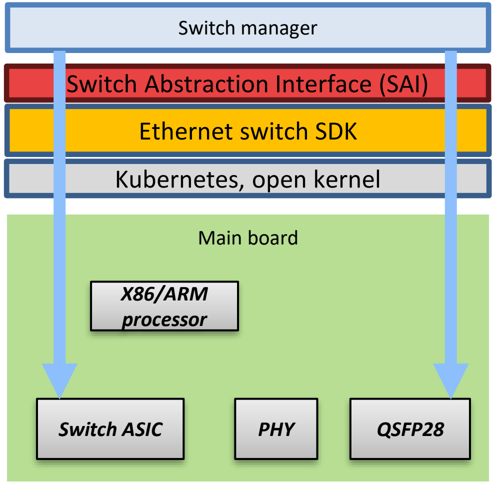
Cloud-native Architecture

- Traditionally, transponders have been developed using closed, tightly coupled hardware architectures under vertically integrated business models.
- From an operator's perspective, this opacity poses a barrier to open innovation and limits the adoption of advanced technologies such as automation and digital twins.
- The architecture of whitebox switches has embraced a clear separation between hardware and software.



API: Application Programmable Interface
CPU: Central Processing Unit
FPGA: Field-Programmable Gate Array
DSP: Digital Signal Processor
CFP: C Form-factor Pluggable
SAI: Software Abstraction Interface
SDK: Software Development Kit

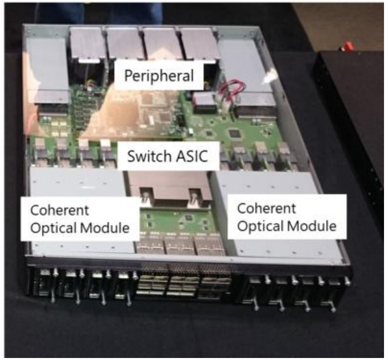
(a) Vertically integrated transponder



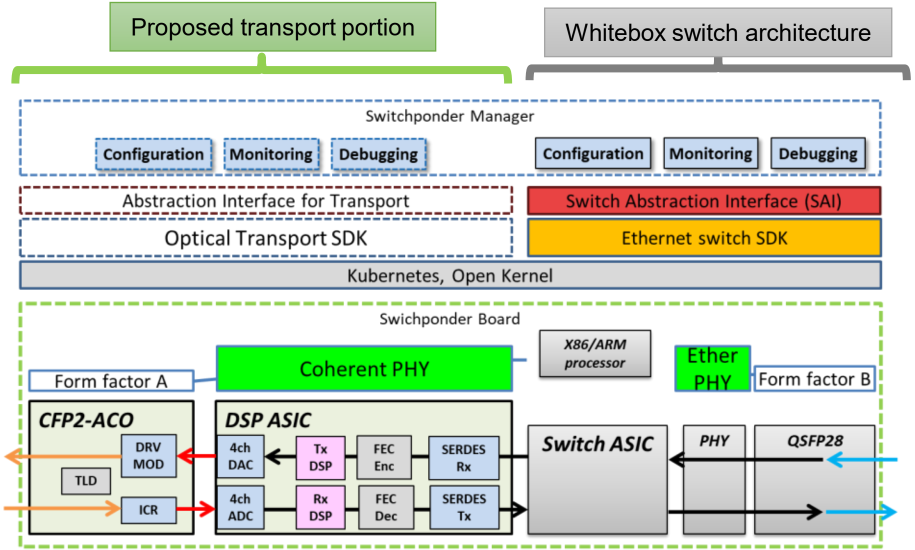
(b) Whitebox switch

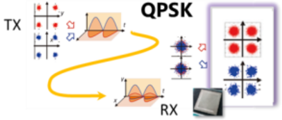
The World's First Multi-vendor Coherent Product

TIP and industry partners proposed a new architecture, launched Cassini commercially in 2018, and pioneered a new market.



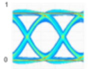
- 16x100Gbit/s QSFP28 ports and 8x200Gbit/s Coherent Optical Modules
- Broadcom Tomahawk+ ASIC (3.2T throughput)
- Redundant 60mm (3+1) FAN
- Redundant Power (1+1 PSU)





NOS: Network Operating System

NRZ (Binary)

