Digital Longitudinal Monitoring of Optical Fiber Communication Link

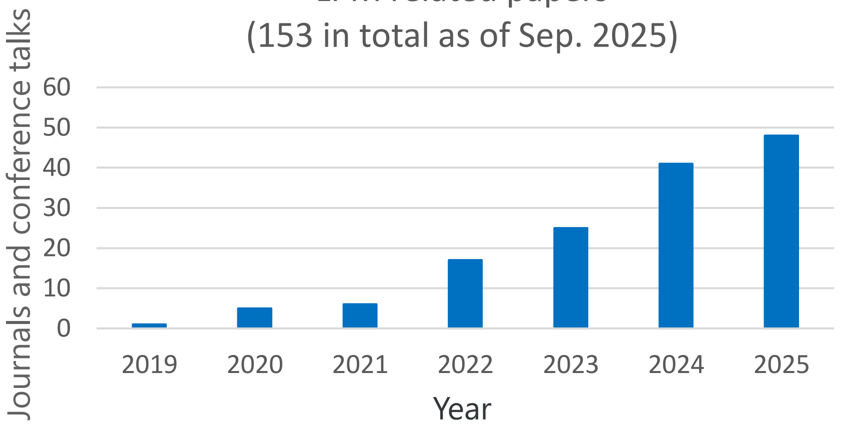
Takeo Sasai, NTT

Our Focus: Forward, distributed monitoring of fiber-optic network

- Distributed fiber sensing has been a hot topic in fiber-optic communications, with main focus on “backscattering-based” sensing
- “Forward distributed fiber sensing” (**longitudinal power monitoring / link tomography**) has also gained traction
  - Possibly deployed within a few years in real operational networks
- In this talk:
  - Similarities & differences between backward and forward distributed sensing
  - Why forward distributed sensing will be employed in networks within a few years

	Backward (OTDRs)	Forward	
		SOP-based	LPM
Physical Quantities	Amplitude, Phase	SOP	Nonlinearity (Phase)
Sensing target	Environment and Power	Environment	Power
Spatial resolution	~1 m	No localization	~1 km
Extra HW	Required	Not required	
Deployment	Dedicated	In-service	

Our focus today



...and 14 talks in ECOC2025
20 talks in OFC2026

Why physical layer monitoring matters in real networks

- OTDR
- OCM
- OSA

- Power monitor

DSP monitor
- CD
- DGD
- PDL
- SOP
- SNR
- BER

Why

- **Data capacity maximization**:
  - Optical power dominantly determines SNR
  - Insufficient and excessive signal power lowers data capacity
  - Needs optimization
- **Fault Management:**
  - Root cause analysis
  - Proactive maintenance and fault prediction
- **Network Automation:**
  - Closed loop control of monitor, analysis, and actions

Existing Methods

Equipment-based monitoring

✓ Offering robust and accurate measurement
- Not always available
- Probing interferes with live signals
- CAPEX and OPEX

Receiver-based monitoring

✓ No probing or equipment required
- Cumulative parameters only

Longitudinal power monitoring (LPM) at coherent receiver

- LPM visualizes distributed optical power solely by processing signals received at a coherent receiver
- Leveraging fiber nonlinearity (Self-channel interference) and chromatic dispersion to achieve spatial resolution
- Numerous advantages over conventional equipment such as OTDR

Advantages

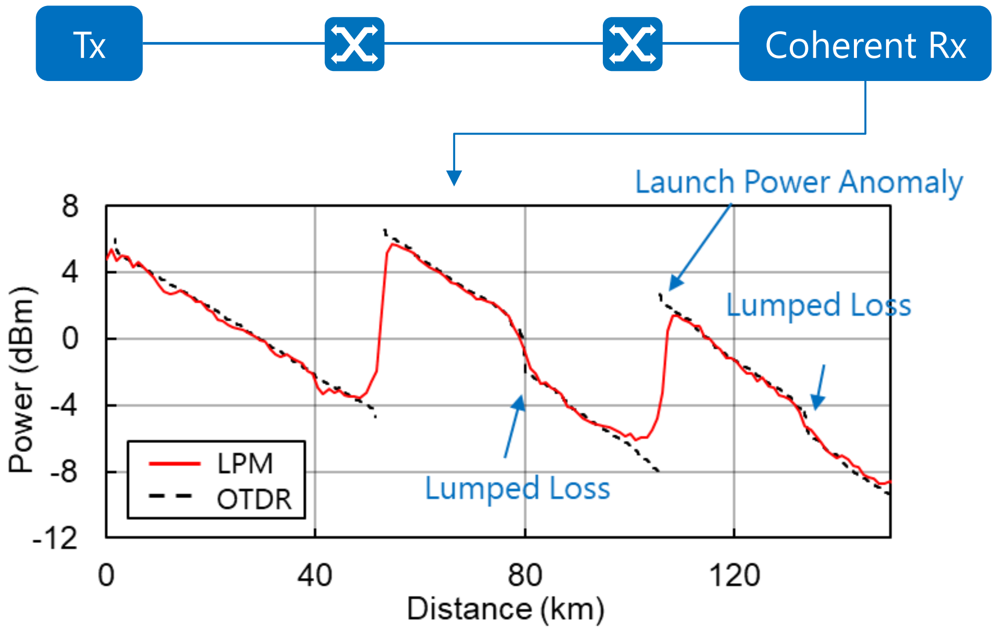
✓ End-to-end measurement
- Distributed forward sensing beyond EDFAs

✓ No need for dedicated equipment
- No reliance on probing light, OTDR, OSA, OCM

✓ No operation interruption
- Operates on live traffic, no impact on adjacent ch.

✓ Multi-functionality
- Power, CD map, PDLs, gain spectra, filter responses, etc.

✓ Low deployment cost
- Implementing software in modems or controller

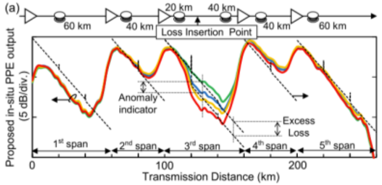


Sasai et al. OFC2024 PDP

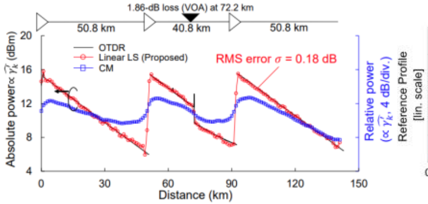
Technology Evolution

2019 → 2026

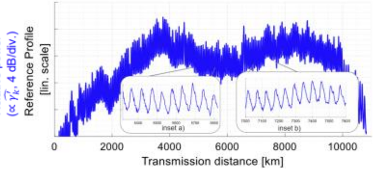
Performance improvement



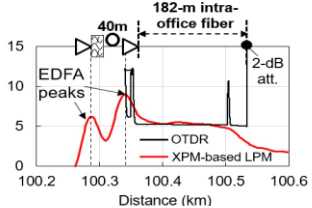
First demonstration of LPM
Tanimura et al. ECOC2019 PDP



Experiment approaching OTDR
Sasai et al. OFC2023



10000-km LPM
May et al., OFC2023



20-40m resolution LPM
Sasai et al. ECOC2025 PDP

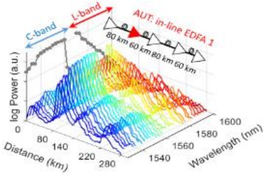
Functionalities

CD map
Sasai et al. OFC2020

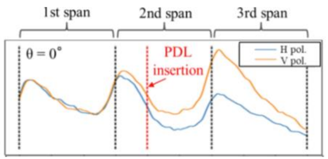
Filter responses
Sasai et al. ECOC2020

Spectral tomography in C band
Sasai et al. OFC2021

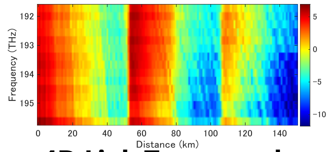
Multi-path interference
Hahn et al. OFC2022



Spectral tomography in C+L band
Sena et al. OFC2022



PDL localization
Eto et al. OFC2022
Takahashi et al. ECOC2023
Andrenacci et al. PTL2023



4D Link Tomography
Sasai et al. OFC2024 PDP

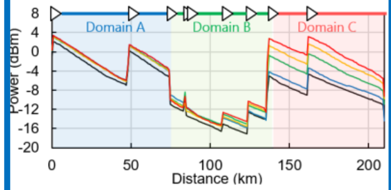
Applications/ implementation

Software prototype
Shinzaki et al., OFC2023

LPM using commercial transponder
Sasai et al., ECOC2023
Chang et al., ECOC2023

Provisioning using LPM
Nishizawa et al., IEEE Com Mag. 2023

Nonlinear SNR estimation using LPM
Kim et al., OFC2023
Andrenacci et al., JLT 2024