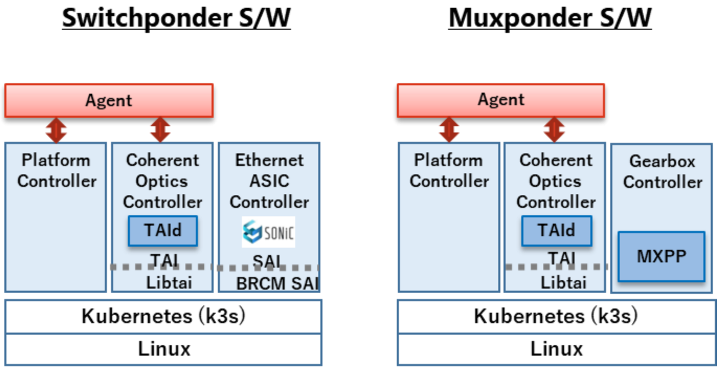


Cloud-native Switchponder/Muxponder

TELECOM INFRA PROJECT

ip infusion™ OcNOS

Switchponder S/W   Muxponder S/W

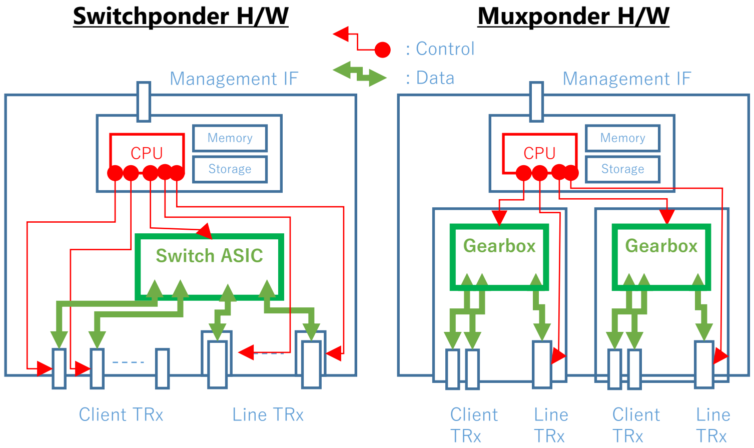


NEC

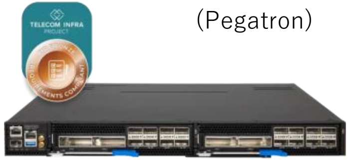
AGR 400
(Edgecore)

400G DCSG
(Ufispace)

Switchponder H/W   Muxponder H/W

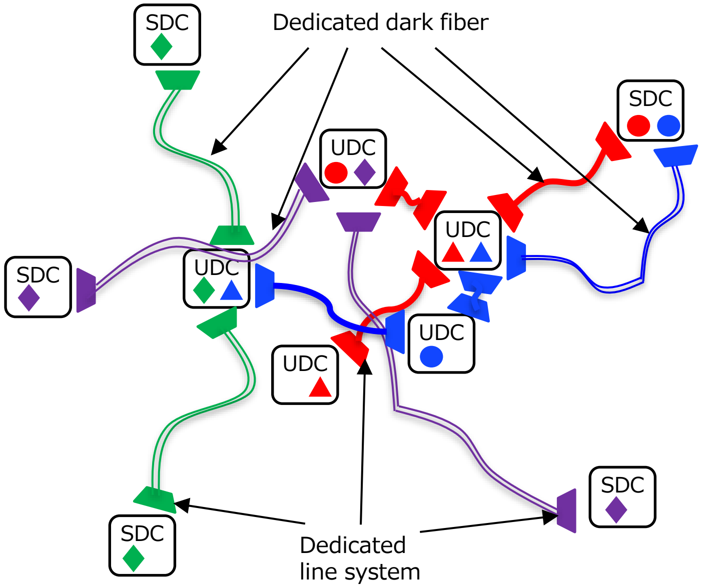


Endeavor
(Pegatron)



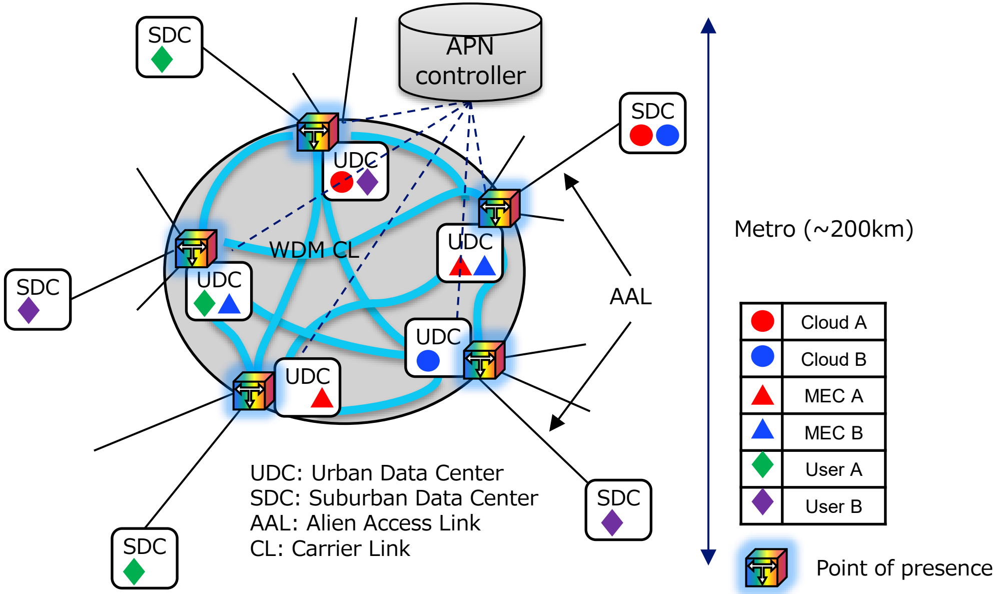
AMX 3200
(Edgecore)