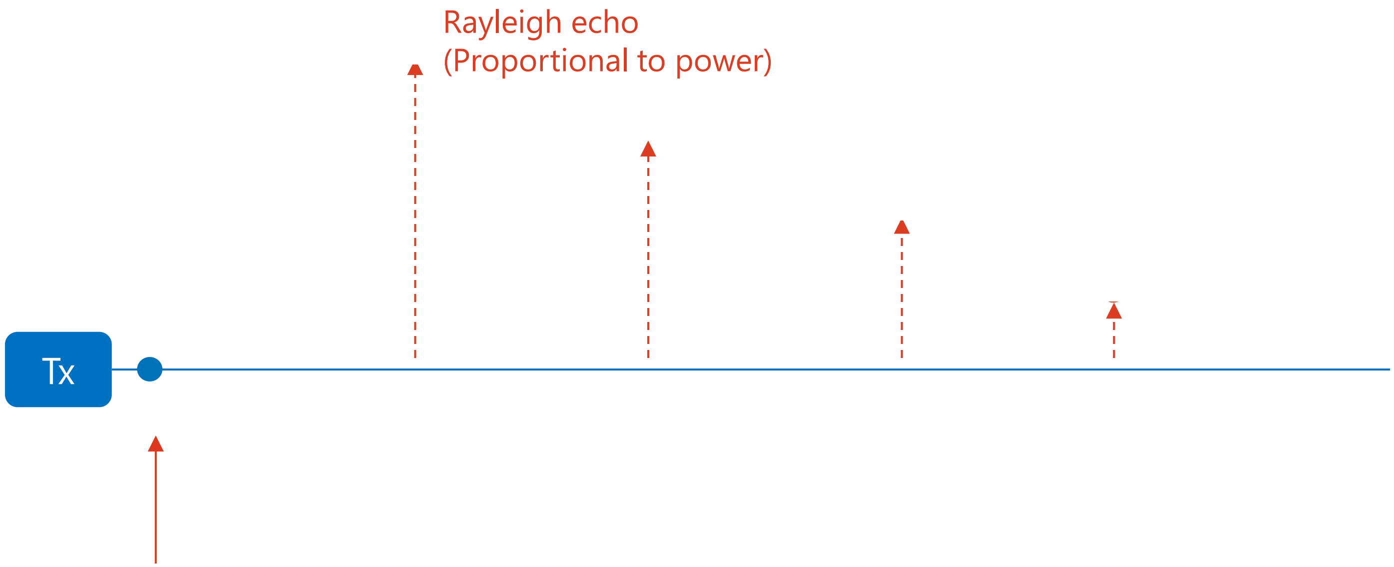


First trial over live network
Sasai et al. ECOC2025

First DSP implementation
Sasai et al. OFC2026

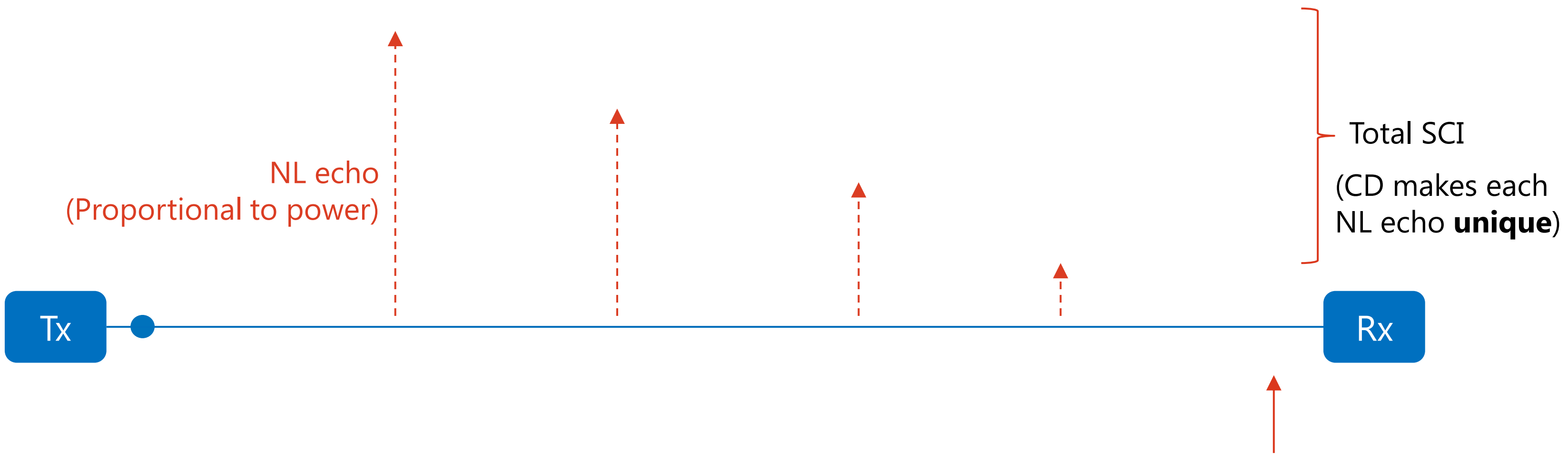
Outline

What they share: Physical picture (OTDR)



Spatial resolving based on different arrival time

What they share: Physical picture (LPM)