Design for Data Center Xchange (DCX)



Topology: Point-to-point
Connection: Fixed
Configuration: Single vendor, single transmission mode

(a) Conventional DCIs with dedicated dark fibers/line systems



- ✓ Topology: Multipoint-to-multipoint
- ✓ Connection: On-demand (w/controller)
- ✓ Configuration: Multi vendor, various transmission mode

(b) Data Center Xchange with APN controller

Feedback Architecture Based on Open APIs

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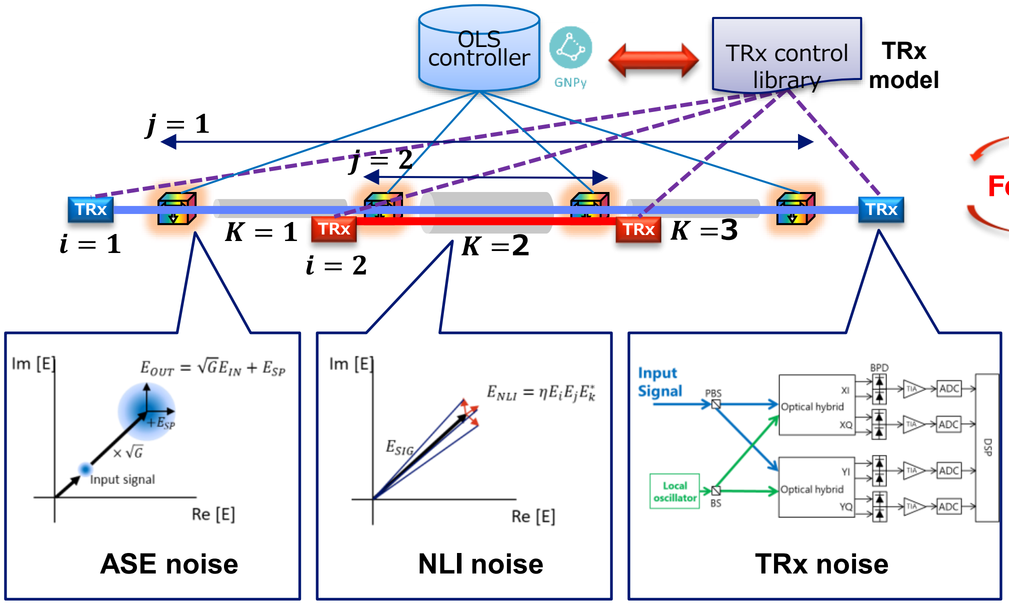
OLS: Optical Line System
TRx: Transceiver
Tx/Rx: Transmitter/Receiver

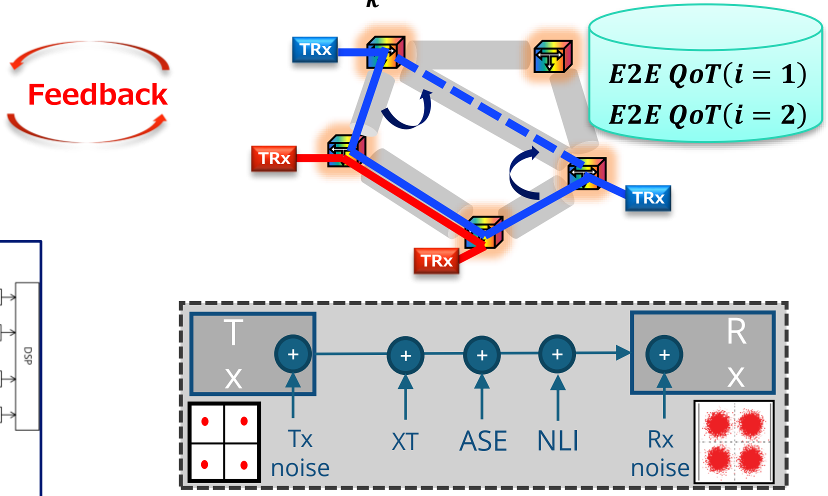
ASE: Amplified Spontaneous Emission
NLI: Nonlinear Interference
XT: Crosstalk

$$E2E\ QoT_{ij} = TRx_{\_Mod_i\_Baud_i\_SNR_{TRx_i}}(Rx\_in_i, GSNR_j)$$

$$GSNR_j^{-1} = \sum_k \left(SNR_{ASE_k}^{-1} + SNR_{NLI_k}^{-1}\right)$$



(a) Physical model

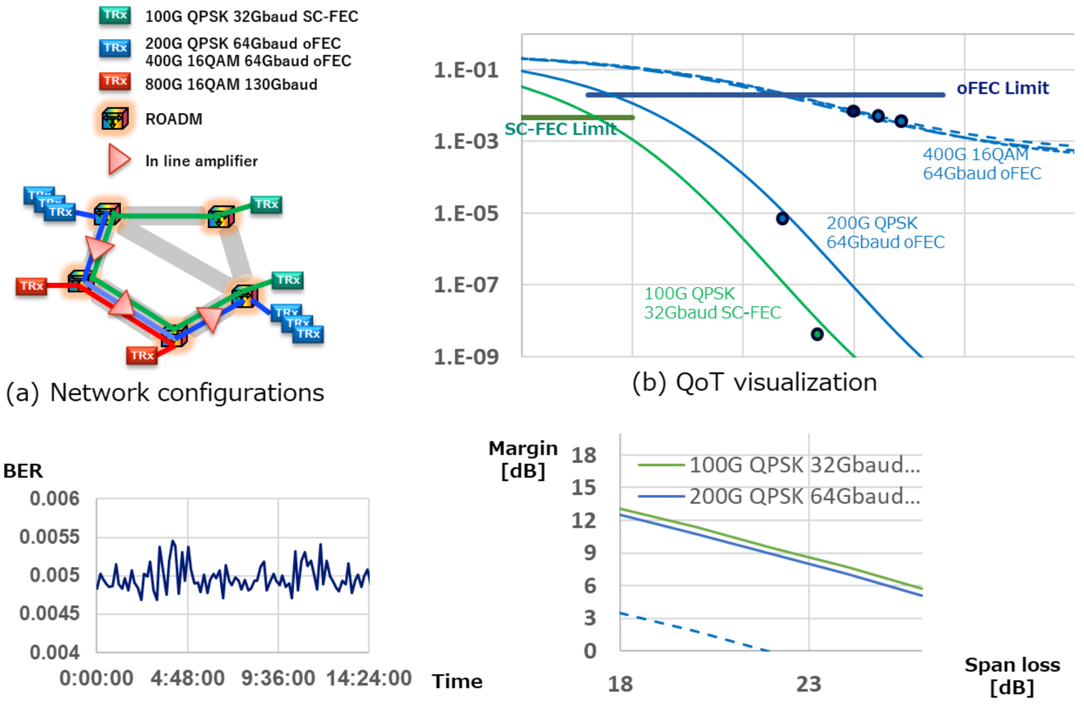


(b) Digital model

H. Nishizawa, T. Mano, and K. Anazawa *et al.*, "Optical Network Digital Twin — Commercialization Barriers, Value Proposition, Early Use Cases, and Challenges," *arXiv preprint* arXiv:2511.06368, Nov. 2025.

Value proposition and QoT visualization

- Freedom of device selection
- Topological flexibility
- Minimization of unnecessary margins
- On-demand provisioning
- Rapid restoration
- Proactive maintenance
- Flexibility in service-level