Spatial resolving based on **waveform uniqueness of NL echoes** created by CD

Where they differ

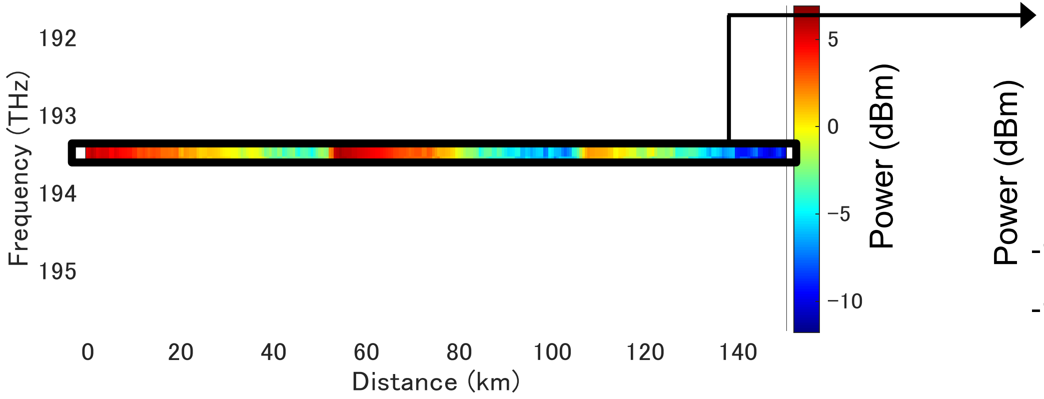
[1] Yokogawa, OTDR AQ7820 data sheet.
[2] A. May et al., OFC2022.
[3] T. Hoshida et al., OFC2025.
[4] T. Sasai et al., ECOC2025 PDP.

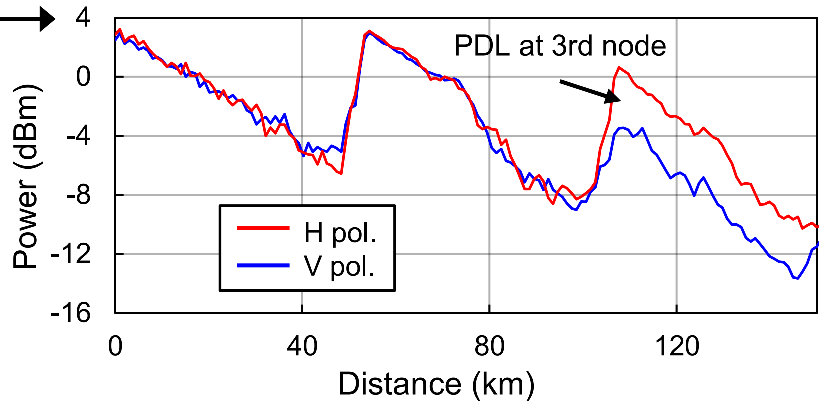
	OTDR (Backward)	LPM (Forward)
Accuracy	< 0.1 dB [1] (depends on position, averaging, power, pulse width)	0.2 dB ~ 2 dB (depends on position, averaging, power, β_2, BW, Δz)
Measurement range	One span (extendable with high loss loopback configuration)	Multi-span (10000 km demonstrated [2][3])
Spatial resolution	Sub-m ~ 500m [1] (depends on pulse width)	20 m~1 km [4] (depends on β_2, BW, Δz)
Functionality	Vibration Strain, temperature (**with** additional configuration)	CD maps, power spectrum, PDL, filter responses, etc. (**without** additional configuration)
Out-of-band probe light	Required	Not necessary
Additional optical components	Required	Not necessary
Interference with other channels	Yes	No
Fiber cut detection	Yes	No