(a) Network configurations

(b) QoT visualization

(c) QoT history

(d) Aging degradation

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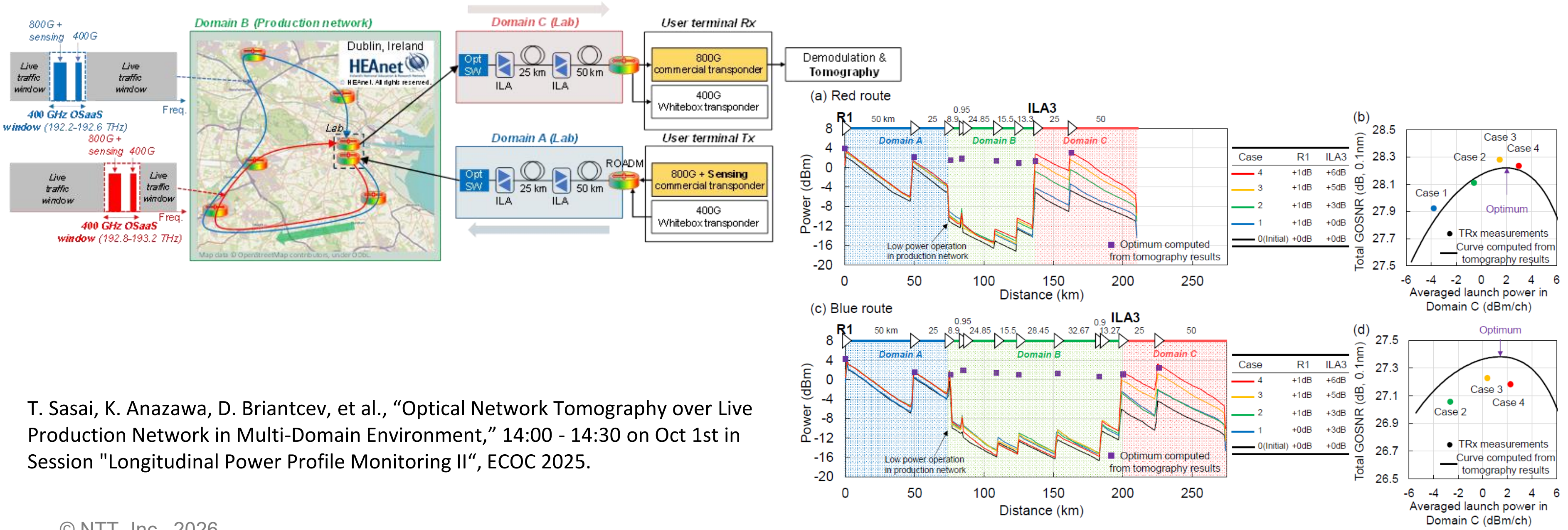
Optical Network Tomography over Live Production Network in Multi-Domain Environment

- Visualize end-to-end optical powers along multiple routes across multiple domains solely from a commercial transponder, enabling performance bottleneck localization, power and routing optimization, and lightpath provisioning at CONNECT testbed.



Case (a)	R1	ILA3
4	+1dB	+6dB
3	+1dB	+5dB
2	+1dB	+3dB
1	+1dB	+0dB
0(Initial)	+0dB	+0dB

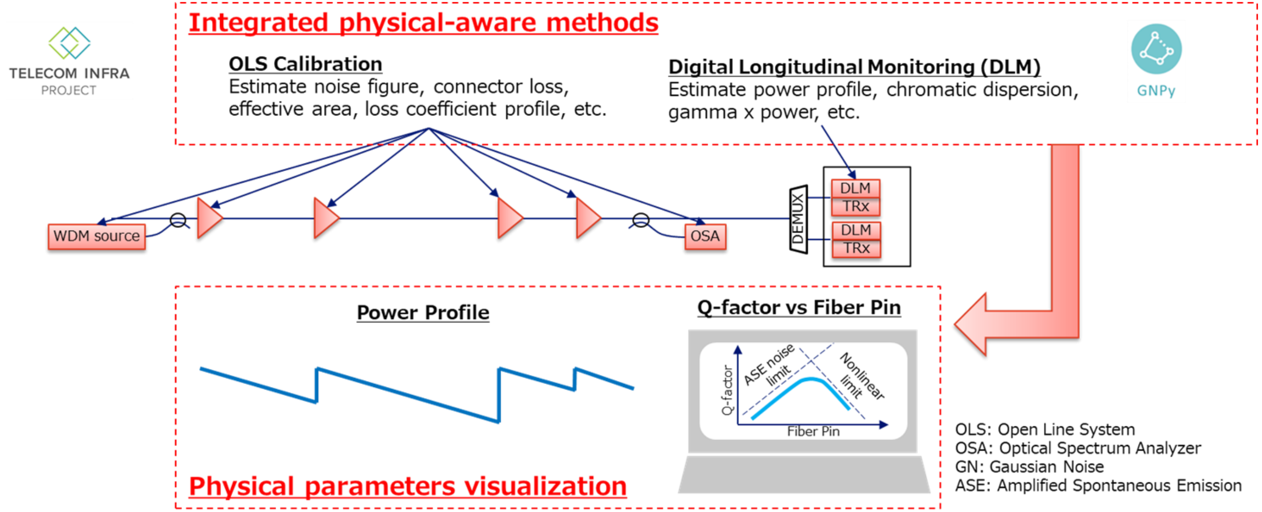
Case (c)	R1	ILA3
4	+1dB	+6dB
3	+1dB	+5dB
2	+1dB	+3dB
1	+0dB	+3dB
0(Initial)	+0dB	+0dB

T. Sasai, K. Anazawa, D. Briantcev, et al., "Optical Network Tomography over Live Production Network in Multi-Domain Environment," 14:00 - 14:30 on Oct 1st in Session "Longitudinal Power Profile Monitoring II", ECOC 2025.

A grant program (adoption number 50201) by the National Institute of Information and Communications Technology (NICT), Japan.
Taighde Éireann (Research Ireland) under 22/FFP-A/10598 (Twilights), 18/RI/5721 (Open Ireland), 13/RC/2077 P2 at CONNECT.

Link Parameters Extraction

- Perform link parameter estimation and refinement for automatic provisioning based on physical models
- Not a blackbox approach, including digital longitudinal monitoring and OLS physical parameter calibration method.



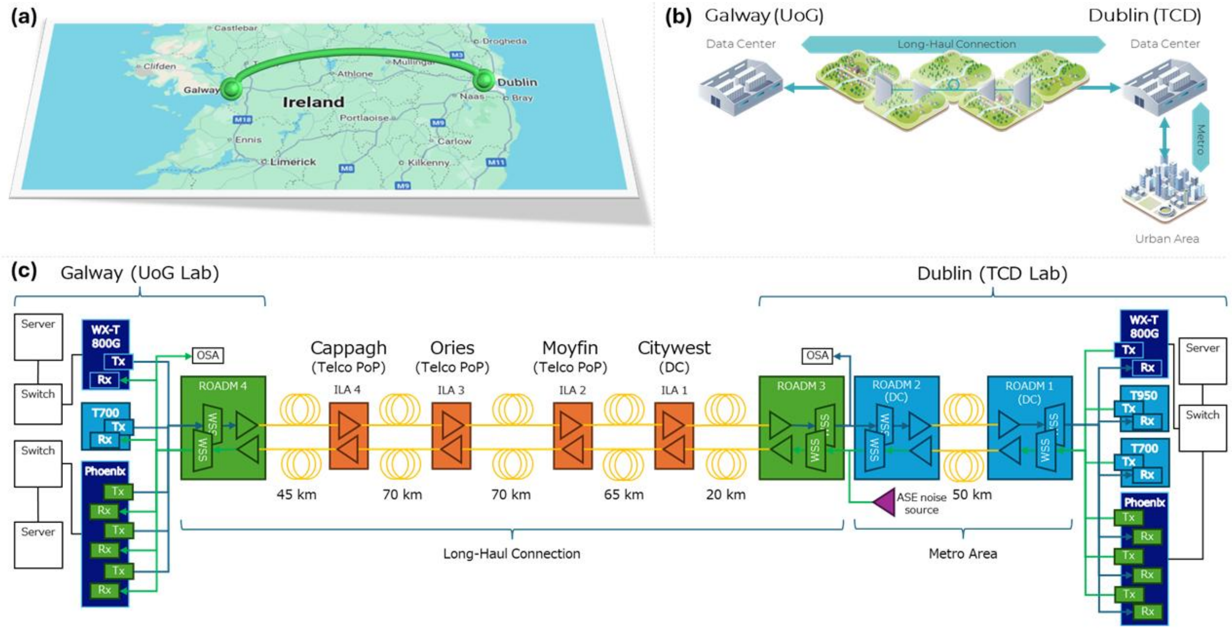
OLS: Open Line System
OSA: Optical Spectrum Analyzer
GN: Gaussian Noise
ASE: Amplified Spontaneous Emission

H. Nishizawa, G. Borraccini, T. Sasai, et al., "Semi-automatic line-system provisioning with an integrated physical-parameter-aware methodology: field verification and operational feasibility," Journal of Optical Communications and Networking, vol. 16, no. 9, pp. 894–904, Aug. 2024.

National Institute of Information and Communications Technology (50201); National Science Foundation (CNS-2211944, CNS-2330333).

Network Configuration for Accurate QoT Estimation

- An experimental validation was carried out at CONNECT testbed in Ireland over a fiber route of 280 km, including local station facilities, utilizing a line system constructed from devices of multiple vendors.



- Field-trial optical network connecting Galway and Dublin for data center applications.
- Dark fibers and amplification sites are deployed in field alongside the production network.
- Color variation indicates vendor differences.