Outline

Sasai et al. "4D link tomography:…"OFC2024 PDP

OFC2024 PDP: 4D Optical Link Tomography

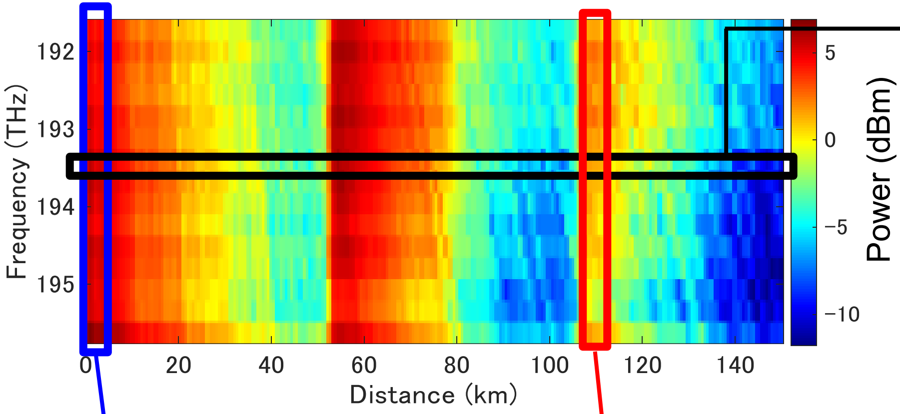


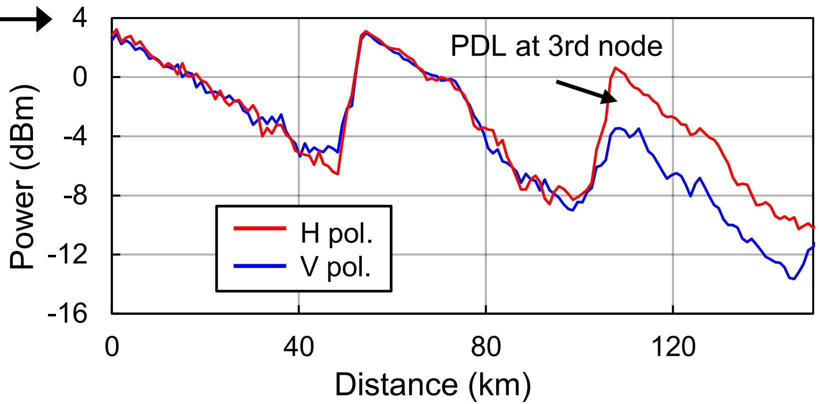


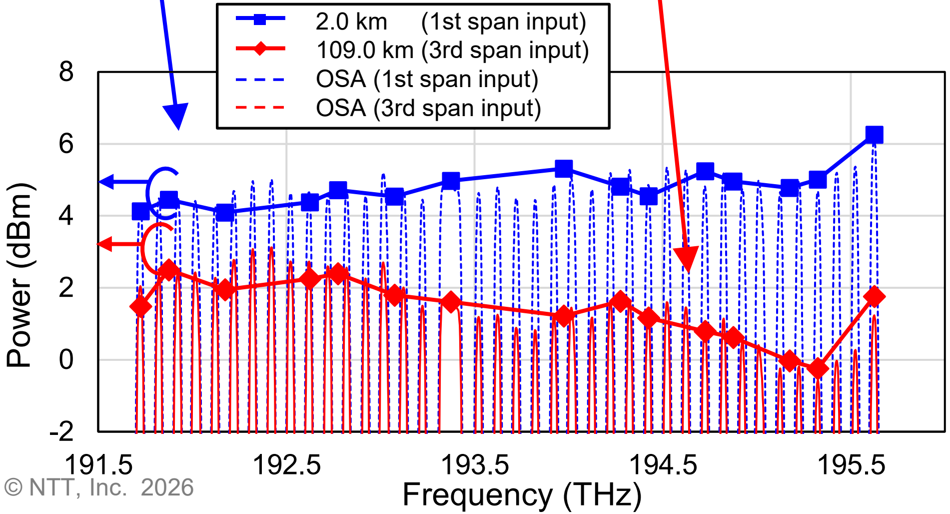
Polarization tomography

✓ Localization of PDL

OFC2024 PDP: 4D Optical Link Tomography