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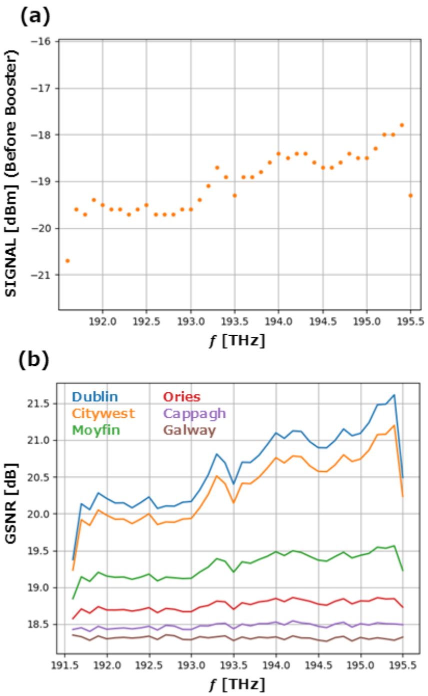
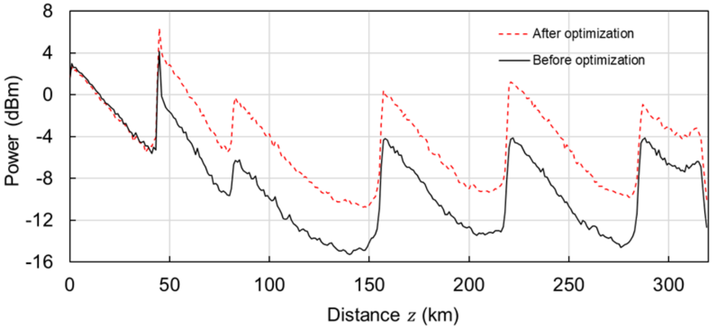
Experimental Results

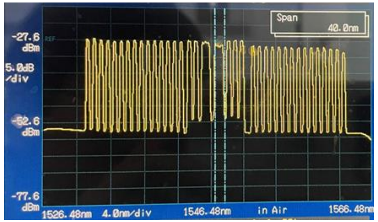
- Visualization of fiber and amplifier characteristics enabled remote optimization in a way compatible with conventional operations.



Calibration results for the OLS from Dublin to Galway.



Analyzed power profile with DLM.



Received WDM spectrum during validation, consisting of DLM 800G(130 GBd), 400G (63.1 GBd) and ASE noise loading (50 GHz) channels.

Fault Localization

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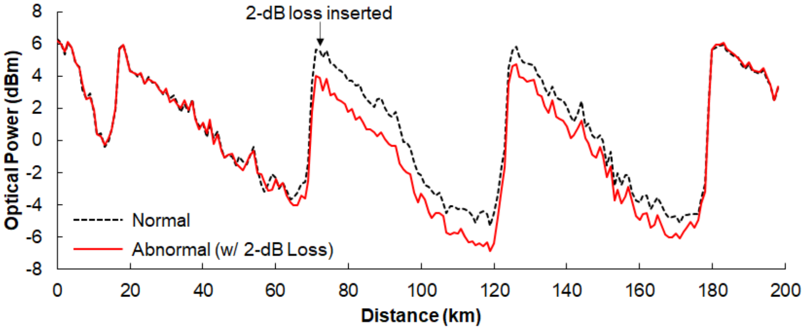
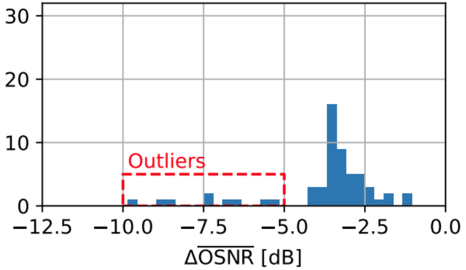
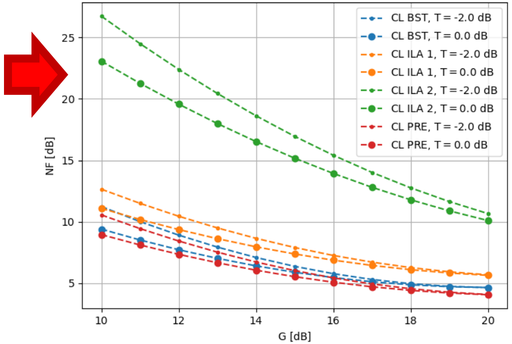
- Demonstration of a physical-layer-aware methodology to detect and localize network faults at Duke university testbed.
- In addition to reporting the anomalous loss of the connecting fiber, it is also possible to localize a degraded EDFA.



An 2-dB attenuator is inserted into the output of the EDFA #.