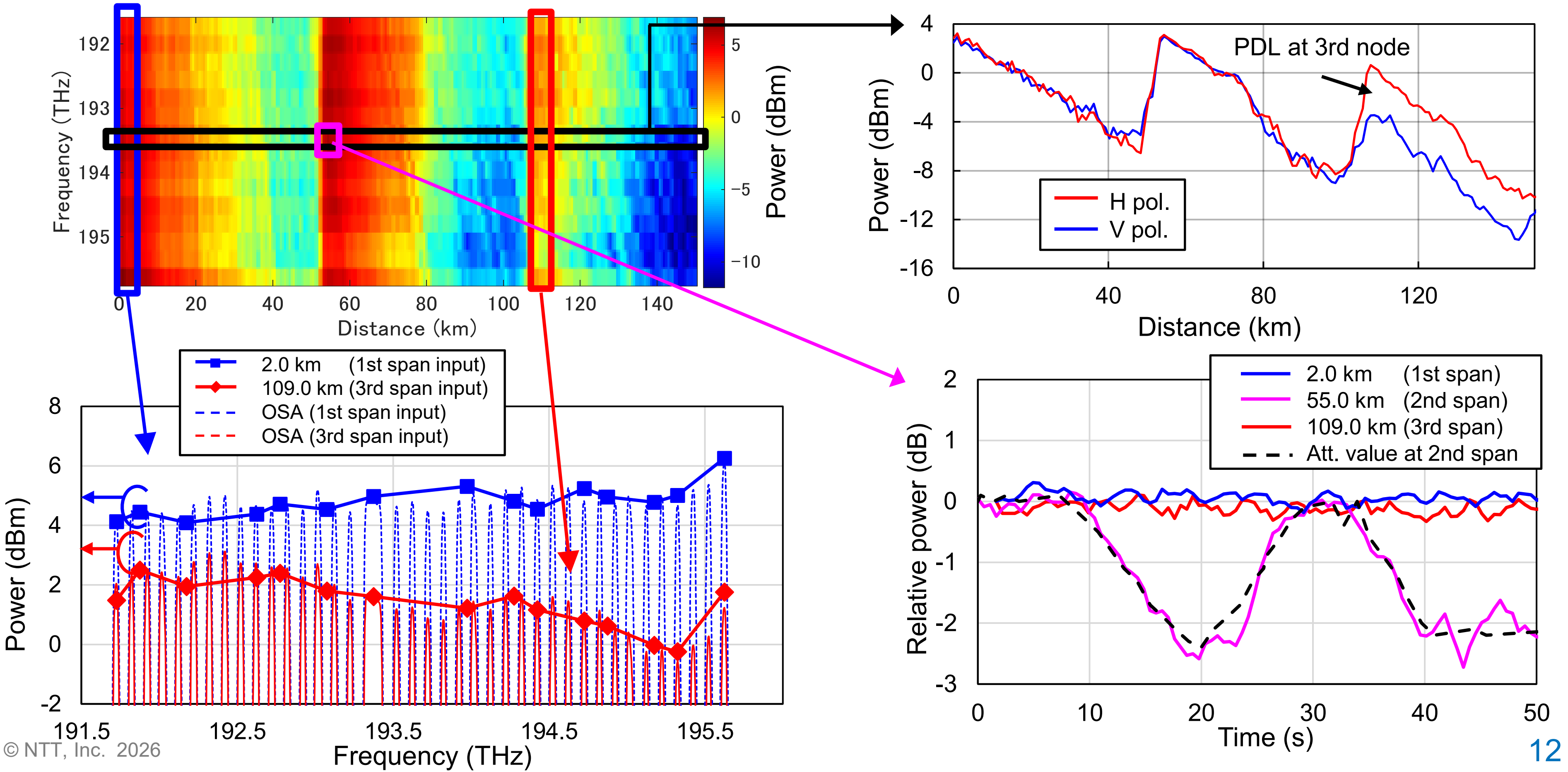


Polarization tomography
- ✓ Localization of PDL

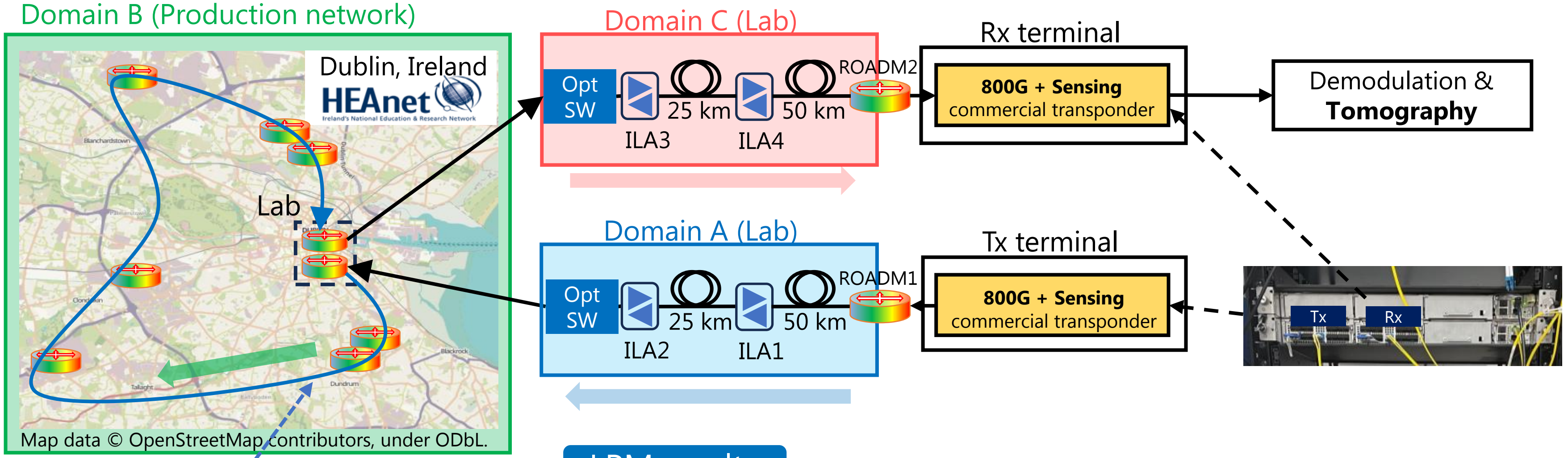
Spectral Tomography
- ✓ Max. error: 0.69 dB
- ✓ RMS error: 0.29 dB

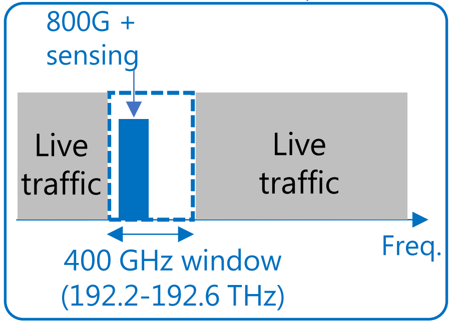
Sasai et al. “4D link tomography:..”OFC2024 PDP

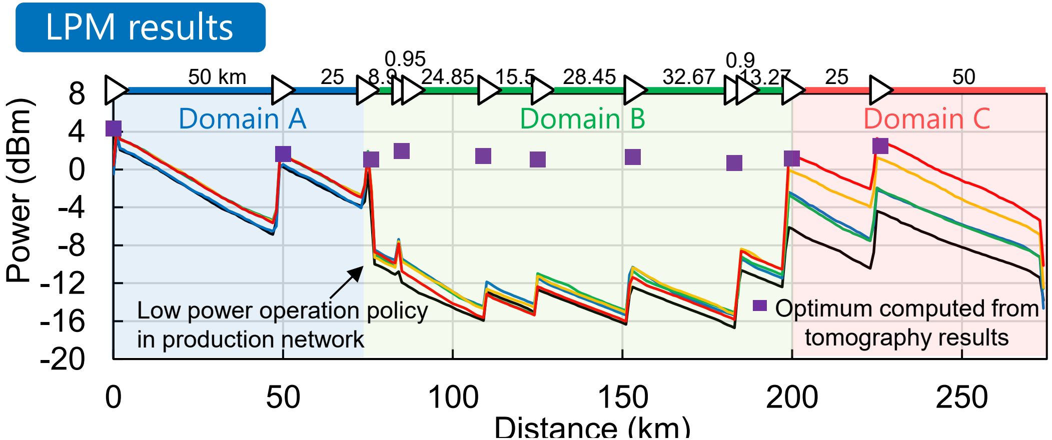
OFC2024 PDP: 4D Optical Link Tomography



ECOC2025: First trial over live network







OFC2026 PDP: First coherent DSP capable of distributed monitoring

Prior limitations

LPM was processed outside TRx

- Due to large computation and memory required for LPM
- All prior works relied on external processing

This work

✓ First coherent DSP integrating LPM

- **Fully** implemented **on real-time DSP chip**
- 1005-km range distributed monitoring

✓ Enabling LPM in coherent pluggables

- Using 800/400ZR+ signal, without specialized sequence
- Negligible power consumption overhead

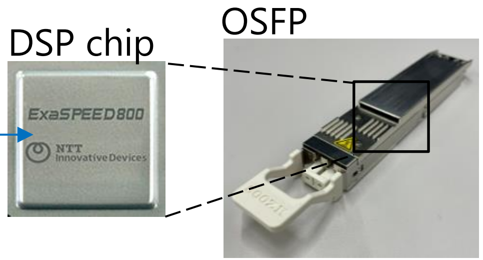
✓ Multi-vendor interoperability

- Works with third-party transmitters

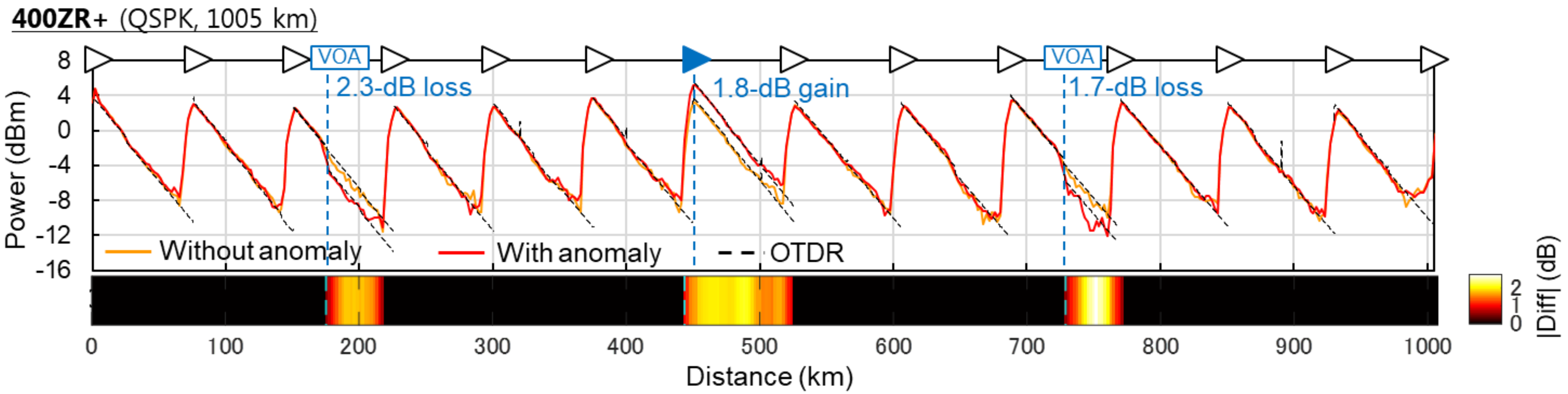
	Implementation location	Receiver type	Payload based	Interop-erability	Distance
[1]	Offline	Discrete	No	No	260 km
[2]	Offline	Transponder	Yes	No	900 km
[3]	Offline	Transponder	No	No	163 km
[4]	Offline	Transceiver	Yes	No	200 km
[5]	Rx-adjacent + controller	Transponder	Yes	No	~400 km
This work					