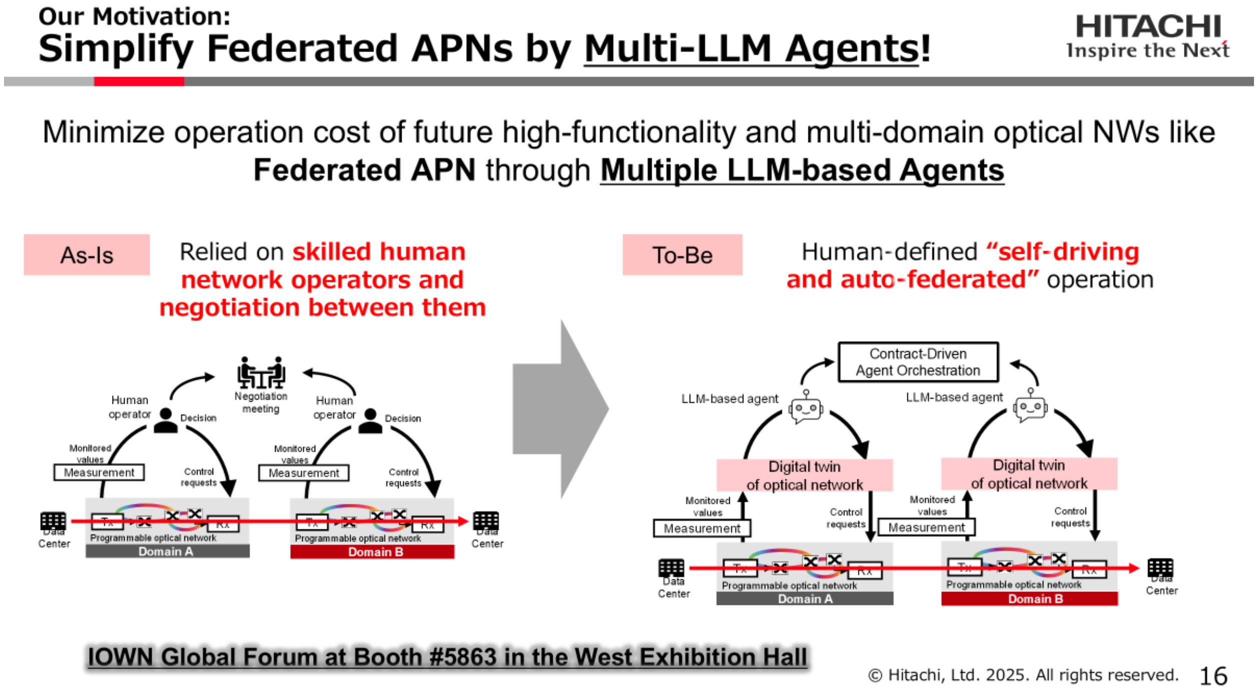
An 8-dB attenuator is inserted into the intermediate stage of the EDFA #3.

H. Nishizawa, G. Borraccini, T. Sasai, et al., “Field Verification of Fault Localization with Integrated Physical-Parameter-Aware Methodology Dynamic Optical Path Provisioning for Alien Access Links: Architecture, Demonstration, and Challenges,” IEEEE Photonics Conference, November 2024.

National Institute of Information and Communications Technology (50201);
National Science Foundation (CNS-2211944, CNS-2330333).

Next Challenge: Multiple LLM-based Agent

- Growing expectations for OPEX reduction and faster service provisioning through autonomous optical networks.
- Common metrics provided by an optical digital twin framework are crucial for delivering flexible services while ensuring infrastructure quality.



Conclusion

- Background
  - Emerging DCI: Low latency, Data security and privacy, Power supply limitation
  - The Evolution of Digitalization and Standardization

- Leveraging the Optical Network Digital Twin
  - Transponder: Cloud-native architecture

  - Controller: Feedback Architecture Based on Open APIs

  - Line system: Link parameter extraction with DLM and OLS cal

- Multiple LLM-based Agent
  - Common metrics provided by an optical digital twin framework are crucial for delivering flexible services while ensuring infrastructure quality.

Reference

- H. Nishizawa, T. Mano, K. Anazawa, et al., “Optical Network Digital Twin -- Commercialization Barriers, Value Proposition, Early Use Cases, and Challenges,” Arxiv, https://arxiv.org/abs/2511.06368.
- H. Nishizawa, K. Anazawa, T. Inui, et al., “Leveraging Digital Twin Technologies: All-Photonics Networks-as-a-Service for Data Center Xchange in the Era of AI [Invited Tutorial],” Arxiv, https://www.arxiv.org/abs/2601.10153.

Optical Network Digital Twin – Commercialization Barriers, Value Proposition, Early Use Cases, and Challenges

Hideki Nishizawa, Toru Mano, Kazuya Anazawa, Tatsuya Matsumura, Takeo Sasai, , Masatoshi Namiki, Dmitrii Briantcev, Renato Ambrosone, Esther Le Rouzic, Stefan Melin, Oscar González-de-Dios, Juan Pedro Fernandez-Palacios, Xiaocheng Zhang, Keigo Akahoshi, Gert Grammel, Andrea D’Amico, Giacomo Borraccini, Marco Ruffini, Daniel Kilper, Vittorio Curri

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