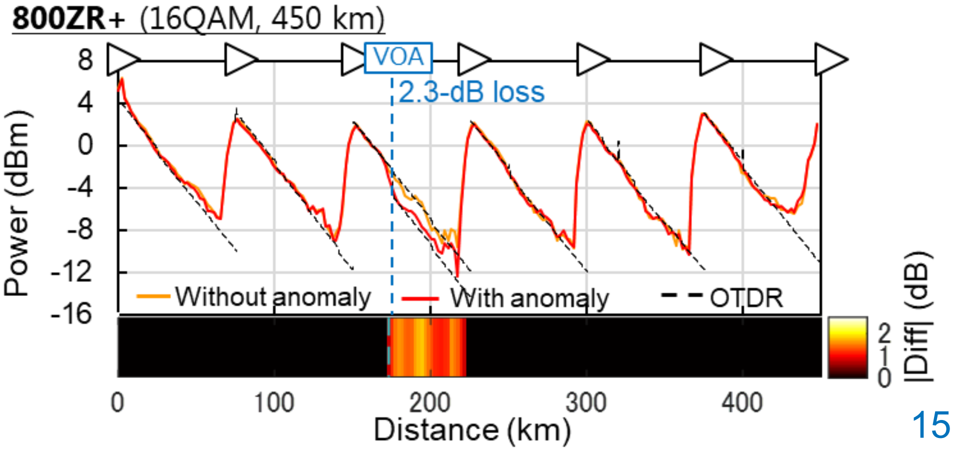
[1] Tanimura et al. ECOC2019 [2] Chang et al. ECOC2023
[3] Sasai et al. OFC2024 [4] Andrenacci et al. JLT2025 [5] Pacini et al. JOCN2025

LPM implemented on chip



OFC2026 PDP: On-chip LPM results



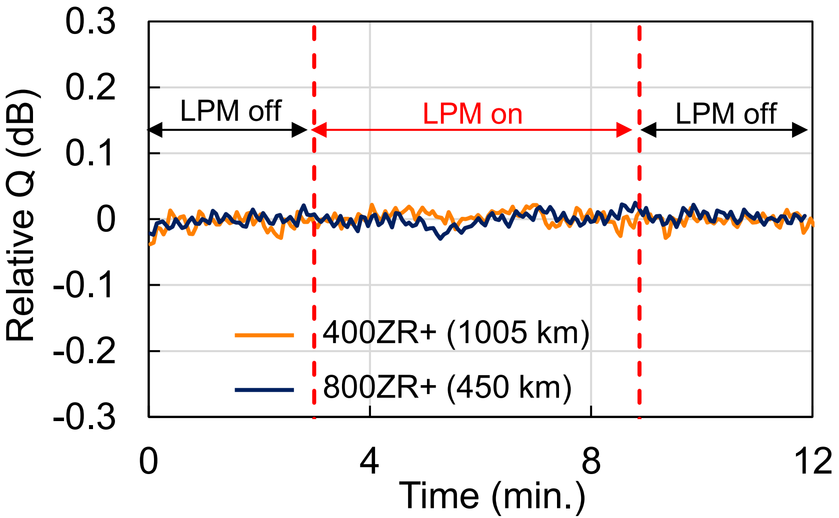


- ✓ Highly reproducible power for no anomaly spans
- ✓ Clear deviations for anomaly spans observed, localizing multiple ~2-dB losses
- ✓ RMS error from OTDR: 0.43 dB for 1005-km case
- ✓ Operates on standard ZR+ signals

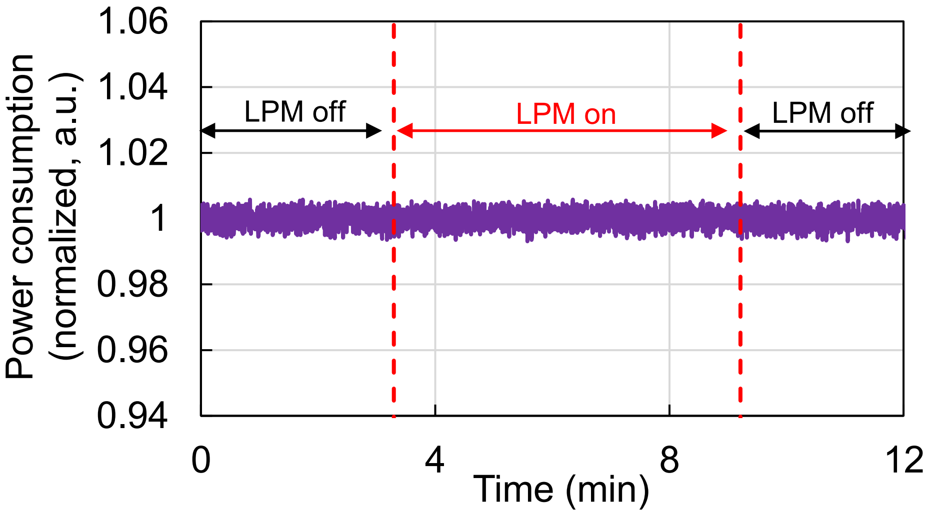
OFC2026 PDP: Transmission and power consumption stability

- ✓ Stable Q within ±0.04 dB (max/min) and post-FEC error-free observed, irrespective of LPM on/off
- ✓ No measurable increase in power consumption, satisfying the strict power constraints of OSFP
- ✓ Confirming genuine simultaneous communication and distributed monitoring

Pre-FEC Q stability



Power consumption stability



Outline

Why forward distributed sensing will be deployed within a few years

- Limited obstacles
  - ✓ **No impact on existing networks**: Operates on live signals; no dedicated probing required
  - ✓ **Limited cost**: Only software/firmware development on DSP involved
  - ✓ **Already implemented in coherent DSP**: LPM is available immediately, once operators deploy transceivers with LPM-integrated DSPs